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Study on Safety of Up-righting Project for a Capsized Ship Model Based on Cable Tensions, Theoretical Model and Numerical Method Accounting for Dynamic Effect

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Abstract

During an up-righting project for a capsized ship, the dynamic effect enlarges the tensions of cables. The cable tensions which are calculated based on statics and the safety evaluation which is based on these tensions cannot ensure the safety of the up-righting project. Due to the above reasons, a numerical simulation project is applied to investigate the dynamic effect on cable tensions of up-righting projects and evaluate the safety of up-righting project in current research. Firstly, a theoretical equation of the quasi-static up-righting project model is established in current research and is solved. Subsequently, the precision of the numerical simulation method applied in current research is checked by comparing cable tensions which are calculated by theoretical model and numerical simulation method. The cable tensions in different cases are solved by the numerical simulation method which accounts for dynamic effect in order to investigate the relationship between cable tensions and capsized ship weights, cable stiffness and winding-in speed. Finally, the safety of up-righting project is evaluated based on all the cable tensions calculated. It is pointed out that cable tension increases with the value of capsized ship weight, cable stiffness or winding-in speed approximately. The safety coefficients of cable in some high winding-in speeds are bellow 1.0. The results indicate that the dynamic effect is significant and should be accounted for during the up-righting project.

Keywords: safety; up-righting project; capsized ship; theoretical model; numerical method; dynamic effect.

1.Introduction

It is very important to ensure the safety of a ship during its voyage. Therefore, it is of great significance to carry out the researches on ship safety evaluation. Soding (2002) has carried out the research on ship safety evaluation based on its hydrodynamic performance. In his research, Soding presents a fast calculation method of hydrodynamic performance of a ship instead of a method based on the computational fluid dynamic (CFD) technology, and discusses the hydrodynamic performance of ships in different environments and navigational conditions. Then, Soding evaluates the safety of the ships based on the results above in the same research; Lee et al., (2005) has presented a framework of evaluation system of ship safety with the consideration of different sea state, loads and ship hull damage conditions. After that, Lee evaluates the safety of a structural damaged ship with the framework presented by himself; Maki et al. (2011) present a method to evaluate ship performance based on real code genetic algorithm. Based on this method, ship safety and economy can be evaluated effectively.

It is valuable to carry out the researches on ship safety assessment method. Also, it is important to figure out the factors that influences the ship safety. These factors can be classified into structural factors which may cause ship structures not reliable or fail to work, and hydrodynamic factors which may cause a ship capsized. There are a lot of researches on the two types of factors.

With respect to the structural area, Wang et al.,(2000) have carried out a research on the mechanical behavior of double bottom hull of ships in different collision or grounding cases with nine series of tests. The results show that: the position of the contact point of a contact surface and the ship as well as the curvature of the contact surface have significant influence on the hull structure when the ship is in collision or grounding. Subsequently, Wang presents and discusses the formulas of ship structural analysis under collision or grounding in the same study; Zhu et al., (2002) has provided statistics of the damaged range of a ship in grounding and evaluated it based on a semi-empirical formula . This method is applied to a research on structural damaged range distribution of a VLCC impacted by a single rock and a ship grounding in an area with rock respectively; Parunov et al., (2008) has redesigned the structure of the Aframax oil tanker based on Common Structure Rules, and has calculated the structural failure probability with the application of the first order reliability theory. Its results show that: the structural failure probability can be reduced significantly after the structure of Aframax oil tanker was redesigned based on the updated Common Structure Rules; A worst case of accidental ship grounding has been taken into account in Luis's et al., (2009) research on structural reliability analysis of a Suez oil tanker with double hull structure; Hussein et al., (2009) has carried out research on structural reliability of a ship by taking account of the Common Structure Rules, a worst grounding case and the changes of hydrostatic torque acting on the ship which was caused by the ship damage; Choung et al., (2012), has estimated the residual strength of the structure of oil tankers with asymmetric damage. The results show that: the residual strength of ship hull is greatly related to the area reduction caused by hull damage. Besides, the neutral axis of a damaged ship hull can easily be found according to the new convergence criterion established by Choung; Research on measurement of the equivalent thickness of hull decks of aging ships has been carried out by Guo et al., (2012), and the study on estimation of reliability of the hull structure has been carried out based on measurement of the thickness of 1080 decks of nine tankers; The research on stiffness distribution of the deck frame has been carried out by Choung et al., (2012)based on the cross section of 163 vessels according to the Common Structure Rules. Subsequently, Choung carries out a research on the reliability of the ship structure based on the cross section of these ships.

With respect to the ship fluid dynamic area (the capsized area), Surendran et al., (2005), Spyrou, (2006) and Lee et al., (2007) have pointed out that a capsized phenomenon is mainly caused by the ship rolling. Therefore, the research on the rolling characteristics, especially the asymmetric and nonlinear rolling characteristics of a ship, have been carried out for many years. A new method to calculate the rolling damping coefficient of large amplitude nonlinear rolling motion of a ship has been used in Chan et al., (1995), and a new asymptotic method is applied to predict the nonlinear rolling damping coefficient in the same research; The bifurcation theory has been applied in analysis of the ship steady rolling response in

Francescutto et al., (1999); Taylan, (1999) has established a mathematical model of ship rolling movement and carried out its periodic solution. Besides, a solution of the mathematical model with further accuracy has been carried with the application of a first order term in the same research; Subsequently, an equation used to investigate the nonlinear restoring force and the nonlinear damping force of a ship has been carried out in Taylan, (2000), and the solution in frequent domain has been carried out with the application of Duffing method. It is also pointed out in the same research that: taking account of the rolling damping and the restoring force of a ship is very important while establishing a nonlinear rolling model of the ship; Some other research on the different characteristics of ship rolling movement with different methods have been carried by Chakrabarti, (2001), Taylan (2002, 2003), Neves et al., (2003), Surendran et al., (2003), Bulian, (2004), Sarıoz, (2009) and other scholars as the reference for anti-capsized design for a ship.

