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SERVICES FOR SCIENCE AND EDUCATION

Model Experiments for Floating Stability of Self-Elevating Platform and Assessment Based on Theory of Structural Stability

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ABSTRACT

A self-elevating platform (referred to as SEP hereafter), used as a pier, capsized during construction work at sea in March 2014. The structural characteristics of the SEP include a notably high center of gravity due to its long legs and a large rectangular plane, resulting in a shallow draft, which significantly differs from conventional vessels. While the stability of floating bodies is typically assessed using metacentric height and restoring moment curves based on conventional ship algorithms, it is essential to ascertain whether the same principles can be applied to the SEP, given its distinct structural features. In this study, an evaluation method based on structural stability theory, distinct from ship algorithms, was validated through model experiments. An analysis of overturning, based on structural stability theory previously employed for pile drivers on land, was conducted using the experimental results. As a result, it was discovered that both ship algorithms and structural stability theory essentially serve the same purpose in assessing the floating stability of SEP.

Keywords: Self-Elevating Platform, Floating Stability, Okinotorishima SEP, Overturning Model Test, Pile Driver Overturning, Overturning Mechanism, Structural Stability, Soft Foundation

INTRODUCTION

A self-elevating platform (hereinafter referred to as SEP) capsized during afloat construction work at the site of Okinotorishima on March 30, 2014 [1]. The SEP was supposed to be used as a part of permanent pier after placed at the site. Figure 1 illustrates floating SEP schematically. The structural features of SEP shown in Fig. 1 include a very high center of gravity due to its long legs (4 in total, 47.5m long) and a large rectangular pontoon (20m width and 30m length) resulting in a shallow draft, which significantly differ from conventional vessels.

While the stability of floating bodies is typically evaluated using metacentric height and restoring moment curves based on conventional ship algorithms, it is necessary to verify whether the same methods can be applied to SEP, which has significantly different structural characteristics.

In this study, the evaluation method based on structural stability theory will be applied, which is different from ship algorithms. In order to research its applicability, a model experiment was conducted and analyzed based on structural stability theory. It was found through the experiments the assessment of structural stability theory consequently gave the same results as ship algorithms.

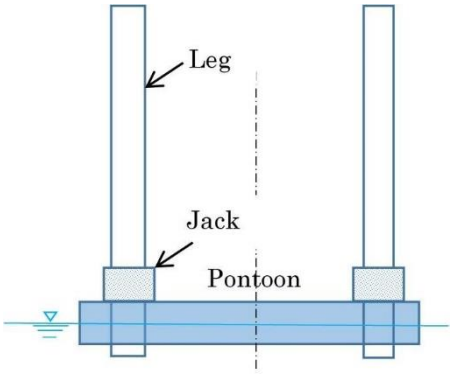


Figure 1: Self-Elevating Platform

Overturning mechanisms using structural stability theory have been studied in the past for pile drivers and other heavy machines on land [2] ~ [6]. The study here will verify the past researches.

EXPERIMENTAL AND ANALYTICAL MODELS

A model experiment has been conducted on the overturning (capsizing) of the floating body of the SEP illustrated in Fig. 1. In order to perform the experimental study on stability, SEP in Fig. 1 is simplified to experimental model as shown in Fig. 2. The experimental model consists of three parts: a box type of pontoon for the floating body, a leg concentrated at the center, and spacers for height adjustment. A cylindrical water tank at the center was used for the legs, and water was poured into this tank during the experiment until the model capsized, measuring the weight and height. Here, the four legs at the corners were simplified into one central leg as shown in Fig. 2. The water inside the tank has a free surface.

The model shown in Fig. 2 is further simplified as a rigid bar-rotation spring system, as depicted in Fig. 3, for structural stability analysis. This structural model has been utilized in previous studies on the overturning problems of cranes and pile drivers [2 ~ 6], and this experiment also serves as a verification of its analytical approach. While the rotational spring stiffness in the overturning of onshore heavy machines is uncertain because they are supported by soil foundation, it is clear for offshore vessels which are supported by water.

