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Alarm system to prevent the overturning of truck cranes considering possible ground failure

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The aim of this paper is to design an alarm system to prevent the overturning of truck cranes under condition of ground failure. The conditions under which truck cranes tip are first formulated against the cases in which the ground is rigid enough and in which the ground might possibly fail. The ground response under the outrigger pontoon of a truck crane is expressed by a kind of Weibul distribution curve and the degree of danger is formulated by the ratio of the loading stress to the estimated bearing capacity at yield obtained from numerical iteration. An alarm system based on the degree of danger is finally proposed.

1. INTRODUCTION

These past several years, accidents resulting in death due to the overturning of truck cranes have continuously happened in Japan. Although there is required safety equipment to cope with this problem, including moment limiters etc., accidents due to tipping and falling of lifting loads have continued, and there remain many issues concerning the improvement of the safety of the work environment. An alarm system to prevent the overturning of truck cranes considering ground failure is one promising countermeasure and this method is therefore expected to become an indispensable technique in order to achieve fully automated truck crane operation.

2. TIPPING CONDITIONS OF TRUCK CRANES

2.1 Forces applied to truck cranes and the points of action

The forces acting on truck cranes and the points of action are shown in Fig.1. Where W = the weight of the lifting load, W_1 = the weight of the upper (part of the truck crane), W_2 = the weight of the counter weight, W_3 = the weight of the carrier, W_4 = the weight of the boom, L = the length of the boom, l_1 = the distance from the center of revolution to the center of gravity of the upper, l_2 = the distance from the center of revolution to the center of gravity of the counter weight, l_3 = the distance from the center of revolution to the center of gravity of the carrier, r_1 = the distance from the center of revolution to the center of the outrigger, r_2 = the projected dis-

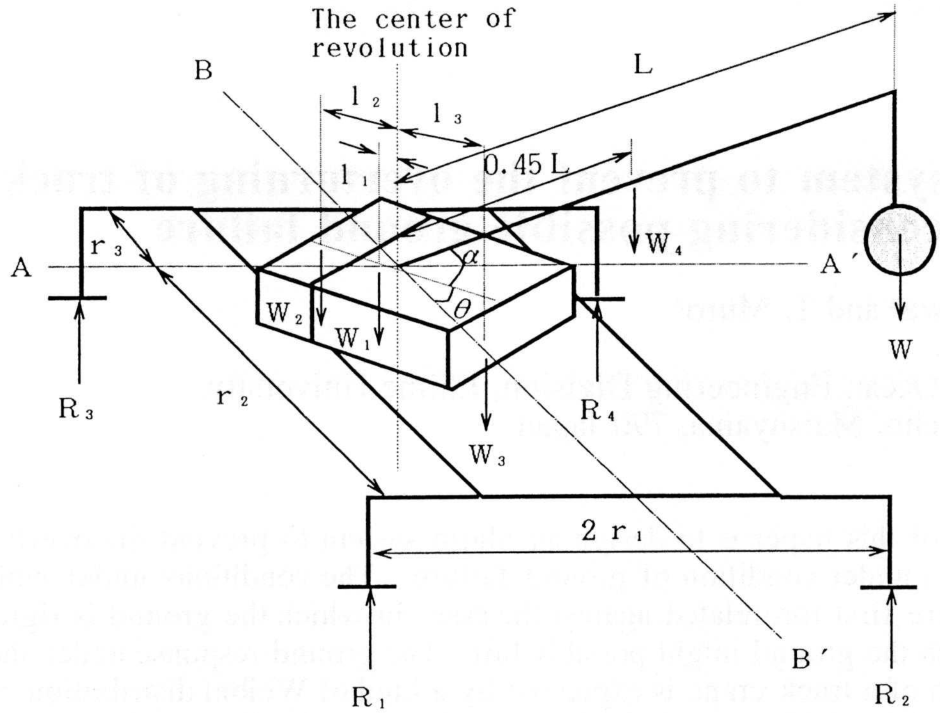

Figure 1. Forces applied on truck cranes and the points of action

tance from the center of revolution to the front outrigger, r_3 = the projected distance from the center of revolution to the rear outrigger, α = the boom angle, θ = the revolving angle of the upper, R_1, R_2, R_3, R_4 = the reaction force at the outrigger pontoons. The following analysis is made based on an actual truck crane [1].