However, in some cases, an essential navigation safety must be guaranteed after a ship was damaged or heeled. In such cases, the current ship rolling characteristics are different from those of a ship without any accidents. Some researches on the rolling characteristics of a ship with structure damage have been carried out by Korkut et al., (2004) and Lee et al., (2007), and the prediction of ship rolling movement has been performed in the same researches. A method to solve the similar research questions has been used subsequently. Since it is very important to guarantee an essential safety for a ship in accident, a research summary on the performance of damaged ships has been given by Wang et al., (2002).

Sometimes, a ship cannot sail with damage, and sometimes it even sinks. A ship may also capsize due to the mistake of a crew or the heavy state of the sea. In such cases, it is necessary for the staff to rescue the people and property on the ship under the water. Besides, in order to guarantee the channel navigable, the staff should upright the capsized ship and refloat it out of the channel. Some researches on the refloating or up-righting project have been carried out: the influence on the stability of a capsized ship which was caused by the free surface and the volume of air in a whole refloating project has been taken into account in Krylov, (1934); An up-righting project for a huge wrecked structure has been simulated by Tikhonov et al., (1997), and the research on vibration in the vertical direction of the system consists of the salvage ship, the wrecked ship, and the cables. A theoretical model for the refloating project has been established and solved by Tikhonov with the application of finite difference method. The results show that: the adjustment of the winding-in speed is influenced by the operation mode of the winch, which can influence the vibration of the whole system in vertical direction and the safety of the refloating project; A longitudinal strength of a wrecked ship with an accidental structural damage has been calculated by Wang et al., (2002). In Wang's research, a series of formulas are applied and the residual strength of a wrecked ship can be estimated immediately without any complex detailed calculation to guarantee the essential safety in an refloating project and protect the ship hull. The importance of up-righting projects has been emphasized in Drobyshevski, (2004). Besides, some different up-righting methods have been discussed, the essential lifting force during the up-righting project has been estimated, and an approximate formula has been used in the same research. The essential force for up-righting a capsized ship at the beginning of the up-righting project can be calculated immediately and temporarily with the formula when the detailed information of the capsized ship is absent. An up-righting for a capsized ship has been simulated by a commercial code GHS in Pan et al., (2017; 2018).

The dynamic effect on the up-righting project for a capsized ship has not been taken into account in the research yet. However, it is clearly pointed in the DNV Certification No.2-22 that: the dynamic effect must be taken into account when the lifting equipment is running. Based on this requirement, the dynamic effect on the cable tension during the up-righting project is taken into account in this research. The accuracy of the numerical simulation method is checked by comparing the numerical solution and the quasi-static theoretical solution of the cable tension. Subsequently, The values of different cable tension of a 2-D up-righting model in different cases are calculated with the application of time-domain response analysis method. And the safety of an up-righting project is evaluated based on the values of cable tension. The dynamic effect on the safety of up-righting projects is discussed at last.

2.A time-domain up-righting project for a ship

A capsized ship is affected by environmental loads, lifting force and the force of sea bed during an up-righting project. Thus, the movement equation of a capsized ship affected by outside loads in a time-domain analysis can be written as:

$$\left(m_{ij}+\mu_{ij}\right)\ddot{x}\left(t\right)+\int_0^t L_{ij}(t-\tau)\dot{x}(\tau)dt+C_{ij}x(t) \\ =F^{wa(1)}(t)+F^{wa(2)}(t)+F^{wi}\left(t\right)+F^{cu}\left(t\right)+T(t)+F^{s}(t) \quad (1)$$

Here m_{ij} is the mass matrix, μ_{ij} is the added mass matrix, $L_{ij}(t-\tau)$ is the time-delay function matrix, C_{ij} is the restoring force matrix, and i, j=1,2,3,4,5,6, $F^{wa(1)}$ is the first order wave force, $F^{wa(2)}$ is the second wave force, F^{wi} is the wind force acting on the wrecked ship, F^{CU} is the current force acting on the wrecked ship, T is the lifting force acting on the wrecked ship, F^{s} is the adsorption force caused by the seabed acting on the capsized ship.

The time-delay function matrix can be solved by the damping coefficient matrix λ_{ij} in frequency domain with the application of a Fourier transformation：

$$L_{ij}(t)=\frac{2}{\pi}\int_0^\infty \lambda_{ij}(\omega)\frac{\sin\omega t}{\omega}d\omega \quad (2)$$

The up-righting project for a capsized ship in this paper does not take consideration of the effects caused by wind, wave and current force. Therefore, equation (1) can be written as:

$$\left(m_{ij}+\mu_{ij}\right)\ddot{x}\left(t\right)+\int_0^t L_{ij}(t-\tau)\dot{x}(\tau)dt+C_{ij}x(t)=F^{s}(t)+T(t) \quad (3)$$

3.Quasi-static model of an up-righting project for a capsized ship

The cable tension varies with the environmental loads and movement of the capsized ship and the salvage ship during an up-righting project. A numerical simulation method will be used to simulate the up-righting project in the current research. First, a quasi-static model based on four assumptions of the up-righting project will be built. Besides, the accuracy of the numerical method used in this research to simulate the up-righting project will be checked by comparing the solution of the cable values calculated by the numerical method and the quasi-static model during the up-righting project with a low winding-in speed.