In the structural system shown in Fig. 3, the structural stability theory derives the following critical load (buckling) Pcr and critical height Lcr from the rotational spring stiffness Ks [7].

$$P_{cr} = K_s / L_{cr} \tag{1}$$

When the load on SEP (own weight) exceeds this critical load Pcr, SEP becomes structurally unstable, and it overturns even if the overturning moment is zero, similarly to the elastic buckling of a long column. Note that the rotational stiffness Ks is assumed as linear in Eq. (1).

When the vessel is tilted as shown in Fig. 2(b), the rotational stiffness will be calculated from the buoyancy change. The change of buoyancy volume V in Fig. 2(b) can be calculated by the following Eq. (2).

$$V = \frac{b^2}{12} l \tan\theta \quad (2)$$

in which b=width of pontoon, l =length of pontoon.

Assuming the water density 1g/cm^3, which results in f =V, the righting moment M_R induced by the force f can be obtained as follows:

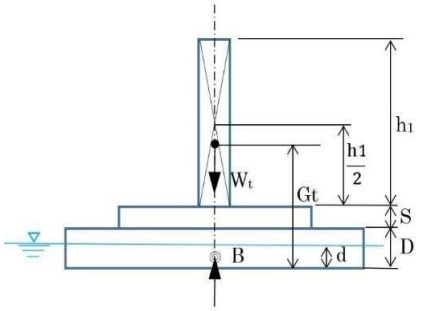
$$M_R = \frac{2}{3} f b \cos\theta = \frac{b^2}{12} l \sin\theta \quad (3)$$

Equation (3) is plotted in Fig. 4, disregarding the height of freeboard. Since sinθ ≈θ for small θ, the rotational spring stiffness K_s can be obtained from the definition shown in Fig. 4 as follows:

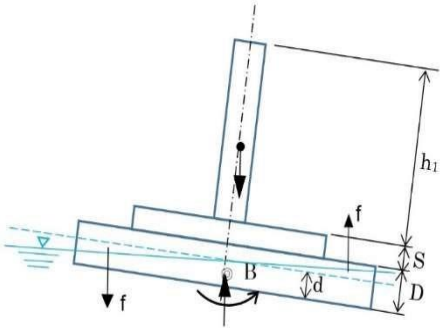
$$K_S = \frac{b^2}{12} l = Iy \quad (4)$$

in which I_y = moment of inertia of draft area with respect to long axis of pontoon.

It is interesting to know that the rotational stiffness is equal to the moment of inertia of the draft area. In general vessels, the center of buoyancy shifts with incline, causing a variation in I_y. However, it is assumed to remain constant in structural stability theory.



(a)



(b)

Figure 2: Experimental Model of SEP.

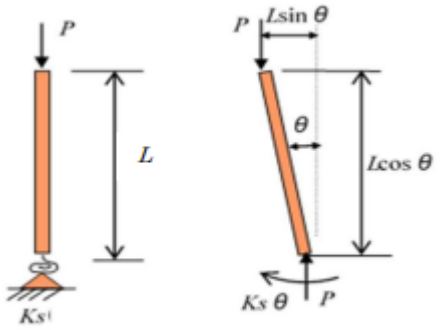


Figure 3: Analytical Model.