2.2 Tipping conditions when the ground is very rigid

If the ground is very rigid, the tipping of truck cranes depends only on equilibrium conditions. When the tipping of the truck crane begins, since the reaction forces at the two adjacent outriggers can be regarded as zero, the tipping conditions are therefore expressed by the following equations for cross section A-A', B-B' (see Fig.1) respectively.

$$L_a\cos\alpha W+0.45L_a\cos\alpha W_4>r_1W+l_{1a}W_1+l_{2a}W_2+r_1W' \tag{1}$$
$$L_b\cos\alpha W+l_3W_3+0.45L_b\cos\alpha W_4>r_2W+l_{1b}W_1+l_{2b}W_2+r_2W' \tag{2}$$

where $W'=W_1+W_2+W_3+W_4$, $L_a=L\sin\theta$, $l_{1a}=l_1\sin\theta$, $l_{2a}=l_2\sin\theta$, $L_b=l_1\cos\theta$, $l_{2b}=l_2\cos\theta$.

2.3. Tipping conditions when ground failure is possible

If the bearing capacity of the ground is insufficient, the truck crane balance becomes unstable and the crane tips even if the equilibrium conditions of moment are satisfied. It is reasonable for the judgement of the bearing capacity of ground to be made based on the load at yield. Accordingly, tipping patterns are classified as follows when the load at yield is described as P_y.

(1) Yielding at only one support

Yielding at R_2 is taken as a typical example in this case. When the yielding load P_y is smaller than the reaction force R_2, the tipping of the truck crane begins. Moreover, if R_3=0, R_3 is diagonal to R_2, the tipping conditions of the truck crane are given as follows:

$$(r_1r_4+2r_1L_b\cos\alpha+r_4L_a\cos\alpha)W+r_1r_4W'+2r_1l_3W_3+(0.9r_1L_b\cos\alpha+0.45r_4L_a)W_4$$
$$>2r_1r_2W+(2r_1l_b+r_4l_{1a})W_1+(2r_1l_{2b}+r_4l_{2a})W_2+4r_1r_2W'+4r_1r_4P_y \qquad (3)$$

(2) Yielding at two supports along the long axis of the carrier

Yielding at R_2 and R_4 is taken as a typical example in this case. When the load at yield P_y is smaller than the reaction force R_2 and R_4, the tipping of the truck crane begins. The tipping conditions of truck crane are as follows:

$$(L_a\cos\alpha+r_1)W+0.45L_a\cos\alpha W_4+r_1W'>l_{1a}W_1+l_{2a}W_2+4r_1P_y \qquad (4)$$

(3) Yielding at two supports along the short axis of the carrier

Yielding at R_1 and R_3 is taken as a typical example in this case. The tipping conditions of the truck crane for this case are obtained in the same way as Eq.(4) and the results are as follows:

$$(L_b\cos\alpha+r_3)W+l_3W_3+0.45L_b\cos\alpha W_4+r_3W'>l_{1b}W_1+l_{2b}W_2+2r_4P_y \qquad (5)$$

3. ESTIMATION OF LOAD-SETTLEMENT RELATION IN PLATE LOADING TEST

When considering the tipping conditions of truck cranes, it is necessary to estimate the bearing properties of the ground. In this section, the load-settlement relation in a plate loading test is expressed by a kind of Weibul distribution curve and it will be shown that the relationship can be estimated to some extent by the initial response of loading by numerical iteration. The loading conditions experienced at the pontoons of the outriggers of the truck crane are almost the same as the conditions experienced in the conventional plate loading test.

Uto and Huyuki [2] proposed a series of exponential mathematical models to be effectively used as geotechnical curves. One of the Weibul distribution curves is employed to estimate the load-settlement relation of ground under the outrigger pontoons. The curve is expressed as follows:

$$p=p_{max}\{1-\exp(-d/\delta_s)\} \qquad (6)$$

where p=loading stress, p_{max}=ultimate bearing capacity, d=settlement, δ_s=positive coefficient. The bearing capacity at yield, p_y, can be defined as the loading stress when $d=\delta_s$. The typical example of the curve is demonstrated in Fig.2. p_{max}=10 and δ_s=2 in this figure.

The residual square sum SSR is given as the following equation for n sets of data.

$$SSR=\sum_{i=1}^{n}[p_i\text{-}p_{max}\{1\text{-}\exp(\text{-}d_i/\delta_s)\}+\varepsilon]^2 \quad (7)$$

where ε is the term of error and p_i , d_i is the number i datum of loading stress and settlement respectively. The method for determining p_{max} and δ_s as the SSR in Eq. (7) approaches minimum is the non linear method of least square. The method employed in this paper is the Newton method [3].