3.1 Four assumptions

A 2-D research question of the up-righting project for a capsized ship is taken into account firstly. A simplified model of the 2-D research question of the up-righting project for a capsized ship is shown in Fig.1:

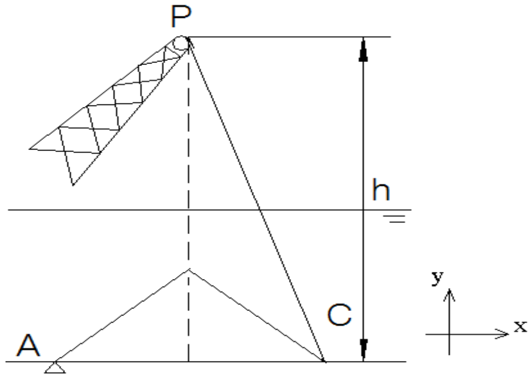

Fig.1 A 2-D model of an up-righting project for a capsized ship

In Fig.1, edge AC is the seabed, the big triangle is the capsized ship, point P is a lifting point located on the lifting arm of the salvage ship, which is a connection point on one side of the deck of the capsized ship and the other side of the lifting cable. h is the vertical distance between point P and the seabed. Let's assume that point P is in the middle of point A and point C in horizontal direction at the start of the up-righting project, and the coordinate system is built up with the original point A.

Four assumptions are taken into account in the establishment of the quasi-static model of the up-righting project in this research in order to simplify the research question of the up-righting project and compare the results calculated by theoretical method and numerical method and check the accuracy of the numerical method (Drobyshevski, 2004):

(1) The displacement of the salvage ship is ignored;

(2) Adsorption force in the up-righting project is ignored;

(3) Effect on the up-righting project caused by up-buildings is ignored;

(4) Added mass and added damping caused by the capsized ship's movement and the coupling effects are ignored. Also, the cable stiffness is ignored.

3.2 Calculation of the cable tension in the quasi-static model of the up-righting project for a capsized ship

The lifting point P on the salvage ship is assumed to be fixed in the current research. Denote h as the vertical distance between point P and the horizontal seabed, 2L as the initial distance between point A and point C, i.e. the deck width is 2L. Denote G as the sum of the value of capsized ship weight and the negative value of the bouncy of the capsized ship, F as the sum value of the support force acting on the capsized ship by point A and the friction force acting on the capsized ship, T as the cable tension. The analysis of the force of the capsized ship in up-righting project is shown in Fig.2:

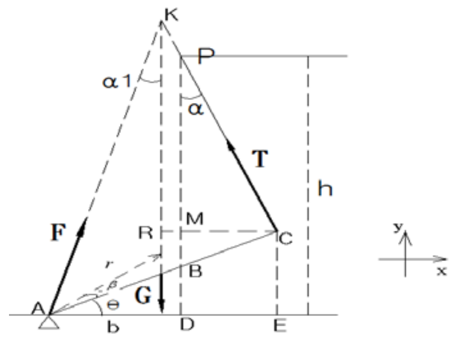

Fig.2 Analysis of the force of the capsized ship in the up-righting project

Values of the cable tension in time domain during the up-righting project calculated by numerical method are the index of safety assessment of the up-righting project in current research. Therefore, only T, the values of cable tension during up-righting project are calculated in the current research. Values of each individual F are not calculated. The cable tension of the quasi-static model of the up-righting project for a capsized ship can be calculated by applying coordinate transformation method and static equilibrium method:

$$T = \frac{G \bullet r\cos(\beta+\theta)}{2L \bullet \cos(\arctan(\frac{1}{2}\frac{L\cos\theta-1}{h-L\sin\theta})-\theta)}$$

(4)

Here G is the sum of the value of capsized ship weight and the negative value of the bouncy of the capsized ship, r is the vector of the center of gravity of the capsized ship in current coordinate system, 2L is the initial distance between point A and point C, θ is the rotational displacement of the capsized ship in the up-righting project. β is the angle between the vector of the center of gravity of the capsized ship and the seabed, h is the vertical distance between point P and the seabed. Equation (4) is the theoretical solution of the cable tension in the quasi-static model of the up-righting project based on the four assumptions above. By taking account of the relationship between the rotational displacement t, the time, and V_d^e, the winding-in speed of the cable winch, the cable tension both in time domain and "θ-domain" can convert into each other.

4. Calculation of the cable tension in time domain in an up-righting project without taking consideration of wind, current and wave loads

4.1 Calculation of the cable tension in time domain

Cable weight can be ignored in the simulation of a short cable (Thkhonov et al., 1997; Tikhonov et al., 1994) e.g. a 200m cable. But the stiffness of the cable cannot be ignored in the time domain simulation during the up-righting project. A linear stiffness cable model is applied to simulate the cable in the current research.

Denote k as the stiffness of the cable applied in the up-righting project, L_0 as original length of the cable, $\vec{X}_1(t)$ is the coordinate of the connection point on the capsized ship in the current coordinate system, $\vec{X}_2(t)$ is the coordinate of the connection point on the salvage ship in the current coordinate system. Therefore, the cable tension can be written as:

$$T = \begin{cases} k(L-L_0), & L > L_0 \\ 0, & L \le L_0 \end{cases} \tag{5}$$

Here, $L = \left|\vec{X}_1(t) - \vec{X}_2(t)\right|$ is the cable length at time t.

From equation (5), the cable applied in the up-righting project can only have tension instead of pressure.