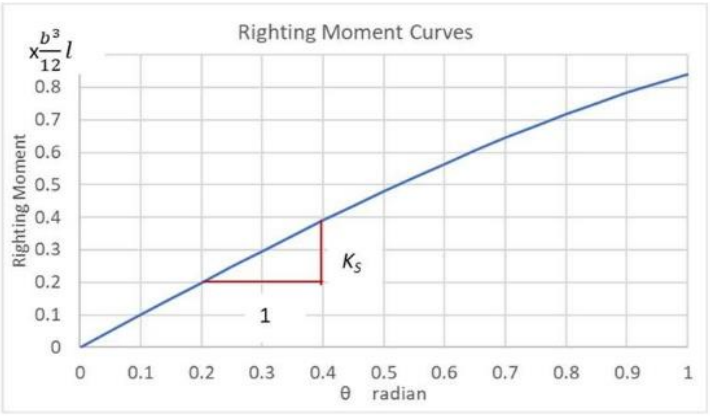


Figure 4: Rotational Stiffness K_s

Theory of structural stability deals with the distinction between stable and unstable status. Figure 5 illustrates the concept of stability and instability which are divided by the neutral value, i.e., the stability limit, given by the critical load Eq. (1). As a ball on the convex surface which is larger than the neutral line in Fig. 5 drops, which corresponds to the unstable status in Fig. 6(c), structures will overturn. On the contrary, as a ball on the concave surface returns to the original position, which means stable status as shown in Fig. 6(a), structures will stand safely. Neutral value in between is the stability limit. In this way, the stability surface in Fig. 5 well illustrates to understand the concept of structural stability and the behaviors of the displacement of structures against the load.

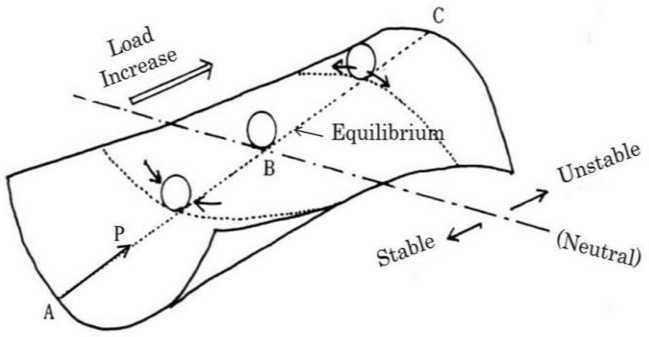


Figure 5: Conceptual Surface of Stabilit

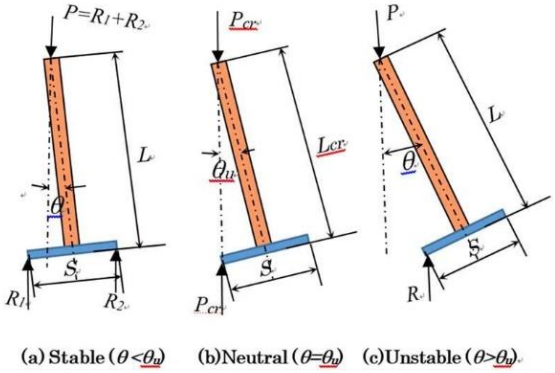


Figure 6: Stable, Neutral and Unstable.

CO-RELATION BETWEEN STRUCTURAL STABILITY THEORY AND SHIP ALGORITHMS

As mentioned earlier, in ship stability algorithms, stability concerning the weight (load) of the hull is determined by the metacentric height *GM*. On the other hand, in structural stability theory, it is determined by the critical load P_{cr} or load height L_{cr} related to the rotational spring stiffness K_s. From here on, we will examine the relationship between these two approaches.

Firstly, the metacentric height *GM* is expressed by the following equation based on its definition. Here, the density of water is assumed to be $1 g/cm^3$, then displacement volume V is considered equivalent to the total weight W_t.

$$GM = I_y/V - (Gt - d/2) \quad (5)$$

where I_y = second moment of area of the hull's waterline section, V = displacement volume, Wt = total weight of the hull, Gt = height of the center of gravity from the hull bottom, d = draft depth.

