The Study on the Stability of a Special Case of Small LPG Ball Tanker YUHWA No.2

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〈목 차〉

Chapter 1 Outline of the accident of sunken M/T YUHWA No.2

1.1 The vessel

- Name: YUHWA No.2
- Type: LPG ball tanker
- Flag: PANAMA
- Registered No.: 17474-87-B
- Owner: YUHWA MARINE S.A.
- Gross tons: 1320 tons
- Master's name: Joon-iee Choi (Korean)
- Date of accident occurred: 29th Jan. ,1998
- Place of accident occurred: Yosu harbor

1.2 The outline of the disaster

M/T Yuhwa No.2 finished temporary repairs on the rail dock of Cho-Yang Shipyard in Busan, Korea sailing for Yosu, Korea and arrived at pilot station of Yosu at 0500 hours on 26th Jan., 1998 and pilot boarded at 0900 hours and got alongside to pier No.1 in Sam-il harbor which lies in the inner side of Yosu at 1140 hours on the same date. She loaded 1037.2 K/T of Butadiene during 1210~1950 hours and scheduled to sail soon for Kaoshiung, Taiwan on the same date but she stopped sailing because in Taiwan they celebrate Lunar New

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Year until 2nd Feb., being 28th of Jan. the first day of Lunar New Year.

So Yuhwa No.2 left loading pier at 2110 on 26th and arrived at Yosu outer harbor at 2230 hours and dropped anchor at anchoring berth A for waiting and re-scheduled to sail at 1200 hours on 29th of Jan. after celebrating themselves Lunar New Year.

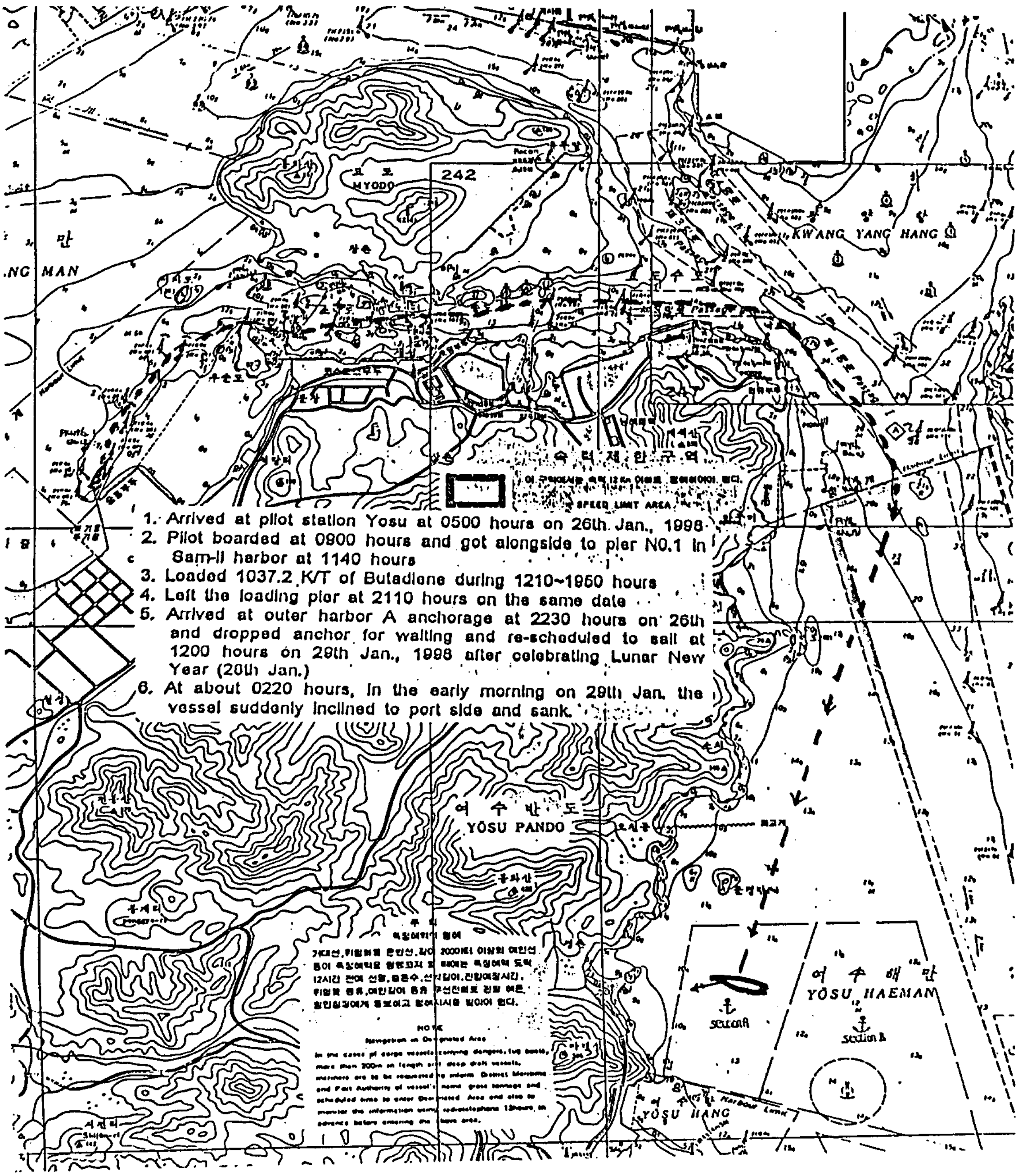


Fig. 1.1 The accident of YUHWA No.2 in Yosu harbor

On the way to Yosu outer harbor from the pier, the master of Yuhwa No.2 insisted some unknown shock felt on the hull navigating through Myodo channel but it could not be certified to be true or not. During the waiting with anchoring in the early morning of 29th, the vessel suddenly inclined to port side and the degrees of inclination was so great that much quantity of sea water flooded successively through the scuttle of crew's toilet on the main deck under the port side of poop deck and the flooded water rushed into engine room through the passage above engine room top and the vessel started sinking soon from the stern but as the depth of water was of 15*m* the stern was touched down to the sea bed and the bow part of the vessel floating above the water. The bow part kept floating above the water inclining to port side due to buoyancy of submerged cargo tanks without capsizing until she was rescued and righted up by salvage works. All of the crew were rescued except 2nd officer who was missed during the sinking. Chief officer (Korean) who was on board when the accident occurred made testimony that he was sitting on the chair in his cabin and was fallen down suddenly on the flour due to sudden great degree inclination of the vessel to port side at about 0220 hours on 29th, Jan. and got up hurrying up to the bridge and found all movable things were shifted to port side leaning to the port-side wall of the bridge and felt the inclined degree of the vessel to be about 15 degrees and he immediately called port authority by VHF requesting rescue. Ordinary sailor (Indonesian) ANDI PANANRINGI made testimony that he ate night meal at about 0130 hours on 29th and went to toilet on main deck under portside poop deck to urinate. During his urinating the vessel suddenly inclined to port by great degrees and sea water rushed into the toilet through the opened scuttle and he hurried up to the bridge shouting help.

By the above testimony we can assume the time accident occurred to be about 0220 hours on 29th and the great degree inclination occurred suddenly but it is unimaginable that sea water would rush through the scuttle into the toilet on the main deck due to the inclination of only 15 degrees which was testimonied by chief officer. Perhaps the inclination might be more than 15 degrees.

Chapter 2 Observation on the nature of the accident

About the weak point of transverse stability of small ball tankers

Generally a small LPG tanker has cargo tank of ball type, the geometric center of which lies on the height of main deck level above the keel line. Such a vessel as a ball tanker may happen to be unconsciously under the condition of being dangerous great degree inclining or capsizing when both of bottom tanks and cargo tanks have free water surface simultaneously. Cargo tanks of ball type have to be put on higher level from the keel line than that of ordinary people would expect because a ball type tank endurable to high pressure can not be put down deeply into the hull due to the type of ball and the free surface effect of liquefied gas cargo in cargo tanks is great when the tanks are not fully loaded. So on board of a ball tanker simultaneous operation of cargo work and ballast operations of bottom tanks are to be avoided

Even in Japan in the early stage of ball tanker operations they often experienced many dangerous situations due to sudden great inclination of more than 15 or 20 degrees in few seconds during cargo work operations of G/T 5,000-ton class tankers because they operated cargo and ballast simultaneously without expecting any danger and then they stopped cargo works until they right up the inclined vessel by ballasting the bottom tanks fully. After then they separated cargo work and ballast operation. Nowadays when it is unavoidable, they operate ballast, tank by tank, limiting ballast operation to one pair of tanks during cargo operation.

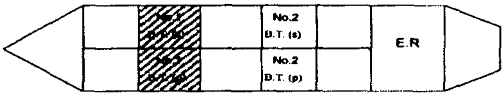


Fig. 2.1

For example in figure 2.1 they finish ballast operation of No.1 ballast tank and after then they start ballast operation of No.2 ballast tank. A gas tanker company in Japan invited a disaster by amending center girders of double bottom ballast tanks of G/T 5,000-ton class ball tankers.

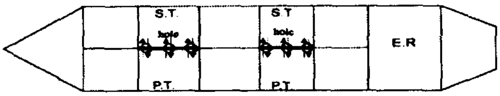


Fig. 2.2

The gas tankers had double bottom ballast tanks separated to port and st'd by a water-tight center girder when they were built. The company made holes on the water-tight center girder to make the ballast tanks to act as anti-rolling tanks by giving a phase difference between the period of water flooding from one side to another and that of ship's rolling. But this attempt caused a great disaster and the attempt failed and they stopped the attempt by recovering the center girder as water-tight as original.