First the following equations are defined.

$$f(x,y)=\frac{\partial SSR}{\partial x}=0,\ g(x,y)=\frac{\partial SSR}{\partial y}=0 \quad (8)$$

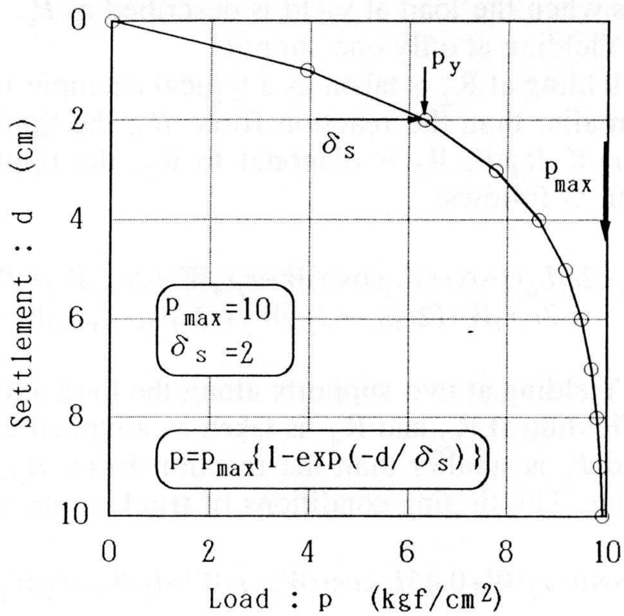

Figure 2. An example of proposed Weibul distribution curve

where p_{max} and δ_s are replaced with x and y in order to simplify the expression. The initial values of p_{max} and δ_s, that is x_0 and y_0, are assumed first. For each iteration, the next simultaneous linear equation (Eq.(9)) are solved, and δ_x and δ_y are calculated. Next, δ_x and δ_y are replaced with $x_0+\delta_x$ and $y_0+\delta_y$ respectively, and the iteration will be repeated until δ_x and δ_y become sufficiently small.

$$\begin{bmatrix} f_x(x_0\text{-}y_0) & f_y(x_0\text{-}y_0) \\ g_x(x_0\text{-}y_0) & g_y(x_0\text{-}y_0) \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix} = \begin{bmatrix} \text{-}f(x_0\text{-}y_0) \\ \text{-}g(x_0\text{-}y_0) \end{bmatrix} \quad (9)$$

The values of x_0 and y_0 when δ_x and δ_y become small enough are the desired p_{max} and δ_s. In the calculations of this paper, the 5 sets of data are used in succession, that is, the first calculation is based on the sets of data from No.1 to No.5, and the next calculation is based on the sets of data from No.2 to No.6. The next, from No.3 to No.7 and so on.

4. ESTIMATION OF THE DEGREE OF DANGER FOR GROUND FAILURE

4.1. Definition of the degree of danger

Since the settlement d is δ_s when p is equal to the bearing capacity at yield, p_y, the following equation is derived from Eq.(6).

$$p_y=0.632p_{max} \quad (10)$$

The degree of danger is defined as the ratio of the loading stress at each time sequence after loading to the estimated bearing capacity at yield from Eq.(10). The definition of the degree of danger $D(n)$ corresponding to the number of data set n is expressed as the following equation.

$$D(n)=p(n)/p_y(n) \tag{11}$$

where $p(n)$ is the most current load value p to be used in the numerical iteration and $p_y(n)$ is the estimated p_y for the data set n.

4.2. Effect of soils on the degree of danger

Many kinds of soils including sand and gravel etc. [4], normally-consolidated (N. C.) clay [5], overconsolidated (O.C.) clay [6] etc. are used to check the effect of soils on the degree of danger. The typical relationships between the degree of danger D and the settlement d are demonstrated in Figs.3 and 4. A set of data was sampled every 0.2 cm of the settlement, and successive 5 sets of data were used for the numerical iteration. Fig.3 shows the results corresponding to sand and gravel and soft rock, while Fig.4 shows the result of overconsolidated clay. Each data in Fig.4 has a different width of the loading plate. The tendency of D-d relations are mainly classified into two patterns as shown in Figs.3 and 4. The pattern in Fig.3, the degree of danger corresponding to the case where d equals 1 cm is roughly from 0.6 to 0.8, was shown in N.C. clay and loose to medium dense sand. On the other hand, the pattern in Fig.4, that is D>0.9 against d=1, was shown in O.C. clay and dense sand.

