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A Study on Safety Criteria for Toppling of Pile Drivers and Cranes Based on Structural Stability

Shouji Toma[1,*] **and Wai Fah Chen**[2]

[1]*Hokkai-Gakuen University, Japan*

[2]*University of Hawaii, USA*

Abstract: The toppling mechanisms of heavy machinery with high center of gravity such as pile drivers, cranes, and jacks can be broadly classified into two categories: overturning moment toppling and structural instability toppling. The structural instability toppling is further divided into buckling toppling and equilibrium transition toppling. These three toppling mechanisms are significantly different, and it is necessary to address their safety separately when discussing safety criteria. Therefore, it is considered that safety criteria should be established coping with characteristics of each toppling mechanism. In particular, toppling in the case of structural instability has not had clear safety criteria so far, and the development of rational safety criteria based on structural stability theory is considered important to prevent future toppling accidents. This paper provides a sample of the safety criteria that align with the classification of the three toppling mechanisms. For the buckling toppling, the criterion is set to restrict the vertical load considering the critical load (buckling). For the overturning moment toppling, the criterion is set to restrict the inclination angle in order not to exceed the stability limit angle. Additionally, for the equilibrium transition toppling, the criterion is set on both the vertical load and the inclination angle so that the maximum displacement angle due to dynamic inertial force does not exceed the stability limit angle. A sample of the safety criteria provided in this paper includes the three toppling mechanisms which should be covered to avoid the toppling accidents of heavy machinery which has high center of gravity.

Keywords: safety criteria of toppling, pile driver toppling, crane toppling, dynamic analysis of toppling, toppling mechanism, structural stability, toppling on soft foundation

1. Introduction

There have been a number of instances on toppling of heavy machinery with high center of gravity, such as pile drivers, cranes, high-altitude work vehicles, and jacks in Japan [1–5] and other countries [6–8]. In order to prevent recurring such accidents, researches were conducted from different points of view in Japan [9–12], in the United States [13, 14], in Europe [15], and in India [16].

Recently, research has been making progress in understanding the mechanisms behind the toppling accidents of pile drivers and other heavy machinery based on structural stability theory [17]. In particular, it is believed that the influence of dynamic inertial forces is a key factor contained in unexpected toppling accidents [18, 19]. In order to prevent such accidents, it is expected that adequate safety criteria have to be established considering the structural stability theory and dynamic inertial forces.

Toppling mechanisms of equipment such as pile drivers and cranes can be broadly classified into overturning moment toppling and structural instability toppling [17]. Here, the structural instability toppling is further categorized into buckling toppling and equilibrium transition toppling. These three toppling mechanisms are significantly different, and addressing their safety requires separate considerations. Presently, the safety criteria are mainly based on the moment overturning toppling [11, 20, 21]. It is deemed necessary to establish the safety criteria that include elements of structural stability theory. There have been no clear safety criteria for the two types of structural instability toppling, and the formulation of rational safety criteria based on structural stability theory is considered crucial to avoid future toppling accidents. This paper serves as a proposal for that purpose, indicating the direction of comprehensive safety criteria corresponding to the three toppling mechanisms: the overturning moment toppling, the buckling toppling, and the equilibrium transition toppling.

Although the toppling accidents of jacks which result in falling of bridge girder under construction are not directly addressed here, the toppling mechanisms are considered exactly the same. The same structural model and thus the same safety criteria can be applied. Therefore, the fall accidents of bridge girder due to toppling of jacks can also be avoided with the safety criteria provided in this paper.

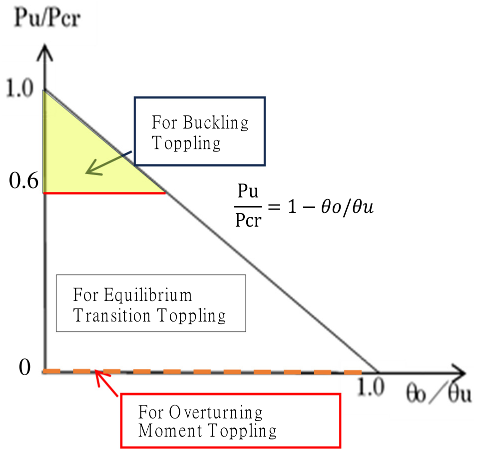
2. Classification of Toppling Mechanisms for Safety Criteria