The disastrous accident caused by the miscalculated attempt was as following; About 7 years ago from now a ball tanker naming M/T Tropi Gas (G/T 5,400-ton) the double bottom tanks of which were amended to be given a role as anti-rolling tanks loaded propylene (density about 0.53) in an Arabian port and sailed for Borneo South-East Asia and disappeared after she passed Ceylon Island and all crew of 18 were missed. When the missing occurred sea had been smooth and the missing was a mystery. But in the process of investigation they found a surprising fact in the explanation told by a chief engineer who had served on board M/T Tropi Gas. He told that M/T Tropi Gas had sudden inclination of over 20 degrees 3 times during doing cargo work and ballast operation simultaneously. The inclination occurred in a few second and the confused crew strongly requested the chief officer to make statement that he should not do dangerous all tanks ballast operations and cargo work simultaneously and also not do ballast operations which would render great free surface effect at sea. Then the chief officer made such statement as requested. Other tankers of the same company experienced similar inclinations and they remade the center girders as water-tight as original because the causes of missing became clear. Generally an inclination of great degrees due to big free surface effect occurs in few seconds and makes crew so confused that they can not consider any counter- measure quickly.

The moment of inertia of a free surface of a square tank can be expressed as $\frac{1}{12}lb^3$.

where, l :length of the free surface

b :breadth of the free surface

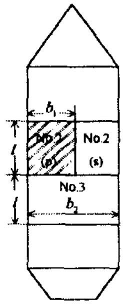


Fig. 2.3

On the Fig. 2.3 the second moment of tank No.2 free surface is $2 \times \frac{1}{12} l b_1^3$ and that of tank No.3 free surface is $\frac{1}{12} l (2b_1)^3 = \frac{8}{12} l b_1^3$. The free surface effect of tank No.3 is 4 times as great as that of tank No.2. Therefore when water floods into a void tank that is not divided to port and st'd tank by longitudinal water-tight bulkhead, dangerous situation leading to capsizing will develop. The reason that great degree inclination happens in calm water suddenly is as following; When the free liquid in cargo tanks or ballast tanks remains quiet, their free surface effects do not exert their effects but when liquid swings due to ship's little swings the free surface exerts its effect suddenly and the center of gravity of a vessel goes up at an instant up to the height of metacenter M or over the height, making the value of GM very small or (−) value. When a vessel seemingly being under good condition of stability forms unconsciously a condition that makes large free surface (for example; ball LPG tanker with half loaded cargo tanks and half ballasted bottom tanks) will become unstable at an instant of few seconds due to gradually enlarging free surface area and incline to great degrees leading to capsizing.

Chapter 3 Study on the causes of the accident of YUHWA NO.2

3.1 Stability calculation of YUHWA NO.2 at the time of leaving from the pier after loading in Sam-il harbor

It will be a shortcut to calculate the GM of the vessel at the leaving stage of the voyage for investigation of finding the causes of the accident that occurred due to the short of stability.

3.1.1 KG and GM calculation

The value of KG is same as in table 3.1

〈Table 3.3〉 KG calculation of YUHWA NO.2 at the time of leaving from pier

Item	W	KG	Mt	
Light condition	996	4.47	4452.12	
Crew's possession	1	7.88	7.88	
Store	4	6.02	24.08	
Provisons	1	6.54	6.54	
F.W.	70	1.38	96.60	
Ballast	0.5×8=4	0.1	0.4	Note 2
Permanent Ballast	101.6	0.33	33.53	Note 1
No.5(P) F.O.(A)	(46KL×0.9) 41.4	1.39	57.55	
No.5(P) F.O.	〃	1.39	57.55	
No.6(P) D.O.	(10KL×0.83) 8.3	1.51	12.53	
No.6(S) D.O.	〃	1.51	12.53	
No.7 F.O.	(3.5KL×0.85) 3.0	0.73	2.19	
L.O. tank	(1.5KL×0.98) 1.47	5.28	7.76	
No.1 cargo tank	518.6	4.90	2541.14	
No.2 cargo tank	〃	4.50	2333.70	
Total	2318.67	4.16	9646.10	

Note 1: 3 blocks of permanent ballast consisting of gravels mixed with sand were cemented on the bottom of the void tank as shown in Fig. 2.4 of attached sheet 2. The total weight of the blocks is 101.6 ton and Japan Company put them when the company operated her.

Note 2: Fore peak tank, NO.1 (P), NO.1 (S), NO.2 (P), NO.2 (S), NO.4 (P), NO.4(S) and after peak tank were empty but 0.5 ton of remain was assumed for each of the tanks and 0.1 *m* height of the remains and it is not necessary to consider free surface effect of the above tanks.

In table 3.2 we find mean draft $4.4\ m$ from the displacement of 2318 ton. So we find 1 ton difference between 2318 ton and 2319 ton and as T.P.C. is 6.5 ton, $1 \div 6.5 = 0.15\ cm$ is draft increase due to 1 ton. We can disregard the increase and mean draft is $4.4\ m$. Master of the vessel testified about the draft as F_d: $3.8m$, A_d: $5.0m$ and in Inspection certificate made by Pan Korea Surveyors Corp. we find the draft as F_d: $3.85m$, A_d: $5.05m$. By now we can not assure which was true but can assume the trim of the vessel as 1.2 m by the stern because both sides accord about the value of the trim as 1.2 m.

Therefore the draft at the time of the accident can be assumed as F_d: $4.4-0.6=3.80m$, A_d: $4.4+0.6=5.0m$ and d_m: $4.40m$.

From the table 3.2, we find KM= 5.26 m when the mean draft is 4.4 m.

$KM = 5.26\ m$ (See Table 3.2)
$KG_0 = 4.16\ m$ (Computed in Table 3.1)

$G_0M = 1.10\ m$

The sufficient value of GM of $1.1m$ as that of a small ball tanker is due to the permanent ballast placed on the bottom of the void tank by the Japan Company because they might have to find the GM of this vessel as insufficient.

〈Table 3.2〉 Various values of Hydro-Static Curves of M/T YUHWA NO.2

d (M)	w (t)	T.P.C (t)	M.T.C (M)	K.M.T (M)	KB (M)	0B (M)	0F (M)
2.0	896	5.41	16.35	6.79	1.10	-1.48	-1.44
2.1	950	5.46	16.65	6.59	1.16	-1.48	-1.42
2.2	1006	5.50	16.90	6.42	1.21	-1.48	-1.39
2.3	1062	5.54	17.20	6.27	1.26	-1.47	-1.36
2.4	1116	5.58	17.45	6.13	1.32	-1.46	-1.33
2.5	1174	5.62	17.75	6.01	1.37	-1.45	-1.30
2.6	1230	5.66	18.03	5.90	1.43	-1.44	-1.26
2.7	1286	5.70	18.30	5.80	1.48	-1.43	-1.22
2.8	1344	5.74	18.60	5.72	1.54	-1.42	-1.18
2.9	1400	5.78	18.90	5.64	1.59	-1.41	-1.13
3.0	1460	5.82	19.20	5.57	1.64	-1.40	-1.09
3.1	1518	5.85	19.53	5.51	1.70	-1.38	-1.03
3.2	1578	5.89	19.85	5.46	1.75	-1.37	-0.98
3.3	1636	5.93	20.20	5.41	1.81	-1.35	-0.92
3.4	1696	5.97	20.55	5.37	1.86	-1.34	-0.85
3.5	1756	6.01	20.90	5.34	1.91	-1.32	-0.78
3.6	1816	6.05	21.30	5.31	1.97	-1.30	-0.69
3.7	1876	6.09	21.67	5.29	2.02	-1.28	-0.60
3.8	1940	6.14	22.05	5.27	2.08	-1.26	-0.50
3.9	2000	6.18	22.48	5.26	2.13	-1.23	-0.38
4.0	2062	6.23	22.90	5.26	2.18	-1.20	-0.25
4.1	2126	6.28	23.35	5.25	2.24	-1.17	-0.11
4.2	2190	6.33	23.85	5.25	2.29	-1.14	-0.04
4.3	2254	6.38	24.40	5.25	2.35	-1.10	0.21
4.4	2318	6.43	24.95	5.26	2.40	-1.07	0.37
4.5	2382	6.49	25.50	5.27	2.46	-1.03	0.54
4.6	2448	6.54	26.10	5.28	2.51	-0.99	0.69
4.7	2514	6.60	26.70	5.29	2.57	-0.94	0.83
4.8	2580	6.65	27.32	5.31	2.63	-0.89	0.95
4.9	2648	6.70	27.95	5.32	2.68	-0.85	1.06
5.0	2714	6.75	28.55	5.33	2.74	-0.80	1.15

3.1.2 Calculations of free surface effect of bottom tanks.

All ballast tanks were deballasted before loading and we need not consider free surface of them. The free surface effects of fresh water tanks were calculated because they consume F.W. always.

The F.O. tanks have free surface always because we can not over flow F.O. through air escape pipes when we receive F.O. considering oil pollution.

The second moment of inertia of free surface of each tank is as followings;

① NO.3 F.W. tank (p)

$b=3.4m$

$l=5.2m$

$i=\frac{1}{12}\times5.2\times3.4^3=17.0m^4$

② NO.3 F.W. tank (s)

$i=17.0m^4$

③ NO.5 F.O. tank (p)

$b=3.4m$

$l=8.4m$

$i=\frac{1}{12}\times8.4\times3.4^3=27.5m^4$

④ NO.5 F.O. tank (s)

$i=27.5m^4$

⑤ NO.6 F.O. tank (p)

$b=3.25m$

$l=2.6m$

$i=\frac{1}{12}\times2.6\times3.25^3=7.4m^4$

⑥ NO.6 F.O tank (s)

$i=7.4m^4$

⑦ NO.7 F.O tank (center tank)

$b=1.2m$

$l=4.9m$

$i=\frac{1}{12}\times4.9\times1.2^3=0.7m^4$

⑧ L.O. tank

$b=2.2m$

$l=2.5m$

$i=\frac{1}{12}\times2.5\times2.2^3=2.2m^4$

Total 2nd moment of free surface $=106.7m^4$

⑨ G.M correction due to the free surface effects of bottom tanks

GM correction

$=-(\frac{i}{V})=(-)106.7\div(2319\div1.025)\approx(-)0.047m$

where, V: submerged volume of the vessel

3.1.3 The free surface effect of cargo tanks (Refer to attached sheets 1 about details)

The type of each end part of the tanks is of half ball and central part of it is of cylinder type.

Therefore detail computation can not be performed by the math. model of an elliptical form. The computing method is a little bit complicated and please refer to the attached sheet 1.

