Evaluation of an Alarm System to Prevent the Overturning of Truck Cranes

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Abstract

The authors have previously proposed a new method to prevent the overturning of truck cranes considering possible ground failures in the 11th ISARC at Brighton. The first aim of this study was to create an alarm system which can predict and judge the degree of danger from the data between the load and the settlement at outrigger pontoons, especially when the ground might possibly fail. A series of model tests by use of a miniature truck crane were carried out to investigate the effectiveness of the alarm system. The second aim of this study was to theoretically make clear the conditions under which the tipping occurs. The tipping conditions for an actual truck crane were formulated against the cases when the ground is rigid enough and when the ground might possibly fail.

1. Introduction

In the 11th ISARC at Brighton, the authors proposed a new method to prevent the overturning of truck cranes considering possible ground failures[1]. In this study, 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. Moreover an alarm system to prevent the overturning of the truck cranes was constructed based on the degree of danger defined by the ratio of the loading stress to the estimated bearing capacity at yield and the tipping conditions for several tipping patterns.

In this paper, a series of model tests by use of a miniature truck crane were carried out to investigate the effectiveness of the alarm system. The experiments were conducted against two ground conditions, that is rigid enough and possible ground failure. Although the effectiveness of the proposed alarm system could be recognized to some extent from these laboratory tests, the effects of some factors, e.g. the bearing capacity at yield of the ground etc. wasnot clear. Therefore, the effect of these factors was theoretically investigated for an actual truck crane.

2. Experimental evaluation of proposed alarm system

2-1 Miniature truck crane

The outline of a miniature truck crane used in the experiments is shown in Fig.1 and some parameters to define the miniature model are shown in Fig.2 and Table 1. The diameter of the outrigger pontoons was 5cm and some outrigger pontoons were equipped with an earth pressure cell.

2-2 Model ground

The tipping experiments of the miniature truck crane on sandy ground were carried out in a soil bin filled with Toyoura Standard Sand. The soil bin has a square shape, the width of which is 120cm, and the model ground thickness is about 15cm. Since the diameter of an outrigger pontoon is 5cm and the ground thickness is about triple that, the slip surface does not interfere with the bottom of the soil bin. The specific gravity of Toyoura