As mentioned above, the toppling mechanisms of heavy machinery such as pile drivers can be categorized into the following three: overturning moment toppling, buckling toppling, and equilibrium

*Corresponding author: Shouji Toma, Hokkai-Gakuen University, Japan. Email: toma@hgu.jp

transition toppling [17]. Figure 1 illustrates the classification of the three toppling mechanisms and the corresponding safety criteria. Figure 1 also shows that the reduction rate of the toppling load is indirectly proportional to the initial inclination angle on the horizontal axis, which is expressed by the following linear equation [17]:

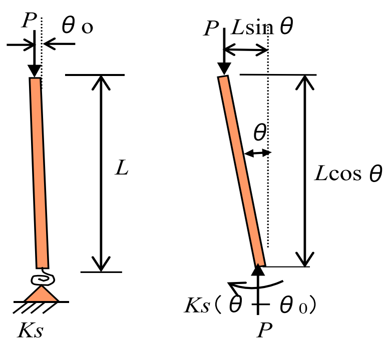
Figure 1
Toppling mechanisms and safety criteria (static analysis)



$$P_u/P_{cr} = 1 - \theta_0/\theta_u \quad (1)$$

where P_u = toppling load, P_{cr} = elastic critical (buckling) load, θ_u = toppling inclination angle (stability limit), and θ_o = initial inclination angle (see Figure 2).

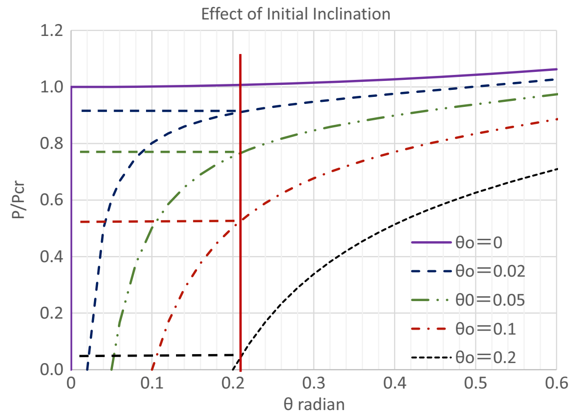
Figure 2
Structural model



It should be noticed that the load and the angle are expressed in normalized forms in Equation (1) and Figure 1. The linear line in Figure 1 is obtained based on the structural model of machinery such as pile drivers and cranes, which is represented by a rigid column-rotational spring system shown in Figure 2 [17]. This model is used to investigate the toppling mechanisms in the past researches by the authors [18, 19].

The static equilibrium curves of load–displacement angle relationship shown in Figure 3 are plotted using the structural model in Figure 2 [17]. It can be seen in the figure that the initial inclination affects significantly so as to lower the load–

Figure 3
Load–displacement angle curves (static analysis)



displacement curves. For each initial inclination angle θ_o in Figure 3, the intersection points of the toppling inclination angle θ_u and the corresponding load P_u/P_{cr} are indicated by horizontal dotted lines, which form the linear line in Figure 1. The linear line implies that the normalized toppling load P_u/P_{cr} decreases proportionally to the ratio of the initial inclination angle to the toppling inclination angle, θ_o/θ_u.

As shown in Figure 1, the safety criteria can be categorized into three zones according to amount of the load ratio P_u/P_{cr}: buckling toppling for higher load ratio; overturning moment toppling for zero load ratio; and equilibrium transition toppling for intermediate load ratio in between. Next, the relationship between the criteria in Figure 1 and each toppling mechanism will be discussed.

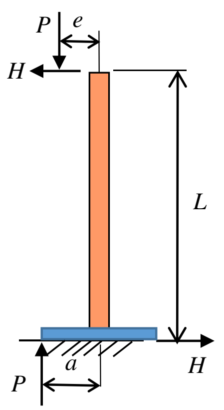
3. Safety Criterion for Overturning Moment Toppling (Solid Foundation)

The toppling condition of the overturning moment toppling on solid foundation is expressed by the following equation, as the overturning moment *(Mt)* exceeds the resisting moment *(Mr)* shown in Figure 4:

$$M_t = Pe + HL > M_r = Pa \quad (2)$$

where P = weight and soil support force of pile driver, H = horizontal force, L = center of gravity height, e = eccentricity of vertical load, and a = distance to soil support force.