① The second moment of the free surface of cargo tank NO.1

$i_1=\frac{1}{12}lb^3+\frac{\pi}{64}d^4$

$i_1=\frac{1}{12}\times9.24\times(6.6)^3+\frac{3.14}{64}\times(6.6)^4\approx304m^4$

② The second moment of the free surface of cargo tank NO.2

$i_2=\frac{1}{12}lb^3+\frac{\pi}{64}d^4$

$$i_2 = \frac{1}{12} \times 14 \times 8^3 + \frac{3.14}{64} \times 8^4 \approx 798m^4$$

$$i_T = 304 + 798 = 1102m^4$$

③ GM correction due to the free surface effects of cargo tanks

GM correction

$$= -(\frac{i}{V}) = (-)1102 \div (2319 \div 1.025) \approx (-)0.487m$$

3.1.4 The final value of GM of YUHWA NO.2 at the time of leaving pier

G_0M .... = 1.100m

GM decrease due to the free surface of bottom tanks = −0.047m

GM_1 .... = 1.053m

GM decrease due to the free surface of cargo tanks = −0.487m

Final GM value = 0.566m

3.2 Appreciation about the stability of YUHWA No.2

Final GM value of 0.566m at the time of leaving pier seems to be sufficient to endure ordinary rough seas except in the case of extra-ordinary ones as in a tropical cyclone. This value is in the scope of safety in figure 3.1 that was made by the shipyard when she was built.

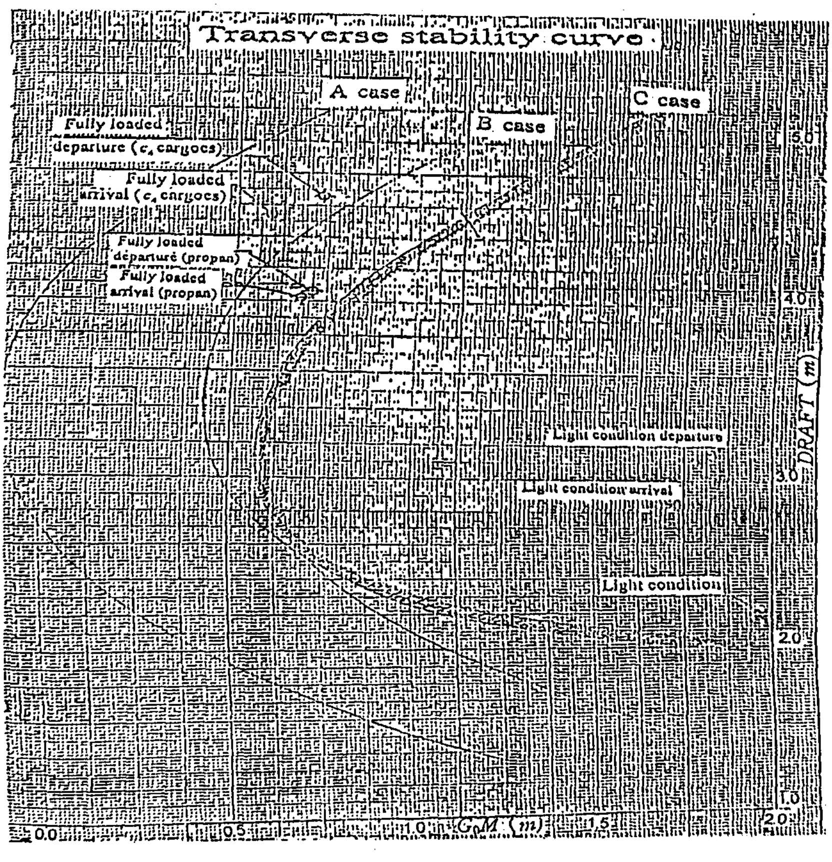


Fig. 3.1 Transverce stability curve of YUHWA No.2

Chapter 4 Calculation of leaking water quantity through hull damage and its effect

The theoretical aspect of computation shall be referred to the attached sheet 2 and 2-1.

4.1 The position of the hull plate on which a leaking hole was formed and the shape and size of it

The place of the hull plate on which the leaking hole was formed is apart 14.4 *m* from the fore perpendicular and 49.1 *m* from the after perpendicular. It is 17.35 *m* forward from mid-ship section and 2.7 *m* off to port-side from the longitudinal center line and 0.24 *m* above the keel line. The plate is port-side B plate of bow bottom (refer to figure 2.4 of attached sheet 2).

The shape of the pitting hole was of almost perfect circle and the radius of the hole was 27 *mm* when it was measured after pulling out the wooden wedge which was pushed into the plate for refloating work. So the size of the original hole can not be certified by now.

Generally when the hole of erosion is made and the leaking of sea water progresses through it, the rust around the edge of it will be parted off gradually enlarging the size of the hole to a constant one at last. So we assumed the diameter of the hole was 10 *mm* at the first stage of leaking, then it was enlarged gradually to 12.5 *mm*, 15 *mm*, 17.5 *mm* and 20 *mm* at last for calculating the quantity of flooded water and the length of time passed.

4.2 Modeling the math. formulas for computing the quantity of leaking water according to the progress of time

4.2.1 Calculation of the water head above the hole

The head of water above the hole

Fig. 4.1 is not the drawing reduced according to actual sizes of the vessel. It was drawn only for the help of understanding. The initial trim was 1.2 *m* by the stern, that is, the trim degree was $\sin^{-1}(\frac{1.2}{63.5}) = 1^\circ$

$$31.75 : 0.6 = 17.35 : x$$

$$x = 0.33\ m$$

The draft above the hole $= 4.4 - 0.33 = 4.07\ m$

The water head of the hole

$= 4.07 - 0.24 = 3.83\ m$

where, 0.24 *m* is the height of the hole above the keel line

4.2.2 Formula computing the quantity of flooding water

$$Q = \frac{2c\rho A}{\alpha\beta}\sqrt{2gh_0}\left(1 - e^{-\frac{\alpha\beta t}{2}}\right) \quad \cdots\cdots\cdots (4.1)$$

The above formula was modeled by the investigator for computing exact quantity of flooding water to certify the causes of the accident of YUHWA N0.2. Details of theoretical aspect will be referred to attached sheet 2 and 2-1.

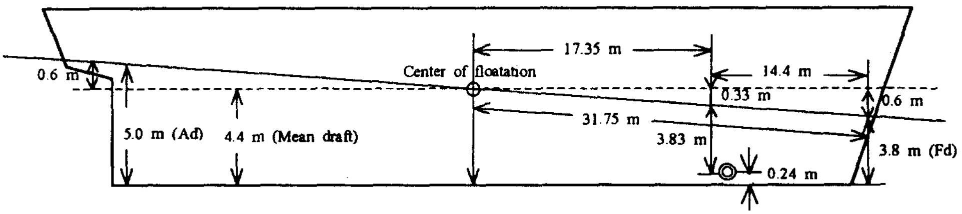


Fig. 4.1 The draft and water head of the hole (It is not actual size reduced)

4.2.3 Quantity computing formulas according to the size of the leaking hole

When we assume the size of leaking holes as 10 *mm*, 12.5 *mm*, 15 *mm*, 17.5 *mm* and 20 *mm* each formula of computing the quantity of flooded water is as following:

① Diameter = 10 *mm*

$Q = 985(1 - e^{-0.00000067t})$ .... (4.1.1)

② Diameter = 12.5 *mm*

$Q = 985(1 - e^{-0.000001t})$ .... (4.1.2)

③ Diameter = 15 *mm*

$Q = 985(1 - e^{-0.0000015t})$ .... (4.1.3)

④ Diameter = 17.5 *mm*

$Q = 985(1 - e^{-0.00000193t}$ .... (4.1.4)

⑤ Diameter = 20 *mm*

$Q = 985(1 - e^{-0.00000269t})$ .... (4.1.5)

4.3 Appreciation about forming the condition of the accident and quantity of flooded water at the time of the accident and progressed time and etc.

4.3.1 The time of the accident occurred and flooded water quantity at that time

The quantity of flooding water per second was so little, even the crew on board had not been conscious of the leaking itself from the start until the sudden accident occurred due to the short of stability.

Therefore all questions will be solved if we can decide what kind of stability defect forms the conditions of a sudden inclination of the vessel and how much quantity of flooded water makes the inclination at what stage of time in the progress of leaking.

This accident occurred due to non-GM condition and such a condition would be able to be formed at an instant when the free surface of the void tank was spreaded all over the floor surface of the tank. On the Fig.4.2 the longitudinal girders demonstrated by the dotted lines would divide the free water surface into many small longitudinal bands and decrease the effect of free surface making no problem until the flooded water flows over the tops of girders. But as soon as the water flows over the tops of girders the heights of which are of 0.65 *m* from the keel line, the effect of free surface integrated into one becomes so great that the stability of the vessel decreases to zero or (−)value making a sudden inclination of great degrees or capsizing of the vessel.

Therefore the accident seems to be occurred at the instant when flooded water flowed up over the tops of girders.

The ship's trim was small and 1 degree by

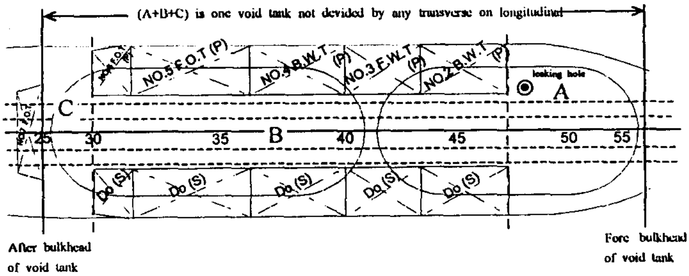


Fig. 4.2 Dotted line demonstrate the longitudinal girders(Bottom tanks and void tank)

the stern at the start of leaking and the trim would decrease as the flooded water quantity increases in the void tank because the center of free surface area is $4.2\,m$ forward from the center of flotation of the vessel.

So disregarding the trim, if we calculate the quantity of flooded water at the instant of accident, it is as following;

$$Q = 251 \times 0.65 \times 1.025 = 167\,ton$$

where, $251m^2$ is the total of the base areas demonstrated in Fig.4.2 as A, B, C. But actual water quantity is smaller than $167\,ton$

$$Q = 167 - 37 = 130\,ton$$

where, $37\,ton$ is the weight of sea water displaced by the volumes of permanent ballast blocks.