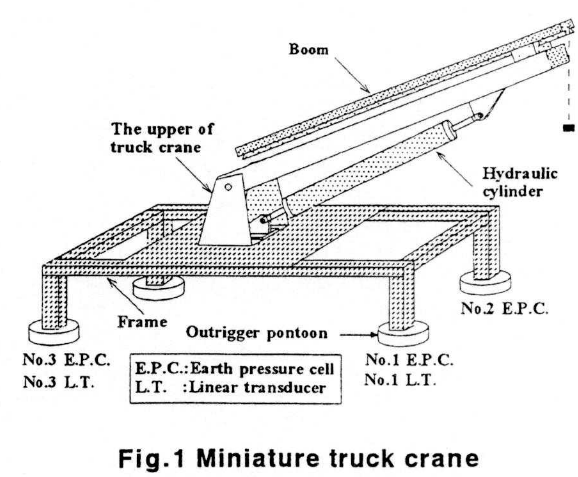

Fig.1 Miniature truck crane

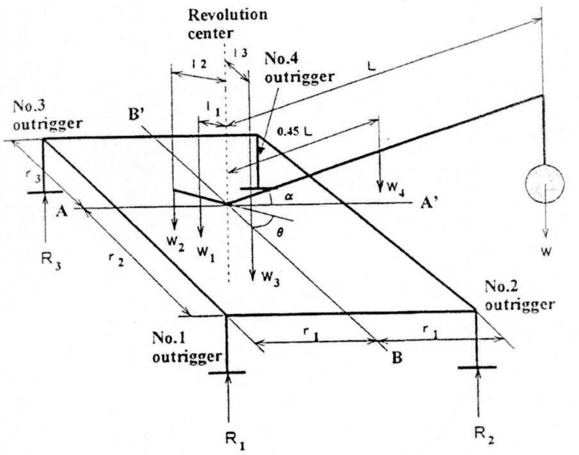

Fig.2 Parameters to define truck crane

Table 1 Parameters used in analysis

Parameters	Variables	Values
The weight of the lifting load	W	variable
The weight of the upper (part of the truck crane)	W_1	1650gf
The weight of the counter weight	W_2	550gf
The weight of the carrier	W_3	9900gf
The weight of the boom	W_4	2750gf
The distance from the revolution center to the gravity center of the upper	l_1	2.0cm
The distance from the revolution center to the gravity center of the counter weight	l_2	2.0cm
The distance from the revolution center to the gravity center of the carrier	l_3	3.0cm
The boom length	L	variable
The strecthing distance of the outriggers	r_1	28.0cm
The distance for long axis direction from the revolution center to the front outriggers	r_2	24.0cm
The distance for long axis direction from the revolution center to the rear outriggers	r_3	39.0cm
The boom angle	α	variable
The revolving angle of the upper	θ	variable

Sand is 2.56, the average of the water contents is 0.32%, D_{50} is about 0.2mm and the average relative density of the model ground is about 60%. In order to check the homogeneity of the model ground, portable cone penetration tests were carried out at ten points randomly selected. The results were shown in Fig.3 and it can be seen that the test ground was roughly homogeneous.

2-3 Measurement devices

Earth pressure cells were implemented at the three outrigger pontoons of the miniature truck crane. Two of the three outrigger pontoons were also equipped with linear transducers, the capacity of which is 30mm. The signal from these measurement devices was sent to a personal computer through an A/D converter and could be monitored on the display of the computer at any time. The logging interval of these data was about two seconds.

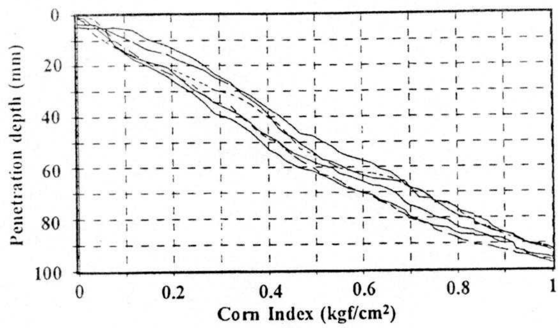

Fig.3 Cone index distribution in model ground ($1kgf/cm^2=98kN/m^2$)

The positions of these devices are also shown in Fig.1.

2-4 Alarm system

The estimation of ultimate bearing capacity and bearing capacity at yield of the ground is required in order to predict and judge the degree of danger when the ground failure is possible.

The following equation employed by Uto et al.[2] to estimate the bearing capacity of a pile was used to express the relationship between loading stress and settlement at outrigger pontoons.

$$p = p_{max}\ \{1 - \exp(-s/\delta_s)\} \tag{1}$$

where p: loading stress, p_{max}: ultimate bearing capacity, s: settlement, δ_s: positive coefficient. The determination procedure of p_{max} and δ_s has already been introduced in a previous paper[1]. Based on these parameters, p_y and D(c) are determined by the following procedure. p_y is the bearing capacity at yield and D(c) is the degree of danger.

$$p_y = p_{max}\ \{1 - \exp(-1)\} = 0.632\ p_{max} \tag{2}$$

$$D(c) = p_c / p_y(c) \tag{3}$$

where p_c is the most current loading stress and $p_y(c)$ is the currently estimated bearing capacity atyield at an outrigger pontoon.

In the alarm system, two different convergence calculations against No.1 linear transducer and earth pressure cell and No.3 linear transducer and earth pressure cell were separately carried out to judge each degree of danger. A flow chart showing the outline of the alarm system was demonstrated in Fig.4. As shown in this flow chart, when the number of data is greater than ten, the convergence calculation is started and the degree of danger is judged against each outrigger and finally some comment for each level of danger is demonstrated on the computer display. Of course if one of the two measurement systems satisfies the condition of the danger, the final output