Figure 4
Overturning moment toppling



The corresponding safety criterion can be given by the ratio between the two moments as follows:

$$M_r/M_t < S_m = 1.25 \text{ or } S_{m'} = 1/S_{m\cdot} = 0.8 \quad (3)$$

Note that the safety factor in Equation (3) is shown as just an example. As the overturning moment toppling operates on a robust soil foundation, it is relatively easy to implem ent mechanical safety measures, such as installing an automatic safety device to measure overturning moments. Accidents involving the overturning moment toppling often seem to result from operator errors, such as switching off the safety devices. Therefore, the safety factor for this mechanism could take relatively small values, for example, S_m = 1.25 ($S_m{}' = 0.8$) as adopted in Equation (3).

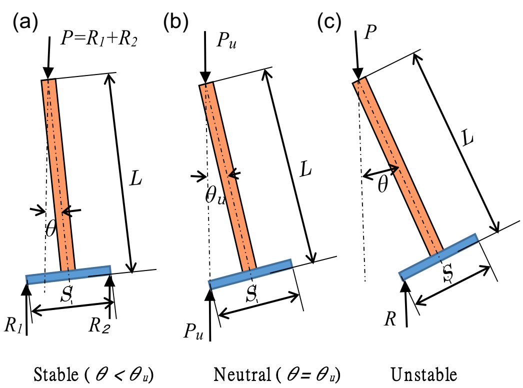
In the mechanism of the overturning moment toppling shown in Figure 4, it is assumed that the soil is solid. Therefore, in the structural model of Figure 2, the rotational spring stiffness K_s of the foundation and the elastic toppling load (buckling) P_{cr} are infinitely large (refer to Equation (5) below).

When viewing this in Figure 1, the load on vertical axis is located near $P_u/P_{cr} = 0$. This means that the safety factor can be considered along the horizontal axis. In other words, by setting $Sm' = 1/Sm = 0.8$ as specified in Equation (3), the initial slope angle is limited for safety up to $\theta_0 = 0.8\theta_u$, in which θ_u is toppling inclination angle (stability limit) and can be determined by Equation (4) from the definition in Figure 5(b).

$$\theta_u = tan^{-1}S/(2L) \quad (4)$$

Figure 5 schematically illustrates the states of structural stability of the pile driver and others, with the slope angle dividing stable in Figure 5(a) and unstable in Figure 5(c) at the neutral (toppling inclination angle or stability limit) in Figure 5(b). The load and the reaction force are on the same vertical line in Figure 5(b), beyond which the righting moment will disappear.

Figure 5
Stable and unstable states of machinery



4. Safety Criterion for Buckling Toppling (Extra Weak Foundation)

Similar to the elastic buckling of a long column under axial force, when the vertical load of heavy machinery such as a pile driver exceeds the elastic limit load due to extremely weak ground and becomes structurally unstable, we refer to this as "buckling toppling." The toppling condition in this case can be expressed by Equation (5) as when the vertical load P exceeds the elastic critical load P_{cr}. Here, P_{cr} is determined as an eigenvalue from the structural model in Figure 2 [17].

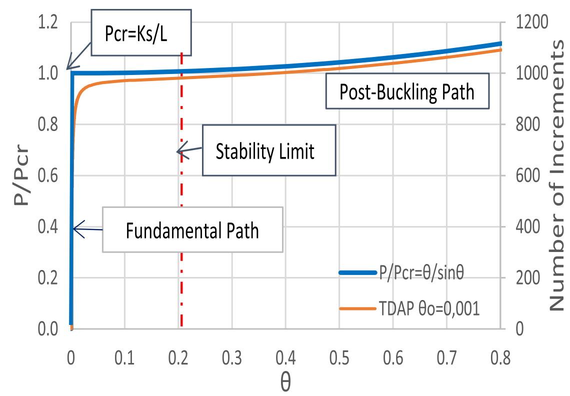
$$P > P_{cr} = K_s/L \quad (5)$$

where Ks is the rotational spring stiffness of the ground, and L is the height of gravity center.