Regardless of the hole size, when the quantity of flooded water grows to $130\,ton$ the accident ought to have occurred.

4.3.2 Computation of the time passed from the start of leaking

As we can not certify the size of the leaking hole at the start of leaking and also those in the progress of leaking, we assume the initial size was $10\,mm$ at the first time and then it was enlarged in the progress of leaking as $12.5\,mm$, $15\,mm$, $17.5\,mm$ and $20\,mm$ at last with the result of the rust parting off from the ridge of the hole gradually. We compute the passed time from the start of leaking for every assumed size of the holes and then we decide mean value of the computed times as the time passed from the start of the leaking. It seems reasonable to decide the passed time as mentioned above.

Each of The following time was computed from the formulas of (4.1.1)~(4.1.5) in chapter 4.2.3.

① Diameter = $10\,mm$

$Time\ length = 211,254\ secs = 58\ hours\ and\ 42\ minutes$

② Diameter = $12.5\,mm$

$t = 141,540\ secs = 39\ hours\ and\ 18\ minutes$

③ Diameter = $15\,mm$

$t = 94,360\ secs = 26\ hours\ and\ 12\ minutes$

④ Diameter = $17.5\,mm$

$t = 73,337\ secs = 20\ hours\ and\ 24\ minutes$

⑤ Diameter = $20\,mm$

$t = 52,617\ secs = 14\ hours\ and\ 36\ minutes$

$$Average\ time\ length = (58.7 + 39.3 + 26.2 + 20.4 + 14.6) \div 5 = 31.8 \simeq 32\ hours$$

4.4 Void space free surface area, center of the area and 2nd moment of inertia

For the calculation of the exact free surface area and the quantity of flooded water, the bottom area was divided into three parts as demonstrated in Fig. 4.2 as part A, B, C.

4.4.1 Base area and volume under the height of 1 m level

① Part A(a trapezoid type) area and volume

$a = 8.3\,m$

$b = 11.8\,m$

$l = 9.7\,m$

$h = 1\,m$ (Height from the keel line)

$A\ area = 68.2\,m^2$ (C_w :0.7 refer to attached 2)

$A\ volume = 68.2\,m^3$

② Part B area and volume

$b = 5.3\,m$

$l = 29\ m$

$h = 1\ m$

$B\ area = 153.7\ m^2$

$B\ volume = 153.7\ m^3$

③ Part C area and volume

$b = 11.8\ m$

$l = 3.5\ m$

$h = 1\ m$

$C\ area = 11.8 \times 3.5 \times 0.7 = 28.9\ m^2$

$C\ volume = 28.9 \times 1 = 28.9\ m^3$

④ Total area and volume

$Total\ area = 68.2 + 153.7 + 28.9 = 250.8 \approx 251 m^2$

$Total\ volume = 251 \times 1 = 251 m^3$

⑤ Center of area

4.2 m forward from the center of floatation (refer to attached sheet 2)

4.4.2 Computation of the free surface in the void tank

① The free surface of part A(i_1)

As part A is of a trapezoid type we divide it into two parts, that is, a trapeziod (forward part) and a square (after part)

The 2nd moment of the free surface of the part A(i_1)

$$i_{11} = \frac{1}{12} \times 5.5 \times 10.1^3 = 472\ m^4$$

$$i_{12} = \frac{1}{12} \times 4.2 \times 11.8^3 = 575\ m^4$$

$$i_1 = 575 + 472 = 1147\ m^4$$

② The 2nd moment of the free surface of the part B(i_2)

$$i_2 = \frac{1}{12} \times 29 \times 5.3^3 = 360\ m^4$$

③ The 2nd moment of the free surface of the part C(i_3)

$$i_3 = \frac{1}{12} \times 3.5 \times 11.8^3 = 479\ m^4$$

④ $i_1 + i_2 + i_3 = 1886\ m^4$

4.5 The effect affected by the flooded water in void tank to the stability of the vessel

As mentioned in the chapter 4.3 the quantity of flooded water at the time when water flows over the tops of girders is 130 *ton*.

4.5.1 Draft correction

① Increase of displacement

displacemet $= 2319 + 130 = 2449\ ton$

② Draft increase

$130 \div 6.54 = 20 cm$ (refer to table 3.2 of chapter 3)

$mean\ draft = 4.4 + 0.20 = 4.6\ m$

$fore\ draft = 3.8 + 0.20 = 4.0\ m$

$after\ draft = 5.0 + 0.20 = 5.20\ m$

③ Trim correction to the drafts

$(130 \times 4.2) \div 26.1 = 20.92 cm$

As the center of flooded area is 4.2 m forward from the center of flotation of the vessel, the correction of draft are as followings;

$$final\ fore\ draft = 4.00 + \frac{0.21}{2} = 4.11\ m$$

$$final\ after\ draft = 5.20 - \frac{0.21}{2} = 5.10\ m$$

$$final\ mean\ draft = 4.60\ m$$

4.5.2 GM correction

Displacement of the vessel at the instant of accident $= 2319 + 130 = 2449\ ton$

Moment addition $= 9646 + 130 \times \frac{0.65}{2} = 9688\ ton \cdot m$

KG $= 9688 \div 2449 = 3.96\ m$

KM = 5.28 m (*refer to table* 3.2 *chapter* 3)
GM = 1.32 m
GM= 1.32 − (*total free surface correction*)

① GM decrease due to the free surface effect of the bottom tanks
$GM_1 = 1.3 - 0.047 = 1.273\ m$

② GM decrease due to the free surface effect of the cargo tanks
$GM_2 = 1.273 - 0.487 = 0.786\ m$

③ GM decrease due to the free surface effect of the void tanks
$1886 \div (2449 \div 1.025) = 0.789\ m$
$GM_3 = 0.786 - 0.789 = -0.003\ m = (-)0.3\ cm$

At last the value of GM became $(-)0.3\ cm$ capsizing the vessel

4.5.3 The result affected by the free surface of the void tank

The conclusion is that when flooded water in the void tank flowed over the tops of longitudinal girders, the value of GM of the vessel became $(-)0.3\ cm$ and the vessel inclined suddenly toward capsizing. Then why was the vessel not capsized? The reason is that the cargo tanks submerged by the great inclination made buoyancy and it prevented the vessel from capsizing and the great quantity of seawater that flooded through the scuttle of toilet on the stern part flooded down into the engine room and the vessel sunk from the stern touching down with sea bed.

Chapter 5 Analysis of the inclination of great degrees

The Vessel lost stability and inclined to port side by great degrees. The analysis of heeling moment and righting moment is as following.

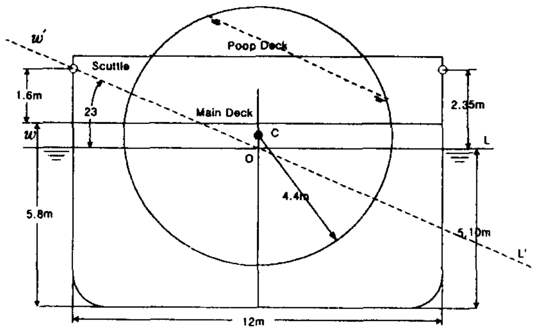


Fig. 5.1 Section diagram seen from the stern at the instant of the accident

One of crew on board actually observed the sea water flooding through the scuttle of the toilet during his urinating and escaped.

As the after draft of the vessel computed at the instant of the sudden great inclination was 5.10 m, if the vessel would heel to the angle of 23 degrees, sea water level reaches the uppermost edge of the scuttle and sea water would flood because of $\sin^{-1}(2.35 \div 6) = 23°$ (see Fig. 5.1).

The trim of the vessel at the instant of the great heeling, was about 0.9° by the stern because of $\sin^{-1}(0.99 \div 63.5) = 0.9°$.

As the value of GM is $(-)0.3\ cm$, the vessel would heel toward capsizing but stop the heeling at the angle where the heeling moment and the righting moment equals. The water shifted from st'd side to port side due to the heeling in void tank and also liquid cargo shifted in cargo tanks would make heeling moment whereas the buoyancy made by the submerged part of cargo tanks due to the heeling would make righting up moment. If we compute the two contrary moments and compare them with each other, we can know the exact status of the inclination at the time of the sudden heeling.

5.1 Calculation of heeling or capsizing moment

5.1.1 The moment due to the move of flooded water

As the length of void tank is 9.7+29 +3.5=42. m the height of water level over the top of girder at the place of after bulkhead of the void tank is $42.2\times\sin 0.9^{\circ}=0.66\,m$ when the free surface was spreaded all over the bottom of the tank and the height of water level of after end of part B is $38.7\times\sin 0.9^{\circ}=0.61\,m$, that of after end of part A is $9.7\times\sin 0.9^{\circ}=0.15\,m$ and the height of water level over tops of girders at the place of fore bulkhead of the void tank is zero. The heights of water level are demonstrated in Fig. 5.2.

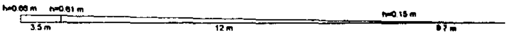


Fig. 5.2 The heights of water level above the tops of girders in the void tank

As the heeling angle was about 23 degrees, we can assume the water moved from the st'd side center to the port side center athwart the vessel. The quantity of water above the tops of girders of each part is as followings;

① the quantity above part C

$$=\frac{0.66+0.61}{2}\times 3.5\times 11.8\times 1.025=26.9\ ton$$

② the quantity above part B

$$=\frac{0.61+0.15}{2}\times 29\times 5.3\times 1.025=59.9\ ton$$

③ the quantity above part A

$$=\frac{0.14+9.7}{2}\times 10.1\times 1.025=7.5\ ton$$

The moment made by the moved sea water of each part (2nd added letter means the part designated).

$$M_{tC}=26.9\times\frac{11.8}{2}=158.7\ t\cdot m$$

$$M_{tB}=59.9\times\frac{5.3}{2}=158.7\ t\cdot m$$

$$M_{tA}=7.5\times\frac{10.1}{2}=37.9\ t\cdot m$$

$$A, B, C\ M_t\ Total=158.7+158.7+37.9=355.3\ t\cdot m$$

5.1.2 Moment due to the move of the cargo

When the great heeling occurred, the condition of ship's stability was of $GM=0$, that is, $KM=KG$ and KM was 5.28m.