4.2 Calculation of the cable tension in time domain with consideration of winding-in speed of a cable winch

The cable applied in the up-righting project is assumed to be very light in the current research, i.e. the weight of the cable can be ignored. Therefore, the cable can be modeled by a straight line connecting point P and point C geometrically. Besides, the cable length can vary during the up-righting project. Denote k as cable stiffness, L_0 as the original length of the cable, EA is the product of the Young's Modulus and the cross section area of the cable and:

$$EA = kL_0 \tag{6}$$

Denote $\vec{X}_1(t)$ as the coordinate of the connection point on the capsized ship, $\vec{X}_2(t)$ as the coordinate of the connection point P on the salvage ship. Thus, the strength length of the cable between those two point is:

$$L(t) = \left|\vec{X}_1(t) - \vec{X}_2(t)\right| \tag{7}$$

If the cable winch starts at time t_s, winding-in speed at time $t > t_s$ is:

$$V_d^e = \frac{dL_u(t)}{dt}, \quad \text{where } t > t_s$$
(8)

Denote $L_u(t)$ as the un-strength length of the cable related to $L(t)$, as shown in Fig.3:

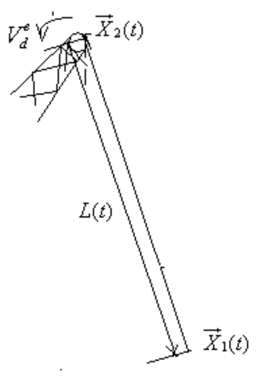

Fig.3 Winding-in Drum Winch

Based on equation (8), the un-strength length is:

$$L_u(t) = L_0 - V_d^e(t - t_s), \quad \text{where } t > t_s \tag{9}$$

The cable tension is:

$$T = \begin{cases} \dfrac{EA}{L_u(t)}[L(t) - L_u(t)] = EA\varepsilon(t), & L(t) > L_u(t) \\ 0, & L(t) \leqslant L_u(t) \end{cases}$$
(10)

In equation (10), $\varepsilon(t)$ is the linear strain of the cable.

5 Calculation of the cable tension in the up-righting project for a capsized ship

In this section, the cable tension of the quasi-static model of an up-righting project of a capsized ship without considering environmental loads is calculated with the application of a numerical simulation method firstly. Here, the winding-in speed of the cable winch is set as 0.001m/s and 0.002m/s individually in order to ensure that the up-righting project is simulated by the numerical method in quasi-static state approximately. Then, the accuracy of the numerical method used in the current research can be checked by comparing the values of the cable tension calculated by the numerical method and the theoretical solution method.

After checking the accuracy of the numerical method applied in the current research, the values of the cable tension with different weight of the capsized ship, different cable stiffness, and different winding-in speed of the cable winch are calculated with the application of the numerical method individually during the up-righting project. After that, the effect on the values of cable tension of the capsized ship weight, the cable stiffness and the winding-in speed of the cable winch will be analyzed.

5.1 Discussion on the accuracy of the numerical simulation method applied in the current research

In section 3, a theoretical solution of the cable tension during the up-righting project has been given (equation (4)). In this section, the weight of the capsized ship is set to 4690 t, while the buoyancy 3690 t, i.e. G=9800kN, g=9.8m/s², r=6.32m, β =arctan 0.333, 2L=12m, h=21m. The depth of the water where the capsized ship located is 11m (the capsized ship will not be out of water during the up-righting project when the depth of water is at least 11m). the cable tension varying with rotational displacement of the capsized ship is shown in Fig.4. during the up-righting project.

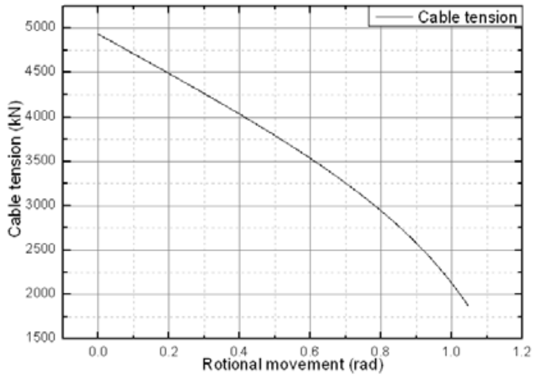

Fig.4 the cable tension varied with the rotational displacement of the capsized ship

The adsorption force is ignored in the calculati on of the cable tension during the whole up-righting project in the current research. Thus, a very small d istance between the "edge point" of the deck and th e seabed is assumed to exist, and at this time the o riginal cable tension is 5192.7kN. The cable tension is approximately 2110.2kN when the edge PC is per pendicular to the seabed.

The result of the cable tension of the up-righting project with consideration of the dynamic effect is not exact in the beginning short period in time domain with the application of equation (3). Thus, the winding-in time is set as t_s=2400s, and the effective values of the cable tension are counted from 2395s. The time step in the current simulation is 0.1s. The up-righting project will be shut while the edge PC is perpendicular to the seabed or the time in up-righting program is over 10800s.

The initial stable values of the cable tension, the stable values of the cable tension after the up-righting project is finished and the maximum values of the cable tension when each individual speed reaches 0.001m/s and 0.002m/s are listed in Tab.1 individually. The cable tension varying with time during the whole up-righting project is shown in Fig.5, and the values varying with time in the beginning 200s are shown in Fig.6. Here, winding-in speeds are 0.001m/s and 0.002m/s individually. Denote the winding-in speed as V_d^e, the initial stable value of the cable tension as F_{ini}, (the initial stable value of the cable tension – the initial theoretical value)/the initial theoretical value as R_{ini}, the final stable value of the cable tension as F_{fin}, (the final stable value of the cable tension – the final theoretical value)/the final theoretical value as R_{fin}, the maximum cable tension as $F_{\max}$, (the maximum cable tension – the initial stable value of cable tension)/the initial stable value of cable tension as $R_{\max}$.