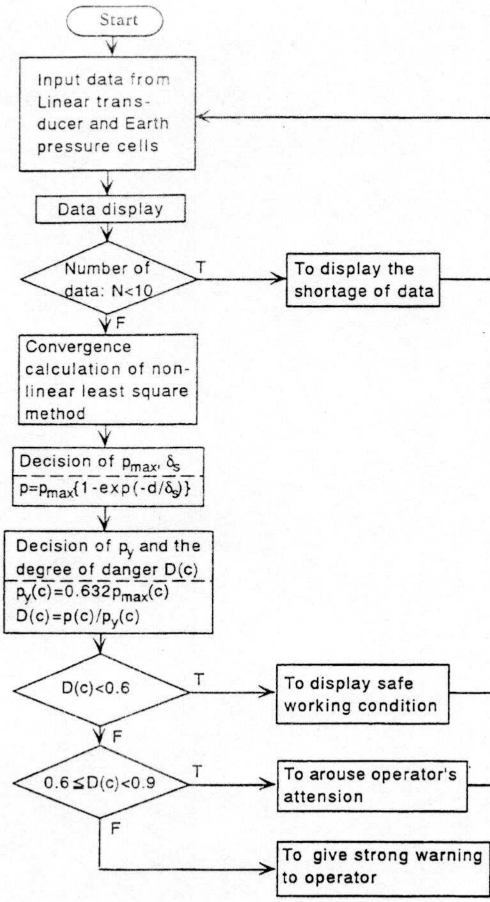

Fig.4 Outline of alarm system

shows that the total condition of the machine is dangerous. Especially when the degree of danger was beyond 0.6, alarm sounds were emitted and the comment on the computer display was colored in red.

2-5 Experiments

The loading procedures are as follows, that is the weights of 0.2 kg were loaded in order, where the time interval is 10 seconds (kept constant). The revolving angles θ were selected as 70 and 90 degrees since the overturning of the miniature truck crane occurred in these cases. The initial values of p_{max} and δ_s were roughly evaluated by plate loading tests. A simple plate loading test by use of outrigger pontoon is also recommended in actual cases. The determined values of p_{max} and δ_s were 1.2 and 0.5 respectively.

2-6 Results and considerations

The predicted relationship between the degree of danger and the loading stress is shown in Fig.5 against the case of θ = 70 deg. It was clearly shown that the overturning of the miniature truck crane happened when the danger of degree estimated from the No.1 outrigger was about 1.0. Therefore, it was concluded that the alarm system worked well in this case. Fig.6 also shows the relationship between the degree of danger and the settlement of outrigger pontoons. The tendency was similar to the case of Fig.5. The relationship between the predicted ultimate bearing capacity p_{max} and the loading stress p was shown in Fig.7. As can be seen from this figure, the converged ultimate bearing capacities calculated by the numerical iteration were both about 2 kgf/cm^2 (196

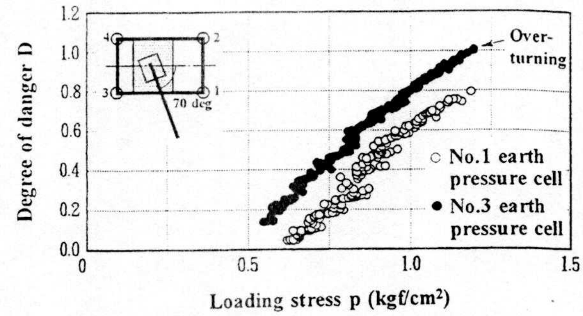

Fig.5 D - p relations in the case of θ=70deg ($1 kgf/cm^2=98kN/m^2$)

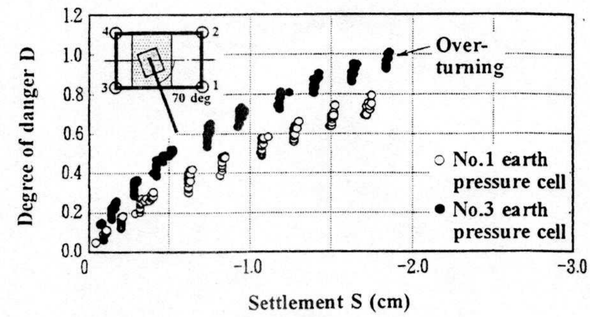

Fig.6 D - S relations in the case of θ=70deg ($1 kgf/cm^2=98kN/m^2$)

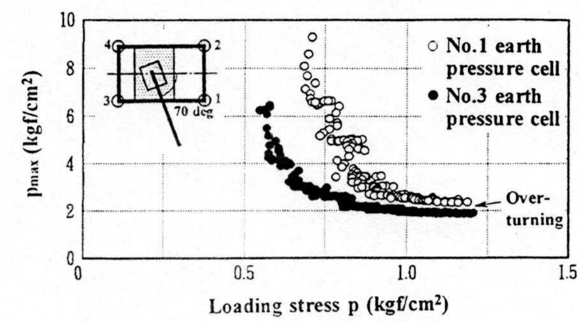

Fig.7 p_{max} - p relations in the case of θ=70deg ($1 kgf/cm^2=98kN/m^2$)