Considering the relations $K_s=I_y$ from Eq. (4) and $V=W_t$, Eq. (5) can be written as follows:

$$GM = Lcr - Lact \quad (6)$$

Equation (6) gives the relation between ship algorithms and structural stability theory. Figure 7 explains Eq. (6) for floating stability based on ship algorithms, and Fig. 8 does the same based on theory of structural stability. Looking at Eq. (6), *GM* represents the margin of safety in terms of load height, as it is the difference between the critical load height L_{cr} and the actual height L_{act} in structural stability theory. As the actual load height L_{act} approaches the critical load height L_{cr}, the metacenter height *GM* decreases, indicating increase of instability. In other words, a negative *GM* value means that the load P_{act} exceeds the critical load P_{cr} and becomes unstable. Consequently, it can be said that both ship algorithms and structural stability theory have the same meaning in the assessment of stability. However, since the *GM* value represents the difference only between the critical and actual values in terms of height and load, it cannot

be evaluated in non-dimension. Hence, comparing *GM* values between different types of hulls, such as conventional hulls and box type of hulls, becomes challenging.

Equation (5) is also transformed to the following Eq. (7), of which the left term expresses in form of structural stability theory and the right one is in ship algorithms.

$$\frac{Lact}{Lcr} = \frac{Gt - \frac{d}{2}}{\frac{ly}{y}} \tag{7}$$

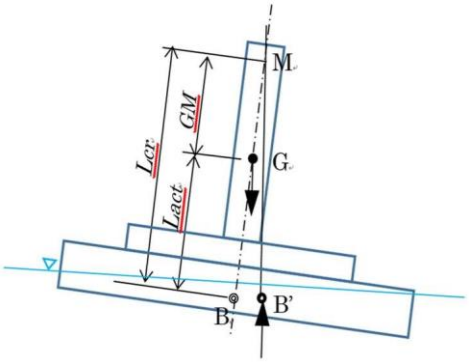


Figure 7: Floating Stability.

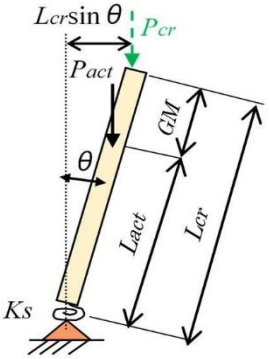


Figure 8: Structural Stability.

From Eq. (6), the following two equations can be derived:

$$\frac{GM}{L_{cr}} + \frac{L_{act}}{L_{cr}} = 1 \tag{8}$$

And

$$\frac{GM}{L_{cr}} + \frac{P_{act}}{P_{cr}} = 1 \tag{9}$$



Figure 9: View of Experiments.

The ratio of actual height to critical height L_{act}/L_c is also equal to the ratio of actual load to critical load P_{act}/P_{cr}. Therefore, equation (8) is equivalent to equation (9). In the above discussion, P_{act} represents the actual load, therefore L_{act} are the values obtained from the experiments. From Eqs. (8) and (9), it is evident that the ratios GM/L_{cr} in ship stability and P_{act}/P_{cr} or L_{act}/L_{cr} in structural stability are inversely related. It's worth noting that equations (8) and (9) can also be verified from the experimental results mentioned later (see Fig. 10).

Table 1: Dimensions of Model.

Pontoon	BxLxD	A (cm2)	W (g)	Iy or Ks
F1	163x240x39	391	126	8661
F2(S2)	110x197x37	217	105	2185
F3(S3)	132x197x52	260	122	3776
F4	158x226x91	357	260	7428
Spacer	D (cm)	–	W (g)	
S1	2	–	30	
S2(F2)	3.7	–	105	
S3(F3)	5.2	–	122	
Water Cylinder		–	W (g)	
P1	Φ62x192	30.2	61	
P2	Φ70x137	38.5	41	

MODEL EXPERIMENTS

While in the case of the toppling problem of pile drivers and cranes Eq. (1) was utilized, the stability of floating bodies are usually assessed by the ship algorithms. Here, to confirm if the same Eq. (1) could be applied to the stability of SEP's floating bodies, model experiments were conducted. The experimental model consisted of three parts: an upper water bottle, a rectangular hull (pontoon), and spacers for adjusting the center of gravity, as seen in Fig. 2. These components were made using commercially available plastic containers which can be seen in Fig. 9. The rectangular hull (pontoon) comprised four types (F1, F2 (=S2), F3 (=S3), F4), the spacers comprised three types (S1, S2, S3), and the water bottles comprised two types (P1, P2), respectively, forming SEP models by combining them. The dimensions and weights of each

component are listed in Table 1. Model experiments were conducted for ten cases (A, B, C, D, E, F, G, H, I, J), and their details are presented in Table 2 below.