The weight of liquid cargo in a ball tank always exerts downward through the vertical line which passes the center of the ball tank regardless of the height of the cargo(see Fig. 5.1). The height of the center of the ball tank K_{gb} is 5.4m above the keel line and the $KM=KG=5.28\ m$.

① Moment due to the weight of the cargo in No. 1 tank

$518.6\times\sin 23^{\circ}\ (5.40-5.28)=24.3\ t\cdot m$

② Moment due to the weight of the cargo in No.2 tank

$518.6\times\sin 23^{\circ}\ (5.40-5.28)=24.3\ t\cdot m$

5.1.3 Total of the heeling moment

$355.3+2\times 24.3=403.9\ t\cdot m$

5.2 Righting moment due to the buoyancy of partially submerged parts of cargo tanks

① Righting moment due to the buoyancy of No. 1 cargo tank

$$\left(905.1\div\frac{360}{23}\right)\times 1.025\times 4.4\times\frac{2}{3}=173.9\ t\cdot m$$

② Righting moment due to the buoyancy of No.2 cargo tank

$$\left(1106.5 \div \frac{360}{23}\right) \times 1.025 \times 4.4 \times \frac{2}{3} = 212.6\ t \cdot m$$

③ Total righting moment

$173.9 + 212.6 = 386.5\ t \cdot m$

5.3 Comparing the two contrary moments and analysis of the situation of the accident

Righting moment-Heeling moment $= 386.5 - 403.9 = -17.4\ t \cdot m \approx 0$

Comparing the above values, we find the difference between the two moments is only $(-)17.4\ ton \cdot m$, which is almost equals to zero considering the errors unavoidable in the progress of computation. Summarizing all of the analysis we can conclude as followings; YUHWA No.2 inclined to port side toward capsizing but the heeling was stopped at the angle of about 23 degrees because of the balancing moment generated by the buoyancy of the cargo tanks. The vessel was standing still in the inclined status and sea water flooded in great quantity through the scuttle of the toilet and flooded down into the engine room sinking the vessel quickly from the stern.

5.4 Analysis about flooding down of sea water into the engine room

The question that was it able to prevent the vessel from sinking by discharging the water flooded down into the engine room by all of the ship's pumps on board available can be answered very easily if we compare the quantity of flooding water with the capacity of pumps available.

① Calculation of the quantity of water flooding through the scuttle in the toilet

The diameter of the scuttle is $30\ cm$ and we assume the head of the water to be $15\ cm$.

$$Q = c\rho_w A\sqrt{2gh} \times t$$

$$= 0.95 \times 1.025 \times 3.14 \times (0.15)^2 \sqrt{2 \times 9.8 \times 0.15} \times 3600 = 424.7\ ton/H$$

② The capacity of pumps to discharge the flooding water

Ballast pump $70m^3 \sim 50m^3/H$

G.S. pump $70m^3 \sim 50m^3/H$

Ejector pump $3m^3/H$

Total capacity $= 143 \sim 103m^3/H$

Taking the situation into account that the vessel heeled suddenly to a great angle that might make the vessel to be capsized, it would be hard for crew to try pumping out the flooding water even in a case of sufficient pump capacity. Therefore comparing the capacity of pumps of around $100m^3/H$ with the quantity of flooding water of 425 ton, it is unthinkable that crew on board would try to discharge the flooding water out of the engine room.

Chapter 6 Conclusion

From the investigations performed by analysing the situations explained by the crew who were on board at the time of the accident and reasonable computations to certify the situations, we can conclude the causes of the accident are as follows;

1. The direct cause of the great degree heeling that led the vessel to sinking was not the quantity of flooded water in the void tank but the free surface of it, the effect of which decreased ship's GM value to zero or $(-)$ value $(-0.3cm)$ and the

vessel lost stability at an instant of few seconds.

2. Sea water had flooded into the void tank through the pitting hole the diameter of which might be about 10 *mm* at the first stage of leaking and enlarged to 20 *mm* at last during considerably long period of time and the flooding was unnoticed till the accident took place. It seems that the crew on board did not well understand the seriousness of free surface effect and also they were busy on celebrating the Lunar New Year and neglected a little bit to the soundings of the tanks including the void tank. So they could not find the leakage in advance to take counter-measure. When the flooded water accumulated flowed over the tops of longitudinal girders and spreaded all over the bottom floor above the tops of girders in the void tank the vessel lost the stability heeling suddenly and greatly in few seconds toward capsizing.
3. The values of computations demonstrated that the initial heeling angle had to be at least 23degrees or more to port side and the buoyancy generated by partially submerged cargo tanks prevented the vessel from capsizing.
4. Computation demonstrated the quantity of flooding water through the scuttle of the crew toilet to be 424.7 ton per hour whereas the capacity of all pumps available on board was between 103~143 m^3 per hour and the water flooded down into the engine room and the vessel sank from the stern touching down with sea bed of 15 *m* depth and the bow partly floated above the water due to the buoyancy of cargo tanks.

The aboves were concluded from the detailed computations, which will be referred to the each of the pertinent chapter and attached sheet.

Attached sheet 1: Calculation of the free surface effect of cargo tanks

1. Calculation of the free surface of No.l cargo tank and its 2nd moment

The cargo loaded in No.l and No.2 tank was liquid of Butadiene the density of which is about 0.65 and the loaded quantity of each tank was 518 K/T (same quantity).

The volume of No.l cargo tank was $905\ m^3$ whereas the volume of loaded cargo was $518.6 \div 0.65 = 798 m^3$. As the remained space of No. 1 cargo tank was $905 - 798 = 107 m^3$, the rate of remained space to the total space is, $905:100 = 107:x$, $x = 11.8\%$, that is, loaded percentage of tank space is $100 - 11.8 = 88.2\%$. The rate of total tank volume to the remained volume is $100 \div 11.8 = 8.46$. From the General Arrangement of the vessel we find the type of cargo tank similar to an ellipse but it is not a perfect ellipse. It is consisted of a cylinder (central part) and two of a half balls (each of the end part). Therefore we use the math. models of a cylinder and a ball for computing the free surface (see Fig 1.1).

Area A of Fig1.1 can be computed with formula(1.1)

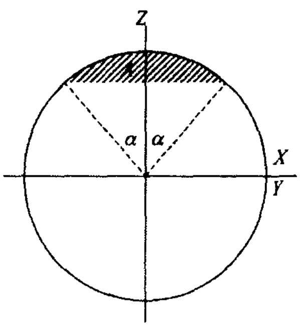


Fig. 1.1 The combined tank section of the cylinder with the central section of the ball

$$A = \frac{1}{2} r^2 (2a - \sin 2a) \quad \cdots\cdots (1.1)$$

$$A = \frac{\pi r^2}{8.46} \quad \cdots\cdots (1.2)$$

$$\frac{1}{2} r^2 (2a - \sin 2a) = \frac{\pi r^2}{8.46}$$

$$2a - \sin 2a = \frac{\pi}{4.23} = 0.742 \quad \cdots\cdots (1.3)$$

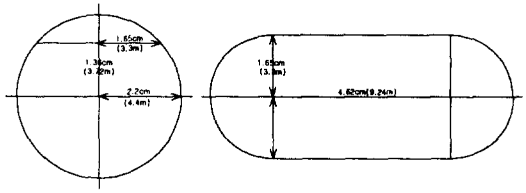
$$\sin 2a = 2a - 0.742$$

From (1.3) a is computed as $a \approx 49.5^\circ$. As $2.2 \sin(90^\circ - 49.5^\circ) \approx 1.4$, we put a point on the vertical centerline apart $1.4 cm$ above the center and can draw the actual free surface form as demonstrated in Fig. 1.2 (b).

Diameter of the half circle part of the free surface $= 6.6 m$

Length of the square part of the free surface $= 9.24 m$

2nd moment of No.1 cargo tank free surface



(a) (b)

Fig. 1.2 Shape of No.l cargo tank free surface

2nd moment computation of No.1 cargo tank free surface (i_1)

$$(i_1) = \frac{1}{12} lb^3 + \frac{\pi}{64} d^4$$
$$= \frac{1}{12} \times 9.24 \times (6.6)^3 + \frac{3.14}{64} \times (6.6)^4$$
$$= 22.4 + 82.3 = 303.7\ m^4 \approx 304\ m^4$$

(Note) If we compute the 2nd moment of the free surface of No.1 cargo tank by the ellipse math. model $i=\frac{\pi}{4}ab^3$ for reference, the moment is as following;

$a=7.92\ m$

$b=3.3\ m$

$i=\frac{\pi}{4}ab^3=\frac{\pi}{4}\times 7.92\times 3.3^3=223.4\ m^4$

So, the ellipse math. model can not be used for precise computations.

2. Calculation of the free surface of No.2 cargo tank and its 2nd moment

The volume of No.2 cargo tank is 1107 m^3 whereas the cargo quantity is 798 m^3 same as that of No.1 cargo tank.

The remained volume $=1107-798=309\ m^3$

The rate of total volume to remained volume $=1107\div 309=3.58$

$\frac{1}{2}r^2(2a-\sin 2a)=\frac{\pi r^2}{3.58}$

$2a-\sin 2a=1.754$

$\sin 2a=2a-1.754$

$\sin 2a=0.0349a-1.754$ (a : *degree unit*)

$a\approx 69^\circ$

The diameter of No.2 cargo tank is same as that of No.1 cargo tank but the length is longer than that of No.1 cargo tank.

$2.2\times\sin(90^\circ-69^\circ)=0.79$

the length of free surface square part is 7.00 *cm* which means 14 *m* of the actual length and the breath or the diameter of semi-circle d is 8 *m*.