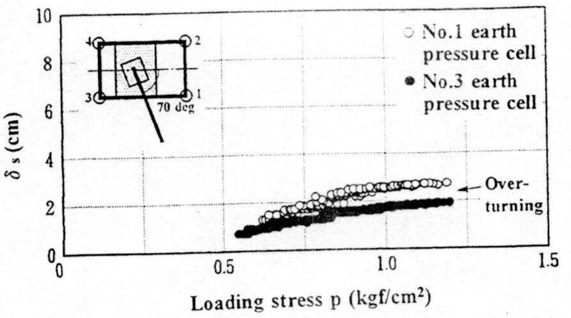

Fig.8 δ_s - p relations in the case of θ=70deg (1kgf/cm²=98kN/m²)

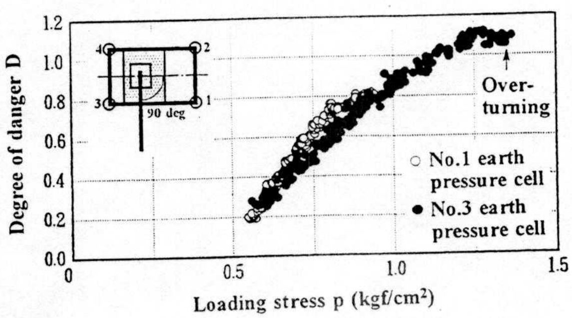

Fig.9 D - p relations in the case of θ=90deg (1kgf/cm²=98kN/m²)

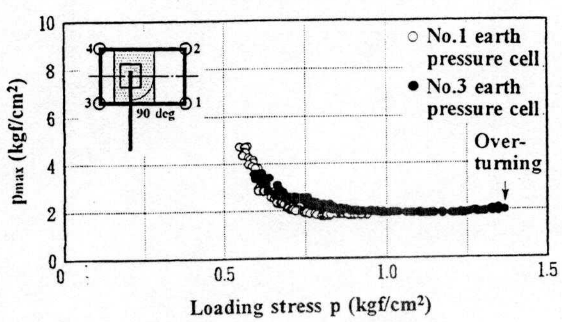

Fig.10 p_{max} - p relations in the case of θ=90deg (1kgf/cm²=98kN/m²)

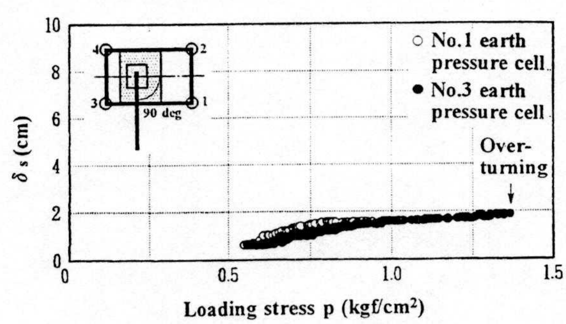

Fig.11 δ_s - p relations in the case of θ=90deg (1kgf/cm²=98kN/m²)

kN/m²). Although this value is a little different from the initial value 1.2 kgf/cm² (118kN/m²), it can be judged that these converged values are reliable since two different convergence calculations gave almost similar results and the degree of danger corresponded well to the experimental results. Fig.8 shows the relationship between the predicted positive coefficient δ_s and the loading stress p. In this case, two different convergence calculations gave slightly different results and those values were much more affected by the non-smooth data sets since δ_s is more sensitive than p_{max}.

In the same way, the relationship between the predicted degree of danger and the loading stress against the case of θ=90 deg was shown in Fig.9. In this case, the overturning of the miniature truck crane happened when the degree of danger showed about 1.1 at the No.3 outrigger. The result also showed the effectiveness of the proposed alarm system. The predicted p_{max} - p relations and the predicted δ_s - p relations were shown in Figs.10 and 11 respectively. The results were almost the same as in the case of θ=70deg. It was reasonable that the predicted p_{max} and δ_s showed a good accordance with the predicted values for θ=70 deg since the ground conditions were almost the same.

2-7 Application to actual truck crane

The alarm system based on the estimation of loading stress - settlement relations carried out in this study would give a wrong message when bad p - s relations were given. Therefore, this method should not be used as a single tool for the judgment and the so-called moment limiter should be used with this proposed alarm system.