The computed results of P_{cr} are represented in Figure 6: the blue line depicts theoretical analysis, while the red line represents the results by numerical finite element analysis [18]. As observed in Figure 6, it exhibits a phenomenon entirely similar to the elastic buckling of a long column. This implies that structural instability can lead to toppling even without any horizontal forces which are essential in the overturning moment toppling. Additionally, determining the rotational spring stiffness K_s accurately might be challenging. One possible approach is to calculate it using the measured values of the inclination angle θ on-site against the overturning moment M_t, as given by the following formula:

$$K_s = M_t/\theta \quad (6)$$

Figure 6
Critical load of eigenvalue

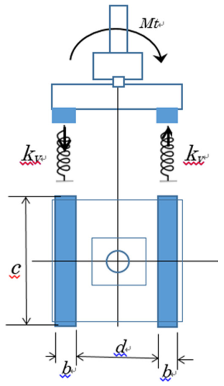


Evaluation of the rotational stiffness K_s is also possible theoretically from the view of soil mechanics or numerically by computer analysis. Figure 7 illustrates the structural model which describes the relations of the overturning moment Mt and the reaction stiffness k_v. From Figure 7 and Equation (6), the rotational stiffness K_s can be obtained by measuring the displacement inclination angle.

As an alternative method, it is also conceivable to utilize the restoring moment in floating pontoons. When evaluating the stability of floating pontoons using ship algorithms, K_s can be easily calculated from the restoring moment due to buoyancy. In particular, self-elevating platforms (SEPs) used in offshore construction have long legs, making them highly unstable with a high center of gravity when it is afloat, and overturning accidents have actually occurred [22, 23]. There are doubts about conducting stability assessments solely using ship algorithms for such offshore structures [24]. The mechanisms and the safety criteria proposed in this paper can also be applied to the pontoons with high center of gravity such as SEP.

It is also important to investigate K_s from the instability toppling point of view when toppling accidents occurred. In the past, the

Figure 7
Overturning moment and bearing forces



research was focused merely on the soil strength from the overturning moment toppling point of view.

The safety criterion formula for the buckling toppling can be expressed as the ratio between the vertical load and the critical load at the buckling limit:

$$P/P_{cr} < S_p\prime = 0.6 \text{ or } P_{cr}/P > S_p = 1.67 \tag{7}$$

Here, the safety factor $S_p = 1.67$ $(1/S_p{}' = 0.6)$ adheres to the design specifications normally used for axial members in steel structures.

The distinctive feature of the buckling toppling is its occurrence even in the absence of horizontal forces, solely relying on vertical loads, particularly in extremely weak ground conditions. However, in practical situations, pure buckling toppling hardly occurs. It is believed that there may be a slight initial inclination or eccentricity of vertical loads, and the influence of these factors can be significant as seen in the next section.

In cases of substantial vertical loads, considering the difficulty in assessing the influence of initial inclinations and the rotational spring stiffness, it is desirable to have a relatively large safety factor. This is why the criterion $P_u/P_{cr} < 0.6$ on the safer side is proposed here against the vertical load in Figure 1. The detailed relationship between vertical load and initial inclinations will be further discussed in the next section, specifically in the context of the equilibrium transition toppling.