$i_2=\frac{1}{12}lb^3+\frac{\pi}{64}d^4$

$=\frac{1}{12}\times 14\times 8^3+\frac{3.14}{64}\times 8^4$

$=579+201=798\ m^4$

$i_T=304+798=1102\ m^4$

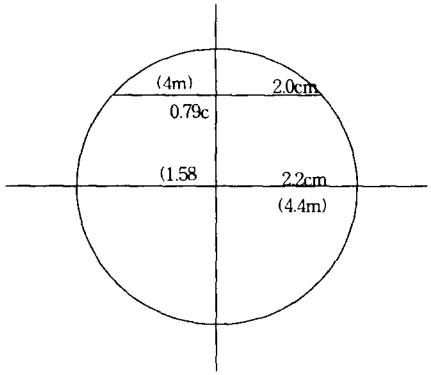


Fig. 1.3 scale:1/200

3. Decrease of GM value due to the free surface effects of cargo tanks

Rising distance of

$G_0=\frac{i}{V}=\frac{1102}{2319\div 1.025}=0.487\ m$

Attached sheet 2: Computation of the quantity of flooded water in the void tank and time passed after beginning of leaking

1. Modeling math. models for computing quantity of leaking water and time passed according to the quantity of flooded water in a compartment of a vessel

(1) Modeling theoretical math. models

If a hole is opened due to damage in a compartment of a vessel, the velocity of the flooding water through the hole is $v=\sqrt{2gh}$. The head of water at initial stage is h_0 but as

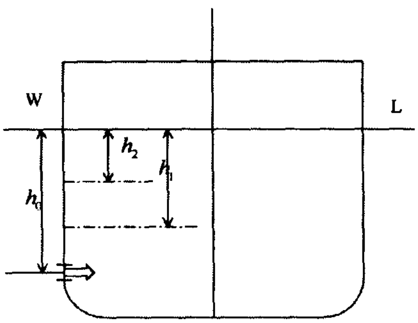


Fig. 2.1

the water level in inside of the compartment rises higher and higher the water head decreases and finally h will approach zero and flooding will stop. If a vessel have extra-buoyancy when h=0, then the vessel will not sink. The computation of the water head at a time point is not simple because the water level in inside of the compartment rises and the ship sinks and flooding water quantity decreases as time passes. The relation between water head h and t will be able to be demonstrated as in Fig. 2.2.

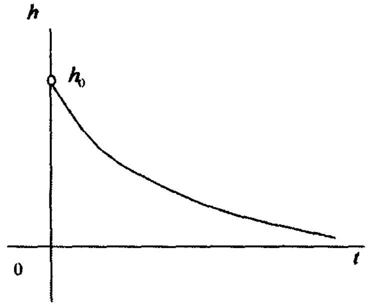


Fig. 2.2 Relation of h and t

At the initial time, $t=0$ $h=h_0$, and in the final stage, $t\to\infty$, $h\to 0$, so this relation can be demonstrated with t (variable) as formula (2.1)

$$h=h_0 e^{-\alpha\beta t} \quad \cdots\cdots (2.1)$$

where, constant α will be decided according to $\triangle h_0$ (head decrease or increase at initial stage) and constant β will be decided according to the head and shape of the compartment and as time passes the quantity of the flooded water Q increases but the increasing rate decreases becoming zero when $h=0$ at last.

The relation between Q and t can be demonstrated as Fig. 2.3 and the formula will be demonstrated as (2.2)

$$Q=Q_0(1-e^{-\frac{\alpha\beta t}{2}}) \quad \cdots\cdots (2.2)$$

(2) Formula for computing of flooding water

$$\frac{dQ}{dt}=C\rho A\sqrt{2gh_0 e^{-\alpha\beta t}}$$

$$=C\rho A\sqrt{2gh_0}(e^{-\alpha\beta t})^{\frac{1}{2}}$$

$$=C\rho A\sqrt{2gh_0}\,e^{-\frac{\alpha\beta t}{2}}$$

$$Q=C\rho A\sqrt{2gh_0}\int e^{-\frac{\alpha\beta t}{2}}dt \quad \cdots\cdots (2.3)$$

$$=C\rho A\sqrt{2gh_0}\,e^{-\frac{\alpha\beta t}{2}}\times\frac{-2}{\alpha\beta}+C$$

$$=\frac{-2C\rho A}{\alpha\beta}\sqrt{2gh_0}\,e^{-\frac{\alpha\beta t}{2}}+C$$

$$Q=\frac{2CpA}{\alpha\beta}\sqrt{2gh_0}\,(1-e^{-\frac{\alpha\beta t}{2}}) \quad \cdots\cdots\cdots\cdots\cdots (2.4)$$

where, C: flooding coefficient, A: area of the hole, ρ: water density

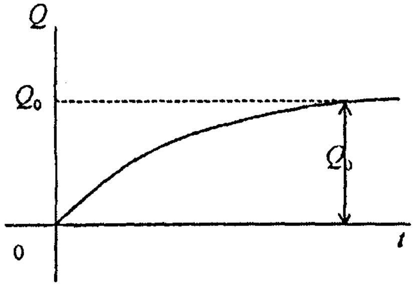


Fig. 2.3 Relation of Q and t

2. Approaching method to compute the quantity of flooding water in the void tank and basic data

(1) Approaching method

The void tank space of YUHWA No.2 is not uniformly distributed horizontally and vertically above the keel line. So we divide it into 3 section, V_1, V_2 and V_3, but we do not need computation about V_2 and V_3 because it seems that water level would not reach up to V_2 space before the accident would take place.

We divide V_1 space into 3 section A, B and C (see Fig. 2.4, page21) to get various data for computing effects of the flooding water. One of the problems to compute the length of the time passed from the start of the leaking to the instant of the accident, is that so far we don't know the exact size of the leaking hole. The exact diameter of it was $27\,mm$, but it was measured for the first time after having pulled out the wooden wedge which was put hard into the hole by hammering it under the water to refloat the vessel.

So we can assume the hole was much smaller than the measured one. When a leaking hole is made due to erosion, it will be small at first but

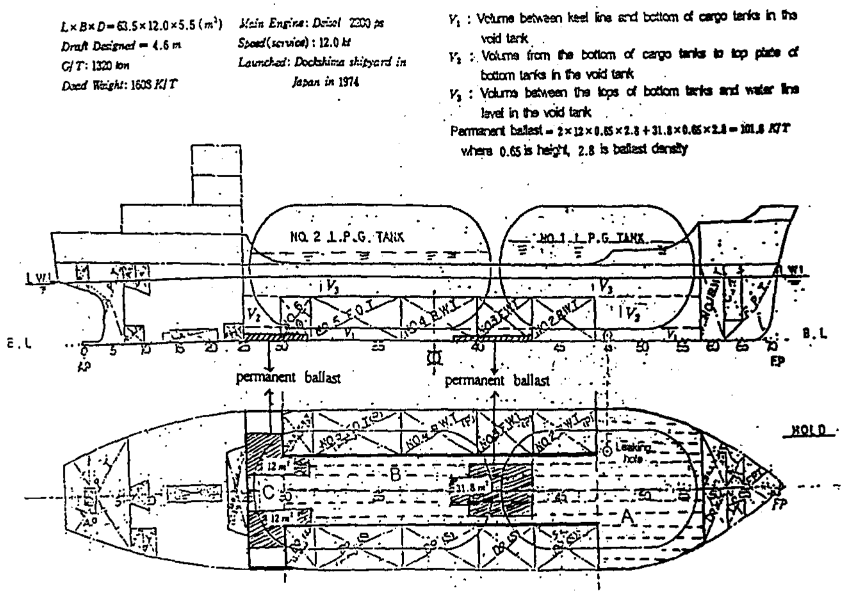


Fig. 2.4 Ship's bottom tank and cargo tanks

grow big little by little reaching to a constant one at last in the progress of the leaking because the rust on the edge of the hole would be parted off gradually by the leaking stream.

Therefore we assumed the diameter to be 10 *mm* at the first stage of leaking and growing gradually as 12.5 *mm*, 15 *mm*, 17.5 *mm* and 20 *mm* at last.

We compute each of the time length according to the hole sizes and then we take the mean length of the times as the length of time passed from the start of the leaking to the instant of the accident. This method seems most reasonable.

(2) Computation of the basic data

(A) Calculation of the base area, center of the base area and V_1 volume in void tank

The height of V_1 from keel line is 1 *m*.

① Area of Part A and its volume (trapezoid type)

$a = 8.3\ m$

$b = 11.8\ m$

$l = 9.7\ m$

$h = 1\ m$ (Keel line - base of cargo tank)

$$area\ A = \frac{8.3+11.8}{2} \times 9.7 \times 0.7 = 68.2\ m^2$$

where, 0.7 is coefficient equivalent to C_w

$volume\ A = 68.2 \times 1 = 68.2\ m^3$

② Part B area and volume

$b = 5.3\ m$

$l = 29\ m$

$h = 1\ m$

$area\ B = 153.7\ m^2$

$volume\ B = 153.7\ m^3$

③ Part C area and volume

$b = 11.8\ m$

$l = 3.5\ m$

$h = 1\ m$

$area\ C = 11.8 \times 3.5 \times 0.7 = 28.9\ m^2$

$volume\ C = 28.9 \times 1 = 28.9\ m^3$

④ Total area and volume

$Total\ area = 68.2 + 153.7 + 28.9 = 250.8 \approx 251\ m^2$

$Total\ volume = 251 \times 1 = 251\ m^3$

⑤ Computation of the center of total area

Computation of the area center is necessary for the calculation of trim change due to the quantity of flooded water.

At first the distance between the fore bulkhead of the engine room and the center of the area is computed and then we calculate the distance between the center of flotation of the vessel and the center of the area.