Tab.1. Cable tension(speed=0.001m/s,0.002m/s)

V_d^e (m/s)	F_{ini} (kN)	R_{ini}	F_{fin} (kN)	R_{fin}	$F_{\max}$ (kN)	$R_{\max}$
0.001	5112.8	1.5%	Not been calculated	Not been calculated	5140.9	0.6%
0.002	5112.8	1.5%	2144.4	1.6%	5169.9	1.1%

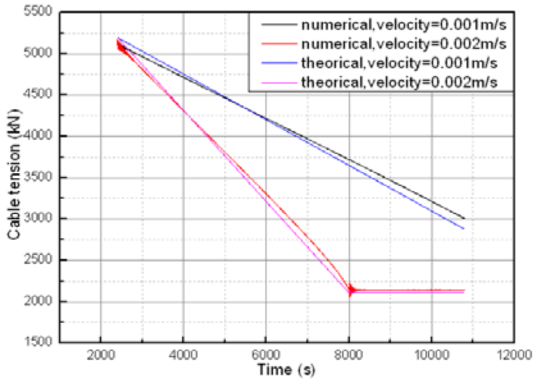

Fig.5 Cable tension varied with time(speed=0.001m/s,0.002m/s)

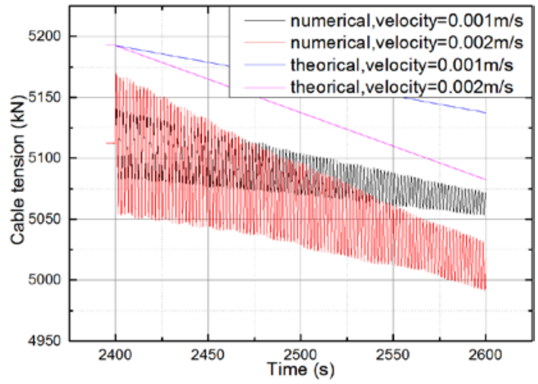

Fig.6 Cable tension varied with time at the beginning 200s(speed=0.001m/s,0.002m/s)

Tab.1 and Fig.5 show that: the up-righting project is not finished at 10800s when the winding-in speed of the winch is 0.001m/s. Besides, the values of the cable tension are similar to the quasi-static solution of the cable tension during the whole up-righting project in Fig.4. Additionally, Tab.1 and Fig.5 show that, the relative error between the cable tension calculated by numerical simulation method applied in the current research and the cable tension calculated by the theoretical solution of the quasi-static model during the whole up-righting project is less than 2%, hence the numerical simulation method applied in the current research to calculate the cable tension during the up-righting project is accurate and effective.

Besides, Fig.5 shows that the maximum value of the cable tension in the up-righting project appears during the beginning 200s. Fig.6 shows that the maximum value of cable tension increases with the winding-in speed, hence the dynamic effect cannot be ignored in an up-righting project. Otherwise, the maximum value of cable will not change with the winding-in speed of cable winch.

5.2 The effect of the weight of the capsized ship on the cable tension

The value of G of the capsized ship is assumed to be varied and the flowing values are set as V_d^e=0.001m/s, k=105kN/m, g=9.8m/s², r=6.32m, β =arctan 0.333, 2L=12m, h=21m. The cable tensions varied with time and different weight of the capsized ship during the up-righting project and the values of cable tension in the beginning 200s are shown in Fig.7 to Fig.9 individually.

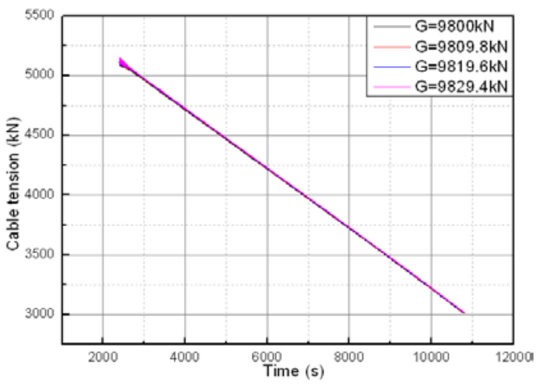

Fig.7 Cable tension varied with time(G=9800,9809.8,9819.6,9829.4k)

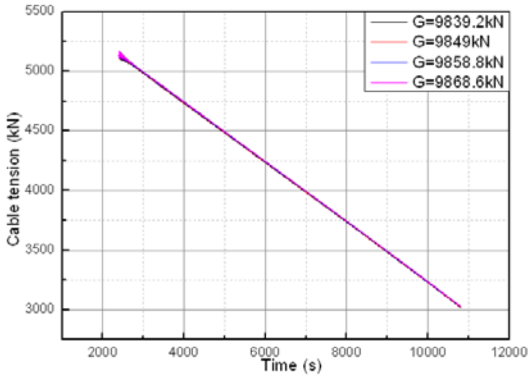

Fig.8 Cable tension varied with time(G=9839.2,9849,9858.8,9868.6kN)