5. Safety Criterion for Equilibrium Transition Toppling (Weak Foundation)

5.1. Toppling conditions

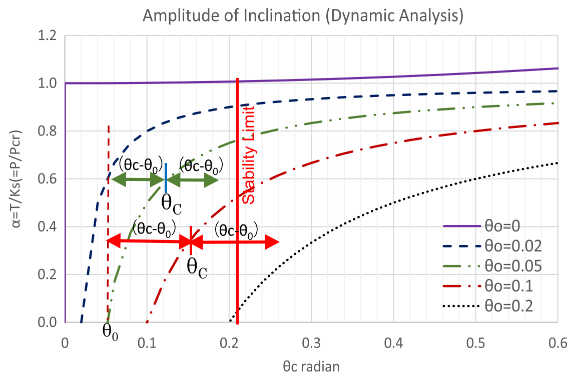
Unexpected toppling accidents with pile drivers or cranes often occur on weak ground while moving, and in such cases, it is believed that the accidents occur through the equilibrium transition toppling due to structural instability [17]. If the toppling of a pile driver or similar equipment occurs during operation, there must be some imbalance deviating from the balanced state. The equilibrium transition type of toppling occurs when the overturning inclination angle (stability limit) is exceeded during the process of returning to a balanced state after an imbalance occurs. The mechanism involves dynamic inertial forces, making it difficult to predict in advance. In the classification of safety criteria in Figure 1, this corresponds to a broad range positioned between the overturning moment toppling and the buckling toppling. Below, we will discuss the safety criteria for the equilibrium transition toppling, which includes elements of structural instability.

While the previous discussions were based on static analysis, the following will be based on dynamic analysis [18, 19]. Figure 8 depicts the relationship between vertical load and displacement inclination angle obtained from dynamic analysis without damping forces. According to dynamic analysis, it has been pointed out that it shows the free vibration behavior starting from the point of imbalance. The horizontal axis in Figure 8 represents the vibration center θ_c, which is determined by the following formula:

$$\theta_c = \theta_u/(1 + P/P_{cr}) \tag{8}$$

The curves shown in Figure 8 have the same shape as the equilibrium curves in Figure 3 in static analysis. However, it is important to note that the horizontal axis in Figure 8 represents the vibration center given by dynamic analysis, while in Figure 3 it is the displacement inclination angle at a static balanced state.

Figure 8
Amplitude of inclination (dynamic analysis)



In Figure 8, the arrows depict the amplitudes for initial inclination angles $\theta_0 = 0.05$ and $\theta_0 = 0.1$, highlighting the significant impact of the initial inclination angle. Also, the curves in Figure 9 show the width with θ_{max} and θ_{min} when $\theta_0 = 0.05$ [18]. It can be seen from those figures that the larger the initial inclination angle, the larger the amplitudes are.

The toppling condition in this case is given by the following equation:

$$\theta_{max} > \theta_u = \tan^{-1} S/(2L) \tag{9}$$

Here, S is the length of the pile driver track or the distance between left and right tracks, and L is the height of the center of gravity (refer to Figure 5).

5.2. Safety criterion

The safety criterion formula can be considered as the ratio of θ_{max} to θ_u from Equation (9). Here, considering θ_{max} without damping forces, we set the safety factor S_f for instance as:

$$\theta_u/\theta_{max} < S_f = 1.0 \tag{10}$$

Taking this safety factor into account, θ_{max} and θ_{min} can be expressed as follows:

Figure 9
Maximum and minimum inclinations (dynamic analysis)

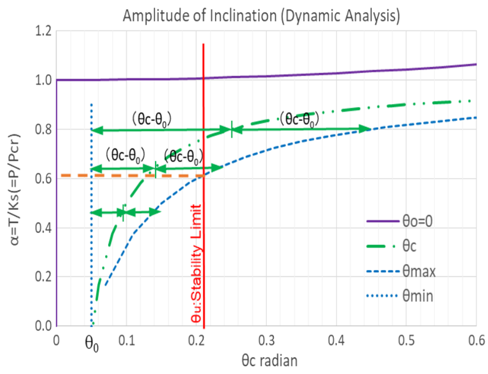
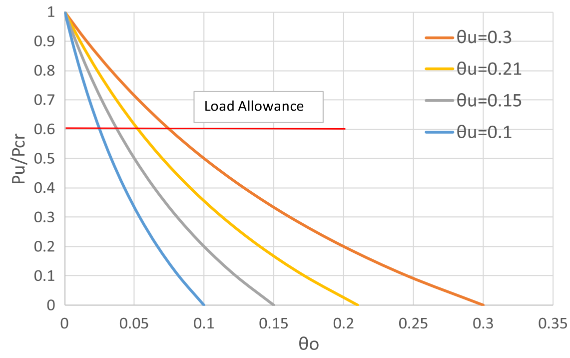