Section	Area	Dist.	1st moment	Basis
A	68.2	37.35	2547.27	Engine room bhd
B	153.7	18.0	2766.6	Engine room bhd
C	28.9	1.75	50.58	Engine room bhd
Total	250.8		5364.45	

Center point dist. from the bulkhead

$= 5364.45 \div 250.8 = 21.4\ m$

Center of flotation dist. from the bulkhead = 17.2 *m*

Center of the area dist. from the center of flotation

$= 21.4 - 17.2 = 4.2\ m$

(B) The head of water, h_0 at the beginning stage

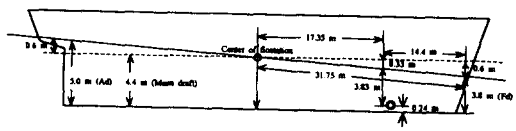


Fig. 2.5 Draft of the pitting hole and water head (not reduced according to actual dimensions)

Water head above the hole

$31.75 : 0.6 = 17.35 : x$

$x = 0.33\ m$

draft right above the hole $= 4.4 - 0.33 = 4.07\ m$

water head above the hole $= 4.07 - 0.24 = 3.83\ m$

where, $0.24\ m$ is the height of the hole above the keel line

3. Formula computing the quantity of flooded water according to the size of the holes

(1) Diameter = $10\ mm$

(A) The quantity at the initial stage and $\triangle h_0$

① The quantity per second

$\triangle Q/\sec = c\rho A\sqrt{2gh_0}\ ton/\sec$

$\sqrt{2\times9.8\times3.83}$

$= 0.00066\ ton/\sec$

② Draft increase per second due to the flooding water

$\triangle dm/\sec = 0.00066 \div 6.43 = 0.0001\ cm/\sec$

③ Sinking rate of the hole due to trim change

$\triangle t/\sec = (0.00066 \times 4.2) \div 24.95$

$= 0.0001\ ton/\sec$

Fore draft increasing rate due to trim change

$0.0001 \div 2 = 0.00005\ cm/\sec$

Shinking rate of the hole due to trim change

$31.75 : 0.00005 = 17.35 : x_t$

$x_t = 0.00003\ cm/\sec$

④ Sinking rate of the hole per second

$+\triangle h/\sec = 0.0001 + 0.00003 = (+)0.00013\ cm/\sec = 0.0000013\ m/\sec$

⑤ Rising rate of water level in the void tank due to the flooding water

$0.00066 = 250.8 \times 1.025 \times x_v$

$-\triangle h_v/\sec = x_v = (-)0.00000257\ m/\sec$

⑥ Changing rate of the water head per second

$-\triangle h_0/\sec = 0.0000013 - 0.00000257 = (-)0.00000127\ m/\sec$

(B) formula computing the quantity of flooded water

$$\frac{dQ}{dt} = c\rho A\sqrt{2gh_0 e^{-0.00000127\beta t}}$$

$$= c\rho A\sqrt{2gh_0}\, e^{-0.00000064\beta t}$$

$$= 0.00066\, e^{-0.00000064\beta t}$$

$$Q = 0.00066 \int e^{-0.00000064\beta t} dt$$

$$0.00066 e^{-0.00000064\beta t} \times \left(-\frac{1}{0.00000064\beta}\right) + C$$

$t = 0,\ Q = 0$

$$C = \frac{1015}{\beta}$$

$$Q = \frac{1015}{\beta}(1 - e^{-0.00000064\beta t})$$

$t \to \infty,\ Q = 251 \times 3.83 \times 1.025 = 985\ ton$

$$985 = \frac{1015}{\beta}$$

$\beta = 1.030$

$0.00000064\beta t = 0.00000064 \times 1.030 = 0.00000067t$

$$Q = 985(1 - e^{-0.00000067t}) \quad \cdots\cdots (2.4.1)$$

(2) Diameter = $12.5\ mm$

The computing method is as same as in the case of (1)

(A) $\triangle Q/\sec$ and $\triangle h_0/\sec$

① $\triangle Q/\sec = 0.001\ ton/sec$

② $\triangle dm/\sec = 0.00016\ cm/sec$

③ $x_t = 0.000046\ cm/sec$

④ $(+)\triangle h/\sec = 0.000002\ m/\sec$

⑤ $-\triangle h_v = x_v = (-)0.0000039\ m/\sec$

⑥ $\triangle h_0/\sec = (-)0.0000019\ m/\sec$

(B) Formula computing Q

$$Q = 985(1 - e^{-0.000001t}) \quad \cdots\cdots (2.4.2)$$

(3) Diameter= 15 mm

(A) $\triangle Q/\sec$ and $\triangle h_0/\sec$

① $\triangle Q/\sec = 0.00149\ ton/sec$

② $\triangle dm/\sec = 0.00023\ cm/sec$

③ $x_t = 0.00007\ cm/sec$

④ $(+)\triangle h/\sec = 0.000003\ m/\sec$

⑤ $-\triangle h_v = x_v = (-)0.0000058\ m/\sec$

⑥ $\triangle h_0/\sec = (-)0.0000028\ m/\sec$

(B) Formula computing Q

$$Q = 985(1 - e^{-0.0000015t}) \quad \cdots\cdots (2.4.3)$$

(4) Diameter= 17.5 mm

(A) $\triangle Q/\sec$ and $\triangle h_0/\sec$

① $\triangle Q/\sec = 0.0019\ ton/sec$

② $\triangle dm/\sec = 0.00030\ cm/sec$

③ $x_t = 0.000087\ cm/sec$

④ $(+)\triangle h/\sec = 0.00000387\ m/\sec$

⑤ $-\triangle h_v = x_v = (-)0.00000739\ m/\sec$

⑥ $\triangle h_0/\sec = (-)0.00000352\ m/\sec$

(B) Formula computing Q

$$Q = 985(1 - e^{-0.00000193t}) \quad \cdots\cdots (2.4.4)$$

(5) Diameter= 20 mm

(A) $\triangle Q/\sec$ and $\triangle h_0/\sec$

① $\triangle Q/\sec = 0.00265\ ton/sec$

② $\triangle dm/\sec = 0.000412\ cm/sec$

③ $x_t = 0.000126\ cm/sec$

④ $(+)\triangle h/\sec = 0.00000538\ m/\sec$

⑤ $-\triangle h_v = x_v = (-)0.00001\ m/\sec$

⑥ $\triangle h_0/\sec = (-)0.00000462\ m/\sec$

(B) Formula computing Q

$$Q = 985(1 - e^{-0.00000269t}) \quad \cdots\cdots (2.4.5)$$

4. Computation of the quantity of flooded water in the void tank

This accident occurred due to non-GM condition and such a condition would be able to be formed at an instant when the free surface of the void tank was spreaded all over the floor surface of the tank. On the Fig. 2.6 the longitudinal girders demonstrated by T letters would divide the free water surface into many small longitudinal bands and decrease the effect of free surface making no problem until the flooded water flows over the height of girders. But as soon as the water flows over the tops of girders the heights of which are of $0.65\ m$ from the keel line, the effect of free surface integrated into one becomes so great that the stability of the vessel decreases to zero or (-) value making a inclination of great degrees or capsizing of the vessel.

Therefore the accident seems to be occurred at the instant when flooded water flowed over the tops of girders.

The ship's trim was small and 1 degree by the stern at the start of leaking and the trim would decrease as the flooded water quantity increases in the void tank because the center of free surface area is $4.2\ m$ forward from the center of flotation of the vessel.

So disregarding the trim if we calculate the quantity of flooded water at the instant of accident, it is as following;

$$Q = 251 \times 0.65 \times 1.025 = 167\ ton$$

where, $251\ m^2$ is the total of the base area. The actual water quantity is smaller than 167 ton;

$$Q = 167 - 37 = 130\ ton$$

where, 37 ton is the weight of sea water displaced by the volume of permanent ballast blocks, that is,

$(2\times12\times0.65+31.8\times0.65)\times1.025=37\ ton$

Regardless of the hole size, when the quantity of flooded water grows to 130 ton the accident ought to have occurred.

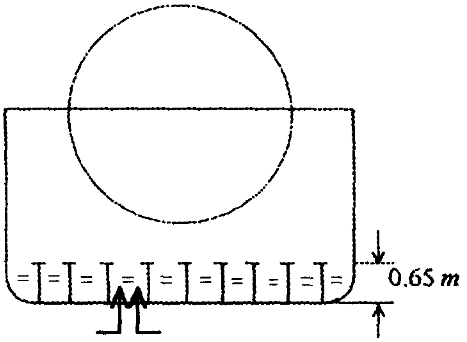


Fig. 2.6 Section Diagram

5. Computing the time passed till the quantity of leaking water grows to 130 ton

When the quantity of leaking water grows to 130 ton, the GM value reaches to zero and the vessel ought to be inclined toward capsizing.

The time necessary to allow 130 ton of leaking water is as follows;

(1) Diameter = 10 *mm*

$130=985(1-e^{0.00000067t})$

$t=211,254$ *seconds* = 58 *hours and* 42 *minutes*

(2) Diameter = 12.5 *mm*

$130=985(1-e^{0.000001t})$

$t=141,540$ *seconds* = 39 *hours and* 18 *minutes*

(3) Diameter = 15 *mm*

$130=985(1-e^{0.0000015t})$

$t=94,360$ *seconds* = 26 *hours and* 12 *minutes*

(4) Diameter = 17.5 *mm*

$130=985(1-e^{0.00000193t})$

$t=73,337$ *seconds* = 20 *hours and* 24 *minutes*

(5) Diameter = 20 *mm*

$130=985(1-e^{0.00000269t})$

$t=52,617$ *seconds* = 14 *hours and* 36 *minutes*

6. Assuming the length of the time from the start of leaking to the instant of the accident

We corrupted the passed time from the start of leaking for every assumed size of the holes and then we had better to take the mean value of the computed times as the time passed from the start of the leaking. It seems reasonable to decide the passed time as mentioned above.

Assumed time passed

$=(58.7+39.3+26.2+20.4+14.6)\div5$

$=31.8$ *hours*

Attached sheet 2-1 : Computation of the quantity of flooding water and time by a simplifing method.