3. Effects of some factors on the tipping conditions of an actual truck crane

The effectiveness of the proposed alarm system could be shown in the former section to some extent. However the effects of some factors including the bearing capacity at yield, the boom angle, the lifting load weight etc. on the estimated degree of danger were not so clear. Therefore, the effects of these factors were theoretically investigated for an actual truck crane in this section.

3-1 An actual truck crane used in the analysis

A series of tipping condition analysis were conducted for the actual 110t size rough-terrain-crane [3]. The outline of the truck crane was as follows; W=100tf (0.98 MN), W_1=13tf (0.13MN), W_2=15tf (0.15MN), W_3=27tf (0.27MN), W_4=17tf (0.17MN), l_1=1.6m, l_2=3.8m, l_3=1.6m, r_1=3.5m, r_2=4.4m, r_3=3.0m. The definition of each variable is the same as in Table 1. In the analysis, the boom angle α was altered from 0 to 80 deg and the revolving angle θ was altered from 0 to 90 deg, and the corresponding boom length L was calculated. Although α can be altered from 80 to 90 deg, when α is close to 90 deg, L approaches infinity. Therefore, these ranges of α -values were omitted from the calculation.

3-2 Tipping conditions when the ground is very rigid

The tipping conditions when the ground is very rigid were obtained in the last ISARC paper [1]. When the point of resultant force applied to the truck crane is within the rectangle determined from the positions of outriggers, the tipping does not occur theoretically if the ground is very rigid. In this analysis, the safety factor 0.9 was introduced considering the actual usage of the alarm system, so that the side lengths of the rectangle became 0.9 times of those of the original one. The result of this analysis, therefore, would give slightly safer values of boom length. Of course the safety factor employed in this analysis gives a direct effect on the analytical result, but does not affect the tipping pattern.

If the tipping starts, the corresponding boom length L is obtained from the following equations:
For A-A' section in Fig.2;

$$L = \frac{(W + W')\,0.9r_1 + l_{1a}W_1 + l_{2a}W_2}{\sin\theta\cos\alpha\,(W + 0.45W_4)} \tag{4}$$

For B-B' section in Fig.2;

$$L = \frac{(W + W')\,0.9r_2 + l_{1b}W_1 + l_{2b}W_2 - l_3W_3}{\cos\theta\cos\alpha\,(W + 0.45W_4)} \tag{5}$$

where

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

The smaller value of the two boom lengths obtained from Eqs.(4) and (5) is the critical boom length when the tipping starts and when the ground is very rigid.

3-3 Tipping conditions when ground failure is possible

The tipping conditions when the ground might possibly fail were also obtained in the ISARC paper [1]. Since the load P corresponding to D=1 is the bearing capacity at yield P_y, i) when the yield occurs at only one outrigger, e. g. at No.2 outrigger in Fig.2, the tipping does not occur theoretically if $R_2<P_y$, in the same way ii) when the yield occurs at two outriggers along the long axis (B-B' in Fig.2) of the carrier, e. g. at No.2 and 4 outriggers, the tipping does not occur theoretically if $R_B=R_2+R_4<2P_y$, and iii) when the yield occurs at two outriggers along the short axis (A-A' in Fig.2) of the carrier, e. g. at No.1 and 2, the tipping does not occur theoretically if $R_D=R_1+R_2<2P_y$. D is the danger of degree for the ground failure and R_i is the reaction force at support No.i. In this analysis, the safety factor 0.9 was also considered, so that L corresponding to $D=R_2/P_y=0.9$ for the case i), $D=R_B/2P_y=0.9$ for the case ii) and $D=R_D/2P_y=0.9$ for the case iii) gave the critical boom length. The safety factor was determined according to the case of very rigid ground.