Figure 11
Toppling load–inclination angle (θ_0) curves



$$\theta_{max} = \theta_u \tag{11}$$

$$\theta_{min} = 2\theta c - \theta_u (= \theta_0) \tag{12}$$

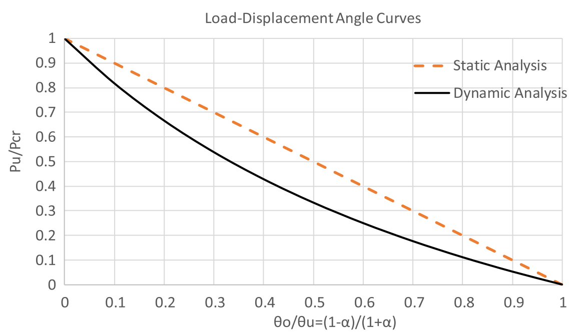
On the other hand, taking the starting point of the vibration θ_{min} as the initial inclination angle θ_0, the permissible value for the initial inclination angle from the safety criterion Equation (10) and Equation (8) is given as [18]:

$$\theta_0/\theta_u < (1 - P_u/P_{cr})/(1 + P_u/P_{cr}) \tag{13}$$

in which P_u is the ultimate load.

When plotting Equation (13), it appears as the solid line in Figure 10. The figure represents the correlation between load and initial inclination angle in normalized dimensions. Comparing the static and dynamic analyses, the reduction rate in dynamic analysis (solid line) is shown to be larger than that in static analysis (dotted line). The difference comes from the effect of the inertial force in dynamic analysis.

Figure 10
Toppling load–inclination angle (θ_0/θ_u) curves

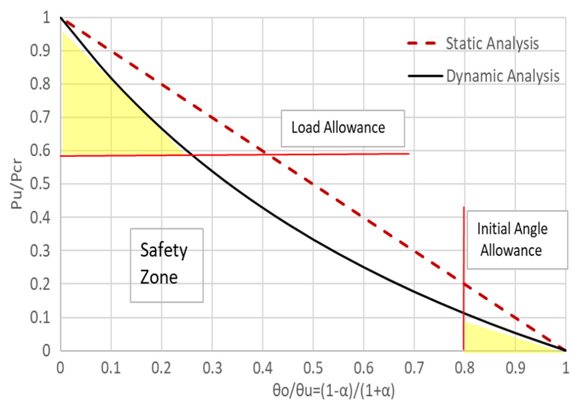


Whereas both the load and displacement angles in Figure 10 are in normalized forms, when plotting the deflection angle in real angles, it appears as shown in Figure 11. The curves in Figure 11 express the relations of the toppling load P_u/P_{cr} and the allowable initial inclination angle varying the toppling angle $\theta_u = 0.1 \sim 0.3$. The figure shows the permissible vertical load $P/P_{cr} < 0.6$ corresponding to the buckling toppling discussed previously (refer to Figure 1). It can be found that from Figure 11 the corresponding initial inclination angle for $\theta_u = 0.21$ and $P_u/P_{cr} = 0.6$ is $\theta_0 = 0.05$, which coincides with the results shown by the cross point of the stability limit (θ_u), the red dotted line (P_u/P_{cr}), and the maximum inclination angle (θ_{max}) in Figure 9.

6. Safety Criteria Based on Structural Stability Theory

When overlaying the classification of safety criteria from the static analysis in Figure 1 onto Figure 10, the result is shown in Figure 12. In other words, Figure 12 consolidates the safety criteria for three toppling mechanisms, namely the overturning moment toppling, the buckling toppling, and the equilibium transition toppling. As mentioned earlier, the safe range is defined as not toppling within the limits set for buckling toppling (upper limit: $P/P_{cr} < 0.6$) and overturning moment toppling (upper limit: $\theta_0/\theta_u < 0.8$), and enclosed by the curve $\theta_{max} < \theta_u$ for the equilibrium transition toppling.