1. Co-relation between h_0 and h

$$\frac{dQ}{dt}(+0)=C\rho_w A\sqrt{2gh_0}$$

$$\frac{dQ}{dt}(t')=C\rho_w A\sqrt{2gh}$$

$$\frac{dh}{dt}(+0)=a_0\frac{\sqrt{h_0}}{s}=dh_0$$

$$\frac{\frac{dh_{0+1}}{dt}}{\frac{dh_0}{dt}}=\sqrt{\frac{h_{0+1}}{h_0}}=C=e^{-\alpha}$$

(*decreasing rate*/sec)

$$\sqrt{\frac{h}{h_0}}=e^{-\alpha t} \qquad \cdots\cdots\cdots (1)$$

$$h = h_0 e^{-2at} \quad \cdots\cdots (2)$$

where,

A: *flooding hole area*

C: *flooding coefficient*

g: *acceleration of gravity*

h_0: *initial water head*

h: *water head*

ρ_0: *water density*

s: *base area of flooding compartment*

v_0: $\sqrt{2gh_0}$

v: $\sqrt{2gh}$

a_0: $C\rho_w A\sqrt{2g}$

2. Flooding quantity and time calculation

$$\frac{dQ}{dt} = C\rho_w A\sqrt{2gh}$$

$$= C\rho_w A\sqrt{2gh_0 e^{2at}}$$

$$= C\rho_w A\sqrt{2gh_0}\, e^{-at}$$

$$Q = \frac{C\rho_w A\sqrt{2gh_0}}{a}(1 - e^{-at}) \quad \cdots\cdots (3)$$

when $t \to \infty$

$$Q = \frac{C\rho_w A\sqrt{2gh_0}}{a} = \rho_w s h_0$$

$$a = \frac{C\rho_w A\sqrt{2gh_0}}{\rho_w s h_0} = \frac{CA\sqrt{2gh_0}}{s} \times \frac{1}{h_0} = \frac{dh_0}{h_0}$$

$$a = \frac{dh_0}{h_0} \quad \cdots\cdots (4)$$

where,

dh_0: *head decreasing rate at initial time*

3. Correcting the value of a in a non-uniform shaped volume compartment

Where the inside space is not uniformly distributed vertically the value of a index can be corrected as followings;

$$h = h_0 e^{-2a\beta t}$$

$$Q = \frac{C\rho_w\sqrt{2gh_0}}{a\beta}(1 - e^{-a\beta t}) \quad \cdots\cdots (5)$$

$$\beta = \frac{C\rho_w\sqrt{2gh_0}}{aQ_0} \quad \cdots\cdots (6)$$

4. Evaluation of the flooding of YUHWA NO.2 case by the simplifing method.

When we use the mathematic formula of simplifing method we can get exact result without the complicated calculations of head decreasing rate.

Example;

(1) Hole diameter = 10 *mm*

$Q = 1.025 \times 251 \times 3.83 = 985$ *ton*

$$dh_0 = \frac{CA\sqrt{2gh_0}}{s} = \frac{0.95 \times \pi r^2 \times \sqrt{2 \times 9.8 \times 3.83}}{251}$$

$$= 0.102969109 r^2 = 0.00002574$$

$$a = \frac{0.000002574}{3.83} = 0.000000672$$

$Q(t) = 985(1 - e^{-0.000000672t})$

$130 = 985(1 - e^{-0.000000672t})$

$e^{-0.000000672t} = 0.860203046$

$-0.000000672t = -0.141540172$

$t = 210,625$ sec $= 58.5$ *hours*

(2) Hole diameter = 12.5 *mm*

$Q = 985$ *ton*

$dh_0 = 0.102969109 r^2 = 0.102969109 \times (0.00625)^2 = 0.000004022$

$$a = \frac{0.000004022}{3.83} = 0.00000105$$

$Q(t) = 985(1 - e^{-0.00000105t})$

$130 = 985(1 - e^{-0.00000105t})$

$t = 134,800$ sec $= 37.4$ *hours*

※ $130 = 985(1 - e^{-0.000001t})$

$t = 141{,}540$ sec $= 39.3$ *hours*
(*when rounded off to the nearest integer*)

(3) Hole diameter = 15 *mm*

$Q = 985$ *ton*

$dh_0 = 0.102969109r^2 = 0.102969109 \times (0.0075)^2 = 0.000005792$

$$\alpha = \frac{0.000005792}{3.83} = 0.000001512$$

$Q(t) = 985(1 - e^{-0.000001512t})$

$130 = 985(1 - e^{-0.000001512t})$

$t = 93{,}611$ sec $= 26.0$ *hours*

(4) Hole diameter = 17.5 *mm*

$Q = 985$ *ton*

$dh_0 = 0.102969109r^2 = 0.102969109 \times (0.00875)^2$

$= 0.000007884$

$$\alpha = \frac{0.000007884}{3.83} = 0.000002058$$

$Q(t) = 985(1 - e^{-0.000002058t})$

$130 = 985(1 - e^{-0.000002058t})$

$t = 68{,}776$ sec $= 19.1$ *hours*

(5) Hole diameter = 20 *mm*

$Q = 985$ *ton*

$dh_0 = 0.102969109r^2 = 0.102969109 \times (0.01)^2$

$= 0.000010297$

$$\alpha = \frac{0.000010297}{3.83} = 0.000002688$$

$Q(t) = 985(1 - e^{-0.000002688t})$

$130 = 985(1 - e^{-0.000002688t})$

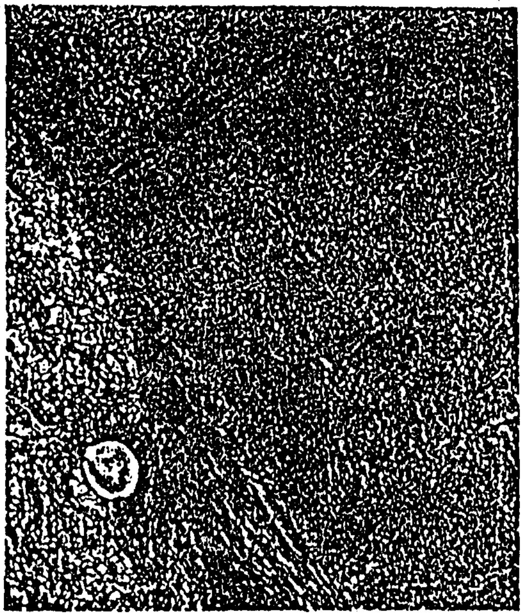
$t = 52{,}656$ sec $= 14.6$ *hours*

(6) Mean value

$(58.5 + 37.4 + 26.0 + 19.1 + 14.6) \div 5 = 31.12$ *hours*

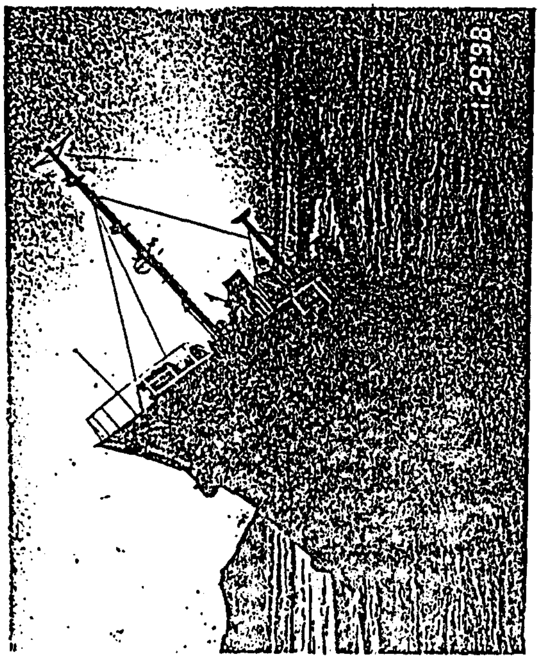
If we round off index of "e" we get the same value of mean time of 31.8 *hours* as in Attached sheet 2

Attached sheet 3: The pitting hole, scuttle in the toilet and sunken status of YUHWA No.2

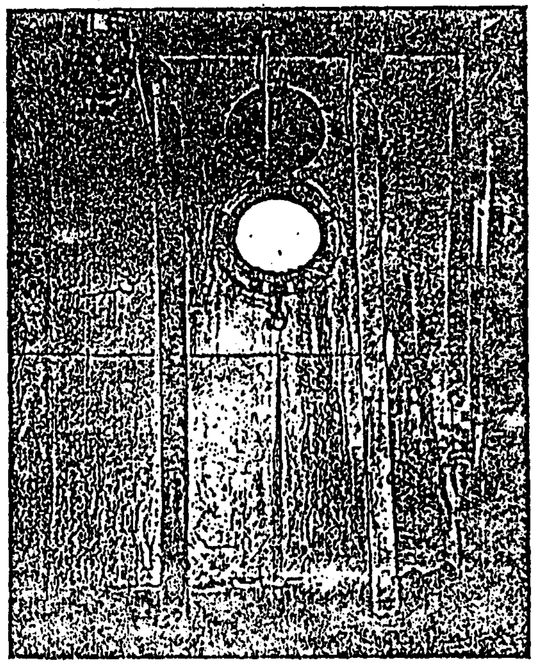


(a) The pitting hole seen from inside

(b) The pitting hole seen from outside bottom



(c) Sunken states of the YUHWA No.2



(d) The scuttle in the toilet

Reference

[1] Master's Report of Accident
[2] Shell Plate Diagram of YUHWA No.2
[3] Lines of YUHWA No.2
[4] General Arrangement of YUHWA No.2
[5] Hydro-Static Curves of YUHWA No.2
[6] GM Calculation Data of YUHWA No.2

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Educational Back-ground

1954-1958 : Graduated Nautical Department of Korea Maritime University Busan, Republic of Korea
1958 : Completed Officer Course of Korea Naval Academy
1974-1976 : Graduated Nautical Department of Graduate School of Korea Maritime University (Master Course)
1979-1981 : Graduated Department of Naval Architecture of Graduate School of Pusan National University Busan, Republic of Korea(Degree Course)

Career

1958-1963 : Served on Board Republic of Korea Navy Vessels
1963-1964 : Served on Board Republic of Korea Coast Guard Vessels
1964-1965 : Chief Officer of Fongshing Shipping Corp., Hong Kong
1966-1967 : Navigator and Master of Choyang Shipping Company Ltd.
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1967-1968 : Master of Training vessel of Korea Maritime University
1969-1970 : Master of Korea United Lines Corp., Seoul, Republic of Korea
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1994-1995 : President of Graduate School of Marine Industry of Korea Maritime University
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