The experiment involves placing the model on the water and, as shown in Fig. 9, gradually adding water to the water bottle until it capsizes (quasi-statically) for measuring the total weight W_t and its corresponding load height L_{act} at that moment. On the other hand, the theoretical critical load height L_{cr} is determined using Eq. (1) from the total weight of the model W_t, which is equal to the critical load P_{cr} in this case, and the rotational spring stiffness Eq. (4). These two values, L_{act} and L_{cr}, are compared by their ratio in Table 2. In this way, by comparing the experimental measured value and the analytical value of the center of gravity height at the time of capsizing, it is possible to determine whether Eq. (1) could be applied to SEP, namely the applicability of structural stability theory to the stability of SEP.

EXPERIMENTAL RESULTS AND DISSCUSSION

The summary of experimental results is presented in Table 2. Ratio of the experimental results L_{act} to the theoretical values L_{cr} based on structural stability theory is supposed to be 1.0 when Eq. (1) is applicable to SEP. As can be seen in the table, the experimental results have differences only within 5% (with an average of about 2%), which suggests a good agreement. From these observations, it can be concluded that the theoretical values of the structural models in Fig. 3 and Eq. (1) can be applied to the stability assessment of SEP. This implies that related studies [2] ~ [6] can also contribute to the stability assessment of SEP.

In theoretical calculations of Table 2, the center of gravity is considered as a point, whereas in experiments, water inside the bottle is used as a weight, which has a free surface. There is a difference between the theory and the experiments. Additionally, in structural stability theory, the rotational spring stiffness K_s is assumed as constant. However, in ship algorithms, it has been shown that the restoring moment slightly increases with the increase in tilt [1]. Despite these factors, the error is very small.

Table 2: Results of Experiments.

Case	Pontoon	Spacer	Water Cylinder	Wn (gf)	Wt (gf)	Gt (cm)	d (cm)	L_{act} (m)	L_{cr} (m)	L_{act}/L_{cr} (Pact/Pcr)	Iy	GM＝Iy/Wt-(Gt-d/2)	GM/L_{cr}
A	F1	S1+S3	P1	379	718	12.80	1.835	11.881	12.063	0.985	8661	0.182	0.015
B	F1	S1+S2	P1	437	776	12.42	1.984	11.425	11.161	1.024	8661	-0.264	-0.024
B'	F1	S1+S2	P1	430	769	12.31	1.966	11.329	11.263	1.006	8661	-0.066	-0.006
C	F1	S1+S2	P2	493	832	11.76	2.127	10.696	10.410	1.028	8661	-0.286	-0.028
D	F1	S2	P1	500	839	11.73	2.145	10.653	10.323	1.032	8661	-0.330	-0.032
D'	F1	S2	P1	488	827	11.55	2.114	10.491	10.473	1.002	8661	-0.018	-0.002
E	F1	S1	P1	546	885	10.73	2.262	9.598	9.786	0.981	8661	0.188	0.019
F	F2 (S2)	0	P1	240	579	5.00	2.672	3.664	3.774	0.971	2185	0.109	0.029
G	F2 (S2)	S1	P1	181	520	5.54	2.400	4.336	4.202	1.032	2185	-0.135	-0.032
H	F3 (S3)	S2	P1	180	519	8.36	2.004	7.354	7.276	1.011	3776	-0.078	-0.011
I	F3 (S3)	S1	P1	243	582	7.31	2.247	6.188	6.488	0.954	3776	0.300	0.046
J	F3 (S3)	0	P1	314	653	6.87	2.521	5.608	5.783	0.970	3776	0.175	0.030
K	F4	S2	P1	248	587	13.44	1.644	12.622	12.654	0.997	7428	0.032	0.003
※B'、D': re-test			SEP NIKKEI [1)]		V=1856m^3	10.87 m	3.16 m	9.29 m	10.5 m	0.886	19466	1.19	0.114
Wn = water weight, Wt＝total weight, G t ＝gravity height (from pontoon bottom), d ＝draft depth, Lact＝loadheight, Lcr＝Ks/Wt, GM＝metacenter height													