The boom length L when the tipping occurs was calculated by the following equations:
For the case of yielding at only one support No.2;

$$L = \frac{r_1\{1.8r_4P_y - (r_4 - 2r_3)(W + W') - 2l_3W_3\}}{\cos\alpha(W + 0.45W_4)(2r_1\cos\theta + r_4\sin\theta)} + \frac{l_1W_1 + l_2W_2}{\cos\alpha(W + 0.45W_4)} \tag{6}$$

For the case of yielding at two supports along the long axis of the carrier, No.2 and 4;

$$L = \frac{(3.6P_y - W - W')\,r_1 + l_{1a}W_1 + l_{2a}W_2\}}{\sin\theta\cos\alpha(W + 0.45W_4)} \tag{7}$$

For the case of yielding at two supports along the short axis of the carrier, No.1 and 2;

$$L = \frac{1.8P_yr_4 - (W + W')\,r_3 + l_{1b}W_1 + l_{2b}W_2 - l_3W_3}{\cos\theta\cos\alpha(W + 0.45W_4)} \tag{8}$$

The smallest value of the three boom lengths obtained from Eqs.(6)-(8) is the critical boom length when the tipping starts and when the ground failure might possibly fail.

3-4 Results and considerations

a) Effect of revolving angle and boom angle

Figs.12 and 13 show the relationship between the critical boom length L and θ, α when the lifting weight W is equal to 100tf (0.98MN). Fig.12 corresponds to the case in which the ground is rigid enough. Fig.13 is for the case in which the ground might possibly fail and P_y is assumed to be 110tf (1.08MN) considering one typical example [1]. In this analysis, the lifting weight W was determined by considering the maximum lifting capacity of the analysed truck crane, that is 110tf (1.08MN). P_y= 1.08MN was equal to the product of 392kN/m^2 (p_y) × 0.28m^2 (the area of the outrigger pontoon)) [1].

When the ground is rigid(Fig.12), L shows slightly larger value when θ is about 25 deg. This coincides with the direction from the revolution center of the upper to the outrigger. When θ is beyond 25 deg, the larger θ is, the shorter the critical boom length is.

When the ground might possibly fail (Fig.13), especially when the boom angle is small, L does not show such a typical change compared with Fig.12 irrespective of the change of θ. Since there are three tipping conditions, the result would become a little complicated.

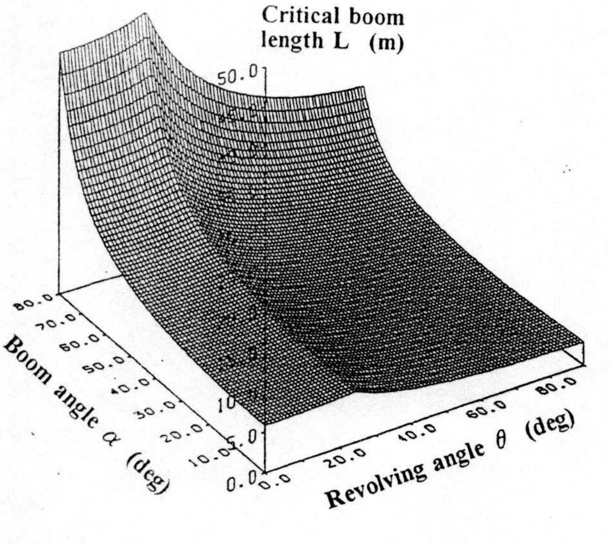

Fig.12 Tipping conditions when the ground is very rigid (W=constant)

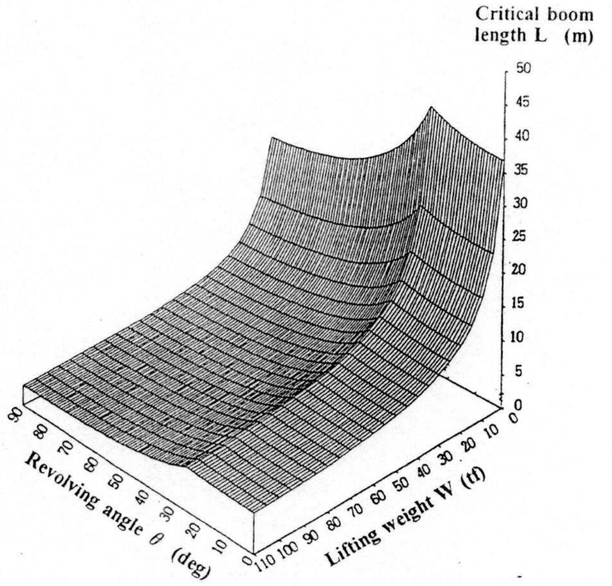

Fig.14 Tipping conditions when the ground is very rigid (α=constant, 100tf=0.98MN)