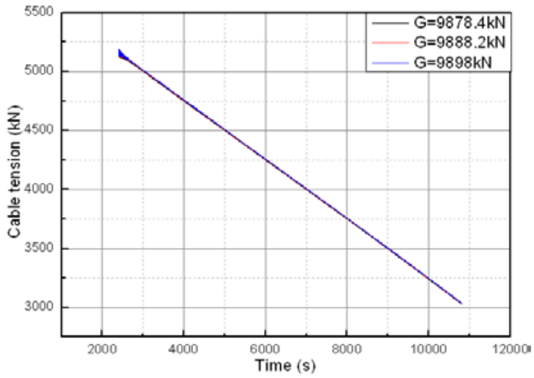

Fig.9 Cable tension varied with time(G=9878.4,9888.2,9898kN)

During the up-righting project, the edge PC is not perpendicular to the seabed when the winding-in speed is 0.001m/s, i.e. the cable winch does not stop in the whole up-righting project, as it was described in section 5.1. Fig.7 to Fig.9. The trend of cable tension in the time domain in each individual case is similar to each other when the weight of the capsized ship changes in a special section applied in the current research. Besides, the maximum values of each individual work case are quite different from each other at the beginning of the up-righting project as the weight of the capsized ship changes in each individual case. The maximum value of the cable tension with each individual G value are show n in Tab.2 and Fig.10:

Tab.2 Maximum cable tension value with each individual G value

G (kN)	F_{max} (kN)	R_{max}
1000	5140.97	0.6%
1001	5146.12	0.6%
1002	5151.08	0.6%
1003	5156.04	0.6%
1004	5161.19	0.6%
1005	5166.53	0.6%
1006	5171.11	0.6%
1007	5175.3	0.6%
1008	5181.98	0.6%
1009	5185.99	0.6%
1010	5192.28	0.6%

Tab.2 shows that the maximum value of cable tension scales up with G during the whole up-righting project while other parameters are constant. The relation between the maximum values of the cable tension and the values of G is approximately linear.

Besides, Tab.2 shows that, R_{max} is approximate 0.6% in each individual value of G when the winding-in speed of the cable winch and the stiffness of cable do not change. Therefore, the maximum value of the cable tension can be estimated based on the value of R_{max} and the initial stable value of cable tension F_{ini} in an existing up-righting project when the values of winding-in speed and cable stiffness are fixed. Here, the F_{ini} can be estimate by the weight of the capsized ship.

5.3 The effect of the cable stiffness on the cable tension

The value of k is assumed to be varied and the flowing values are set as V_d^e=0.001m/s, G=9800kN, g=9.8m/s², r=6.32m, β=arctan 0.333, 2L=12m, h=21m. The cable tensions varied with time and different value of k (cable stiffness) during the up-righting project and the values of the cable tension in the beginning 200s are shown in Fig.10 to Fig.12 individually.

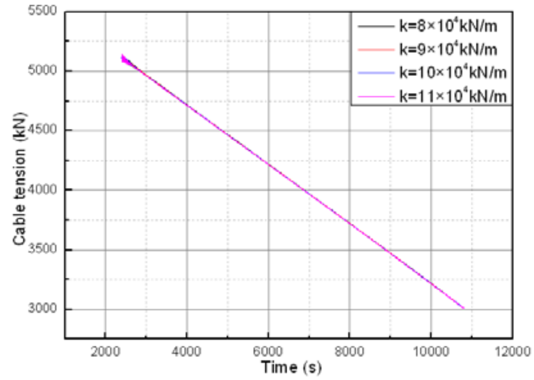

Fig.10 Cable tension varied with time(k=8×104,9×104,10×104,11×104kN/m)

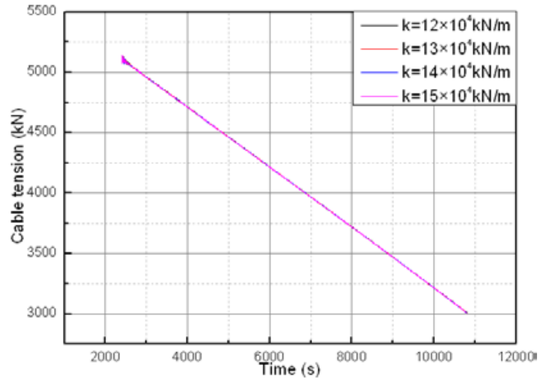

Fig.11 Cable tension varied with time(k=12×104,13×104,14×104,15×104kN/m)

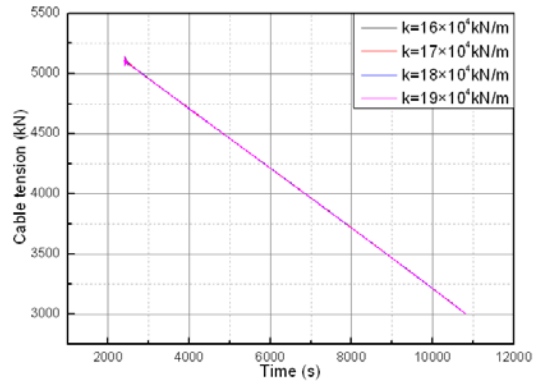

Fig.12 Cable tension varied with time(k=16×104,17×104,18×104,19×104kN/m)

Fig.10, Fig.11 and Fig.12 show that the maximum values of the cable tension and the vibrate cycle vary with the cable stiffness while the weight of the capsized ship is constant. The maximum values of the cable tension in each individual case scale up with the cable stiffness. The maximum value of the cable tension with each individual k value (cable stiffness) are shown in Tab.3:

Tab.3 Maximum cable tension value with each individual k value

k(×10^{4}kN/m)	F_{max} (kN)	R_{max}
8	**5140.98**	0.5%
9	5139.81	0.5%
10	5140.97	0.6%
11	5141.48	0.6%
12	5142.38	0.6%
13	5141.94	0.6%
14	5142.53	0.6%
15	5143.35	0.7%
16	5144.96	0.7%
17	5146.48	0.8%
18	5150.19	0.8%
19	5154.72	0.9%

Tab.3 shows that the maximum values of cable tension in the whole up-righting project scale up with the cable stiffness approximately (which is expected in some special point such as k=9×104kN/m, 12×104kN/m as shown in Tab.3) when the weight of the capsized ship and the winding-in speed of the cable winch are constant. But the relation between the maximum values of the cable tension and the cable stiffness is not linear. In addition, R_{max} scales up with the cable stiffness approximately in the up-righting project.