Figure 10 represents Eq. (9) and illustrates, based on the experimental results in Table 2, the relationship between the ship algorithm's GM normalized by L_{cr} (GM/L_{cr}) and structural stability theory L_{act}/L_{cr} (or P_{act}/P_{cr}), showing a linear relationship. This indicates that in stability analysis of ships, theoretical values from structural stability theory exhibit a consistent relationship and align with experimental findings.

The experimental results are measured at the point of capsizing, which signifies $P_{act}/P_{cr} > 1.0$ or $GM/L_{cr} < 0$. In other words, a negative GM in ship algorithms indicates that the load P_{act} in structural stability theory exceeds the critical load P_{cr}. This corresponds to the "buckling overturning type" in the classification of overturning mechanisms for pile drivers [4]. The "overturning moment type", which assumes the support base to be rigid, is not applicable to the instability of the floating body on water. Additionally, the value of Okinotorishima SEP is plotted in Figure 10 for reference, indicating that it is slightly away from the range of capsizing, positioned on the safer side.

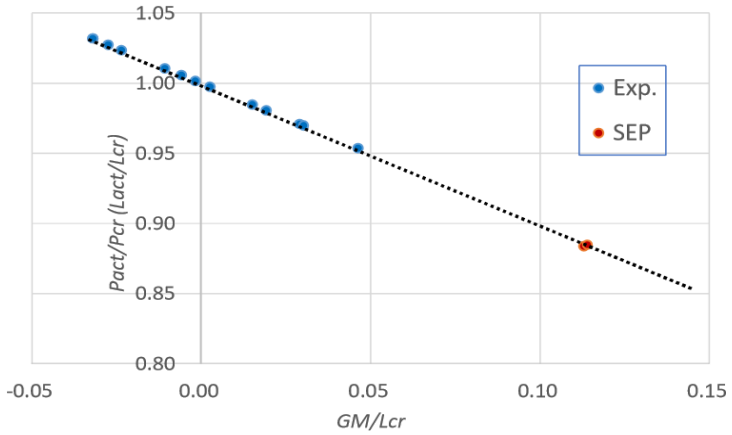


Figure 10: *Pcr-GM* Relationship.

The experimental results suggest that the overturning of SEP is also deeply related to other overturning mechanisms [5]. Particularly, the "balance transition type" of overturning is crucial, and considering these different mechanisms allows for a more comprehensive stability assessment [6].

CONCLUSIONS

The Self-Elevating Platform (SEP) has a structurally distinctive feature as a floating body shape different from conventional ships, due to its high center of gravity caused by its long legs. There is a question whether the ship algorithms commonly used for stability assessment of conventional ships can be applied to such SEP. This paper evaluates the stability of such SEP from a perspective of structural stability theory entirely different from ship algorithms and examines its applicability. Structural stability theory has been proposed for analyzing the overturning problem of onshore structures such as pile drivers and cranes, but here the analysis method is applied to the floating stability of SEP.

Model experiments were conducted to assess its applicability. The comparison between theoretical analysis based on structural stability theory regarding the ultimate load and the

results of model experiments showed errors within 5% (with an average of 2%), indicating sufficient validity for application. Furthermore, regarding the rotational spring stiffness, which was a challenge in the problems of pile driving machines and crane overturning, the modelexperiments conducted here allowed the use of a clear rotational spring stiffness called resistance moment due to buoyancy. This also confirmed the validity of the analysis methods for pile driving machines and cranes used so far.

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