Figure 12
Safety criteria based on structural stability



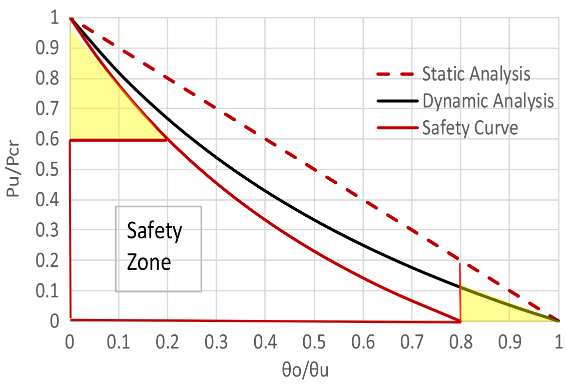
It should be noted that in these criteria the critical load P_{cr} (or K_s) has the crucial influence on the toppling behaviors. If the accuracy of this value is low, it may be necessary to increase the safety factor. Since in real life it is difficult to have an exact estimate of the P_{cr} (or K_s) due to construction reasons, lack of data, or weathering, a quantifiable term that could represent such variation can be introduced.

Through the analysis conducted so far, it is evident that the reduction rate of toppling load is considerably larger in dynamic analysis compared to static analysis. For the toppling of heavy machinery with a high center of gravity, such as pile drivers and cranes on weak ground, it is necessary to consider the influence of dynamic inertial forces.

7. Modification of Safety Criteria Based on Structural Stability Theory

In Figure 12, a discontinuity occurs at $\theta_0 / \theta_u < 0.8$, which is undesirable as safety criteria. To address this issue, the maximum permissible value of θ_0 / θ_u on the toppling load-initial inclination angle curve (solid line in Figure 12) obtained by dynamic analysis is modified from 1.0 to 0.8. Correspondingly, the safety criterion curve of the equilibrium transition toppling is shifted horizontally as expressed by a red solid line in Figure 13, which includes the safety criteria for the three toppling mechanisms with rational modification.

Figure 13
Modified safety criteria based on structural stability



It is worth noting that there is also a discontinuity at $P/P_{cr} < 0.6$ on the vertical axis of toppling load. However, this discontinuity is not modified since it is due to restrictions from the buckling toppling which assumes a large safety factor. The toppling load for the buckling toppling type is highly dependent on accuracy of the rotational spring stiffness K_s, and detailed modifications in this aspect are deemed to be of little significance.

Observing the safety criteria in Figure 12 or 13, it becomes evident that the range of toppling safety is remarkably small when considering the instability by the vertical load P_u/P_{cr}. It is not rational to establish toppling safety criteria based solely on angles. For instance, assuming $P_u/P_{cr} = 0.4$ and using the toppling inclination angle $\theta_u = 0.21$ (equivalent to 12 degrees) as set in Figures 8 and 9, it is found that the safe initial inclination angle is only $\theta_0 / \theta_u = 0.35$ ($\theta_0 = 4$ degrees) according to Figure 13.

In this way, incorporating the elastic critical load (P_{cr}) into the safety criteria, as shown in Figures 12 and 13, allows the safety angles to encompass the influence of two key elements in structural stability, namely the properties of weak ground (K_s) and the center of gravity height (L). After all, Figure 13, obtained through these adjustments, is proposed as the safety criteria including the elements of instability in this context.

8. Conclusions

This paper presents a sample of safety criteria based on the idea that the recent series of toppling accidents involving pile drivers and cranes is rooted in structural instability. The focus is not only on the toppling angle (stability limit) when the overturning moment exceeds the resistance moment but also on proposing safety criteria that incorporate the structural stability elements leading up to toppling. The proposed criteria include the degree of weakness of the ground and the height of the center of gravity, which are crucial elements of structural instability.

Moreover, by segregating safety factors for each type of toppling mechanism, i.e., the overturning moment toppling, the buckling toppling, and the equilibrium transition toppling, the meaning of safety concerning toppling becomes clear. For the overturning moment toppling, the criterion is set to restrict the initial inclination angle; the vertical load is restricted for the buckling toppling; and the maximum inclination angle is restricted for the equilibrium transition toppling not to exceed the stability limit considering the influence of dynamic inertial force. It is expected that these criteria will help to prevent unforeseen toppling accidents of pile drivers, cranes, and jacks in the future.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this paper as no new data were created or analyzed in this study.

Author Contribution Statement

Shouji Toma: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Wai Fah Chen:** Validation, Supervision.

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