5.4 The effect of the winding-in speed on the cable tension

The value of V_d^e is assumed to be varied and the flowing values are set as G=9800kN, k=105kN/m, g=9.8m/s², r=6.32m, β=arctan 0.333, 2L=12m, h=21m. The cable tensions varied with the time and different value of V_d^e during the up-righting project and the values of the cable tension in the beginning 200s are shown in Fig.13 to Fig.17 individually.

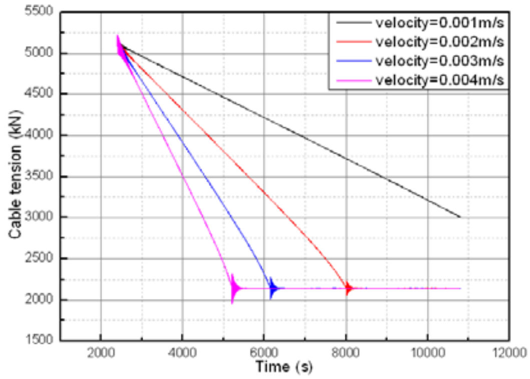

Fig.13 Cable tension varied with time(V_d^e=0.001,0.002,0.003,0.004m/s)

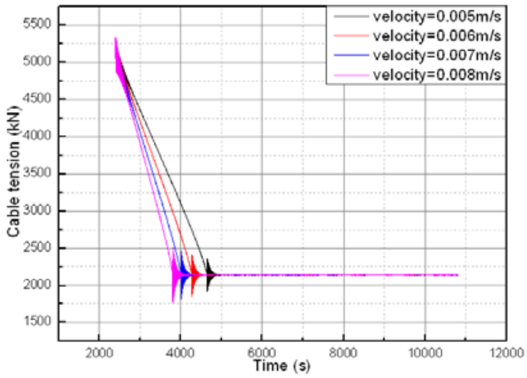

Fig.14 Cable tension varied with time(V_d^e=0.005,0.006,0.007,0.008m/s)

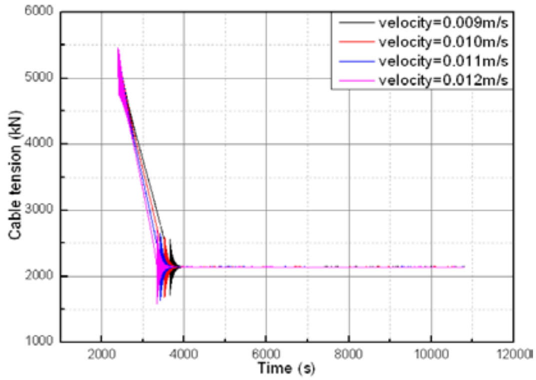

Fig.15 Cable tension varied with time(V_d^e=0.009,0.01,0.011,0.012m/s)

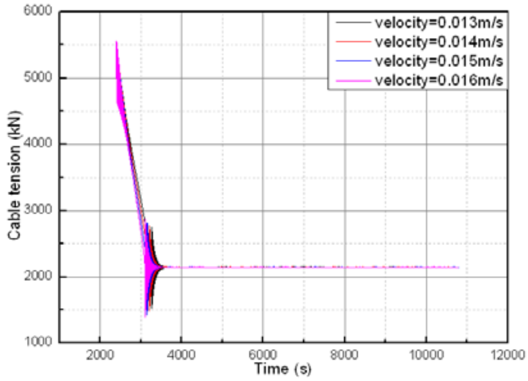

Fig.16 Cable tension varied with

time(V_d^e=0.013,0.014,0.015,0.016m/s)

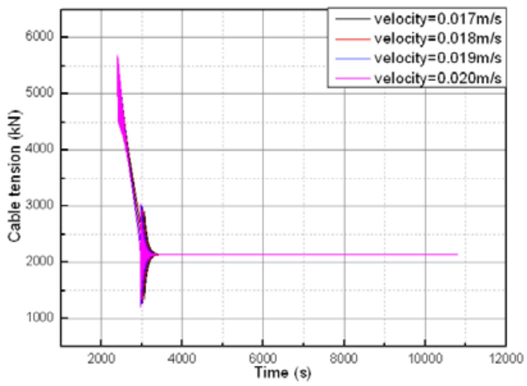

Fig.17 Cable tension varied with time(V_d^e=0.017,0.018,0.019,0.02m/s)

The times that the cable tension become stable are different from each other with each individual value of winding-in speed as shown in Fig.13 to Fig.17: the times that the cable tension becomes stable decrease with the winding-in speed of the cable winch. Besides, the vibration range of the value of the cable tension and the maximum value of cable tension increase with the winding-in speed. In addition, F_{fin} does not vary with the winding-in speed. $F_{\max}$ with each individual V_d^e (winding-in speed) are shown in Tab.4:

Tab.4 Maximum tension value with each individual V_d^e value

V_d^e (m/s)	$F_{\max}$ (kN)	$R_{\max}$
0.001	5140.97	0.5%
0.002	5169.86	1.1%
0.003	5198.57	1.7%
0.004	5227.28	2.2%
0.005	5255.99	2.7%
0.006	5284.89	3.3%
0.007	5313.22	3.9%
0.008	5341.74	4.5%
0.009	5370.45	5.0%
0.01	5399.36	5.6%
0.011	5428.07	6.1%
0.012	5456.6	6.7%
0.013	5485.7	7.3%
0.014	5514.22	7.8%
0.015	5542.56	8.4%
0.016	5571.66	9.0%
0.017	5600	9.5%
0.018	5629.11	10.0%
0.019	5657.45	10.7%
0.02	5686.56	11.2%

Tab.4 shows that: the maximum values of the cable tension in the whole up-righting project scale up with the winding-in speed of the cable winch when the other parameters are constant. Besides, the relation between the maximum value of the cable tension and the winding-in speed is linear. Tab.4 also shows that $R_{\max}$ scales up with the speed of the cable winch.

5.5 Evaluation of an up-righting project for a capsized ship

In this section, the safety of an up-righting project for a capsized ship is evaluated based on the values of the cable tension calculated by the numerical simulation method applied in the current research. An up-righting project for a capsized ship is considered to be safe when the cable tension is not over the allowable stress of the cable.

The winding-in speed of the cable winch can be controlled in an up-righting project. Thus, only the winding-in speed of the cable winch is changed in the calculation of cable tension and the evaluation of the up-righting project safety , but the weight of the capsized ship and the cable stiffness are not changed. In this section, the evaluation of the up-righting project safety for a capsized ship is based on comparison with the maximum value of the cable tension and the allowable stress of the cable: if the maximum value of the cable tension is bigger than the allowable stress of the cable, the up-righting project is not safe. Besides, safety coefficients of the cable used in the up-righting project with different winding-in speed are calculated in this section. Here G=9800kN, g=9.8m/s², r=6.32m, β=arctan 0.333, 2L=12m, h=21m, the diameter of the cable is 24mm, and the cable which includes 16 ones is applied in the up-righting project in the current research. Here, the friction force between cables and the bending movement of cables are assumed to be ignored, and the tension of each cable is assumed to be equaled with each other. The equivalent stiffness (the value of k) of the cable is 9.6×104kN/m, and the broken strength is 5600kN (Luo, 2014). The maximum value of the cable tension $F_{\max}$ varying with the winding-in speed of the cable winch V_d^e are shown in Tab.5.

Tab.5 Maximum tension value with each individual V_d^e value

V_d^e (m/s)	$F_{\max}$ (kN)
0.01	5402
0.015	5548
0.016	5600

The maximum value of the cable tension ($F_{\max}$) is 5600kN while the winding-in speed (V_d^e) is 0.016m/s. Therefore, the maximum value of the cable tension ($F_{\max}$) will be over the broken strength of the cable applied in the current research (5600kN) while the winding-in speed (V_d^e) of the cable winch is over 0.016m/s, and the cable will be broken subsequently. Thus, the winding-in speed of a cable winch should be in a particular range during an up-righting project for a capsized ship. In this section, the speed (V_d^e) should be less than 0.016m/s.

Tab.6 shows the safety coefficient of the cable applied in the current research with each individual winding-in speed.

Tab.6 Safety coefficient of the cable

V_d^e (m/s)	Safety coefficient of the cable
0.01	1.03
0.015	1.01
0.016	Positive value close to 1

If the cable tension of the cable winch applied in the current up-righting project is calculated without taking consideration of the dynamic effect, the cable tension will not vary with the winding-in speed of cable winch, even when the winding-in speed is extremely big. Therefore, the safety coefficient of the cable will not change with each individual winding-in speed of the cable winch. However, Tab.6 shows that, the safety coefficient of the cable reduces with the winding-in speed during the up-righting project. Thus, the winding-in speed of the cable winch must be set in a particular range in an up-righting project in order to guarantee the essential safety for the up-righting project .

6.Discussion and conclusion

The up-righting projects taking account of the dynamic effect for a capsized ship have been simulated with the application of a numerical simulation method in the current research. The safety evaluation for an up-righting project has been evaluated based on the cable tension calculated with the application of the numerical method. Different values of cable tension in each individual work case have been calculated. Some results are concluded as follows:

The accuracy of the numerical method used in the current research has been checked by comparing the values of the cable tension calculated with the numerical method and the theoretical solution method: the values of R_{ini} at V_d^e =0.001m/s and V_d^e =0.002m/s are approximately 1.5% .

During the up-righting project, the maximum values of the cable tension scale up with the weight of the capsized ship, the winding-in speed of the cable winch, and the cable stiffness respectively. Besides, the relationship between the maximum values and the weight of the capsized ship is linear approximately, the relationship between the maximum value and the winding-in speed is linear, and the relationship between the maximum value and the cable stiffness is nonlinear.

The $R_{\max}$ with the winding-in speed V_d^e =0.02m/s is as 22 times as the one with the winding-in speed 0.001m/s. It shows that the winding-in speed of the cable winch influences the maximum cable tension obviously.

The dynamic effect on an up-righting project cannot be ignored. But sometimes, the winding-in speed of the cable winch should be set a little faster in order to avoid the heavy environment state. Thus, the maximum winding-in speed guaranteeing the essential safety of the up-righting project can be estimated by the method discussed in the current research.

A 3-D method to simulate an up-righting project should be investigated in further research to improve the method discussed in the current research.

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