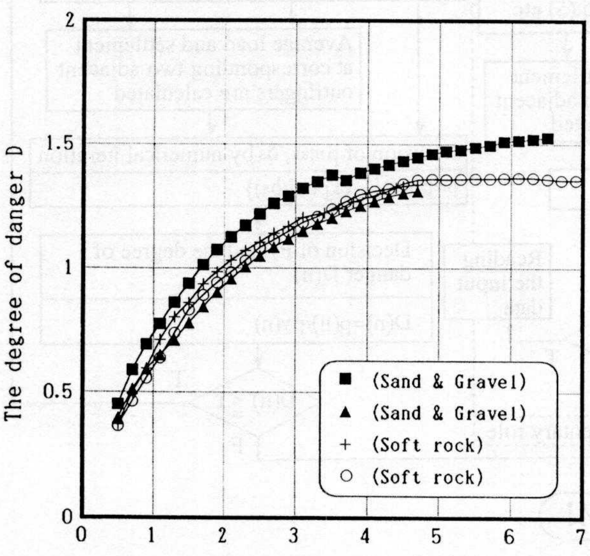

Figure 3. Estimated degree of danger for sand and gravel deposits etc.

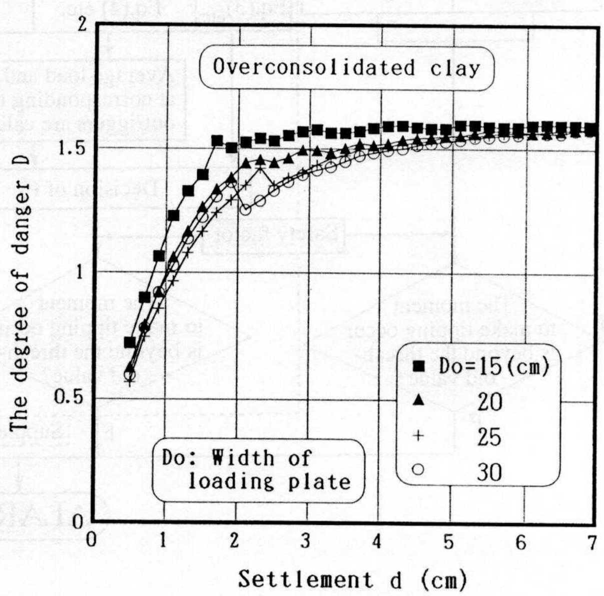

Figure 4. Estimated degree of danger for overconsolidated clay

Judging from these patterns, it will be suggested that if only the settlement d were employed as the index for ground failure, overestimation or underestimation of the degree of danger might occur. If both d and p were employed, since the degree of danger can be correctly judged by use of Eq.(11), overestimation or underestimation would not occur.

5. ALARM SYSTEM ON THE TIPPING OF TRUCK CRANES

Fig.5 shows the flow chart of an alarm system to prevent the overturning of the truck cranes. Let us consider the case of an actual truck crane having 4 outriggers. The load-settlement relations at these 4 outriggers have to be measured to estimate the real tipping patterns. Based on the input data and the measured data, the tipping

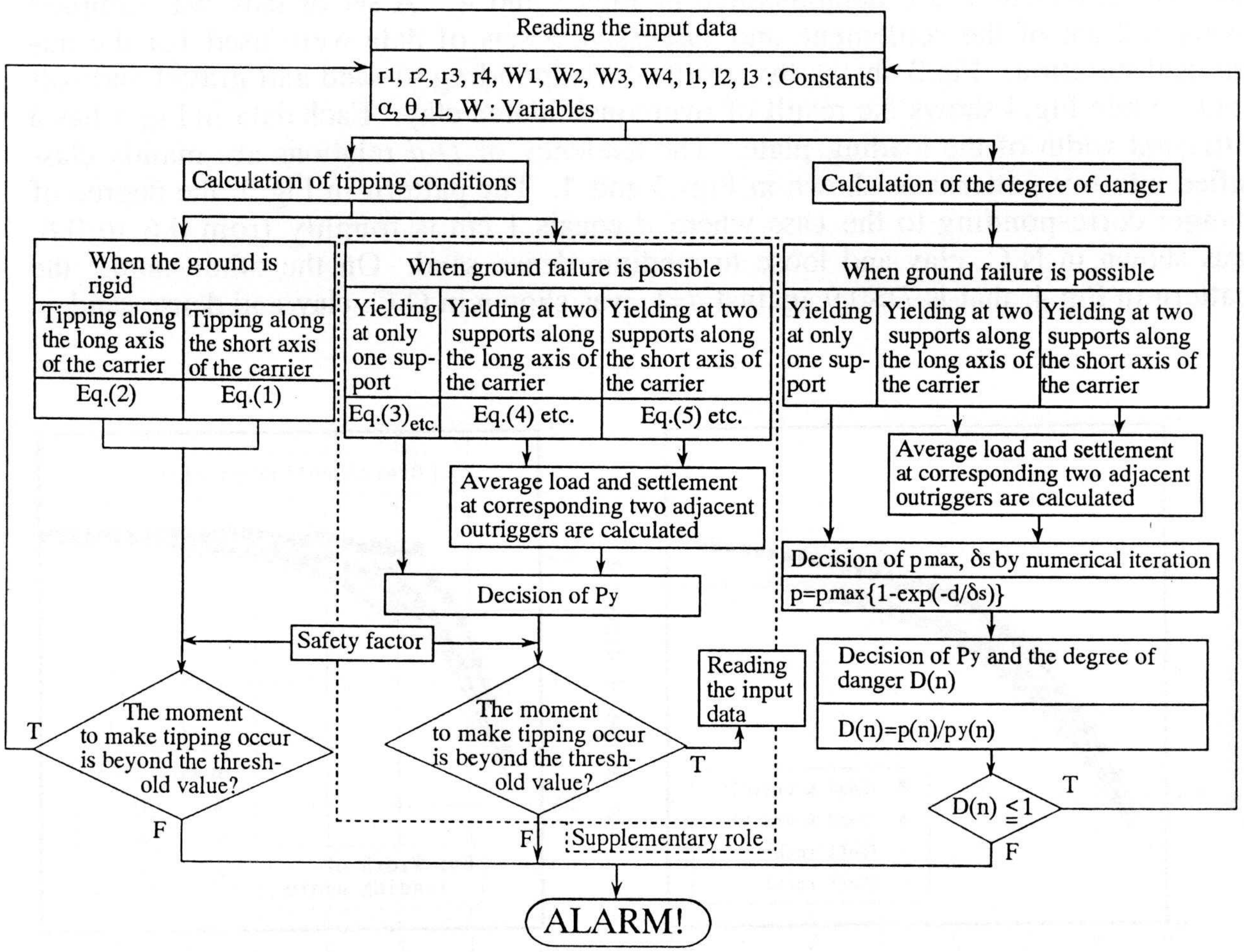

Figure 5. Alarm system to prevent the overturning of truck cranes considering possible ground failure

conditions of the truck cranes and the degree of danger are calculated. Since there are several tipping patterns, the alarm system must be slightly complicated. The system corresponds to the cases in which the ground is rigid enough and in which the ground might possibly fail.

When the ground is rigid enough, if the equilibrium of moment is not satisfied at some instant, the situation is too late to control the safety of the truck crane, so that some threshold value must be considered against the moment to make the tipping occur, that is a kind of moment limiter. Of course, some safety factor should be also considered in actual cases.

When ground failure is possible, the degree of danger will give effective information. The time required for the estimation of a set of p_{max} and δ_s is about 1.5 sec with use of a personal computer (32bit, NEC PC-9801ns/T), if 20 times iteration is needed for the convergence. This results in the realtime evaluation of the degree of danger D. Although an equation, $D(n) \leq 1$, is employed in Fig.5 for the judgement of the tipping, some safety factor, e.g. 0.8, 0.9 and so on, should be used in place of 1. D(n) itself is of course the clear index for the tipping. As for the tipping conditions based on the equilibrium of moment, some threshold value will be considered in the same way as in the case in which the ground is very rigid. However, this criterion should be used as a supplementary one since the method using D gives simpler and more direct index for the judgement of the tipping.

In actual cases, the tipping patterns depend on many factors, so that the calculations of tipping conditions and the degree of danger for every tipping pattern must be carried out as fast as possible. In that sense, it is important to use a highly efficient personal computer and tools for the measurement of load and settlement. It seems that the load can be measured by load cell, and a settlement gauge using laser beam or high precision inclinometer is useful for the measurement of the settlement.

6. CONCLUSIONS

Main conclusions obtained from this study are as follows:

(1) The tipping conditions of a truck crane were formulated against the cases in which the ground is rigid enough and in which the ground might possibly fail.

(2) A kind of Weibul distribution curve was introduced to express the relationship between the load and the settlement at the outrigger pontoons of the truck crane. It was made clear that the load-displacement curve could be successfully estimated by use of a non-linear method of least squares based on the proposed Weibul distribution curve.

(3) The degree of danger could be defined by the ratio of loading stress to the estimated bearing capacity at yield. Almost realtime values of the degree of danger for many kinds of soils could be estimated with only several successive data of load and settlement sampled. Based on the degree of danger and the tipping conditions for several tipping patterns, an alarm system to prevent the overturning of the truck cranes was constructed.

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