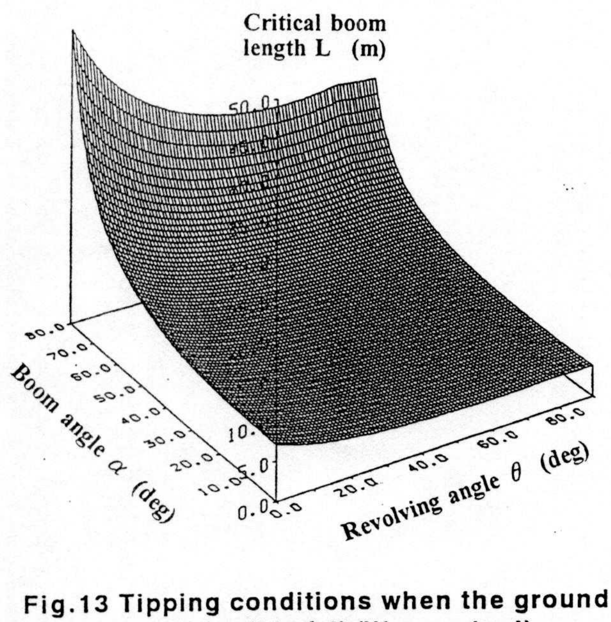

Fig.13 Tipping conditions when the ground might possibly fail (W=constant)

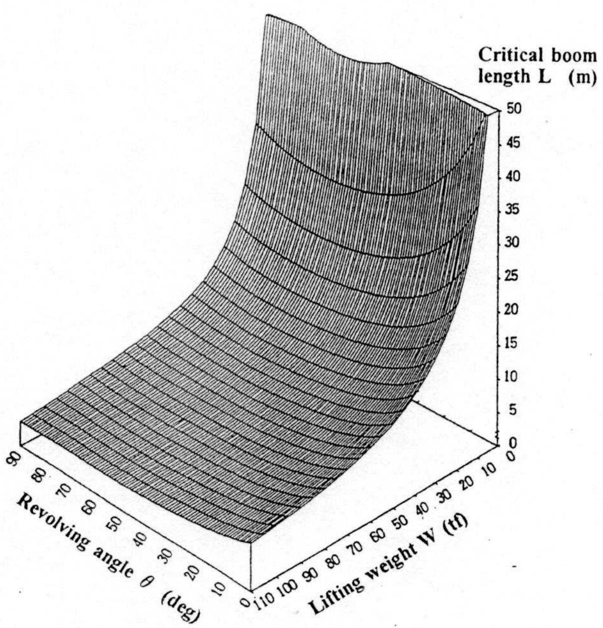

Fig.15 Tipping conditions when the ground might possibly fail (α=constant, 100tf=0.98MN)

As shown in the later section, L showed a complicated response according to the values of θ, α and p_y. The simple comparison of Figs.12 and 13 has no significant meaning because L in Fig.13 depended strongly on the value of p_y.

b) Effect of lifting load weight The relationships between L, θ and W are shown in Figs.14 and 15 when the boom angle α=0 deg and P_y is 100tf (1.08MN). The condition as α=0 is corresponding to the most dangerous state concerning α-values. The overall trend was similar to Figs.12 and 13.

c) Effect of bearing capacity at yield when the ground failure is possible When W=100tf (0.98 MN) and θ=60 deg, the relationship between L and p_y was shown in Fig. 16 as a typical example. The analysis was

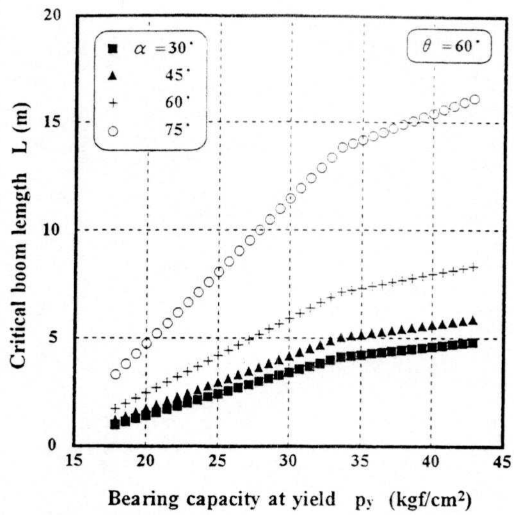

Fig.16 Effect of p_y and α on L (θ=60deg, 1kgf/cm²=98kN/m²)

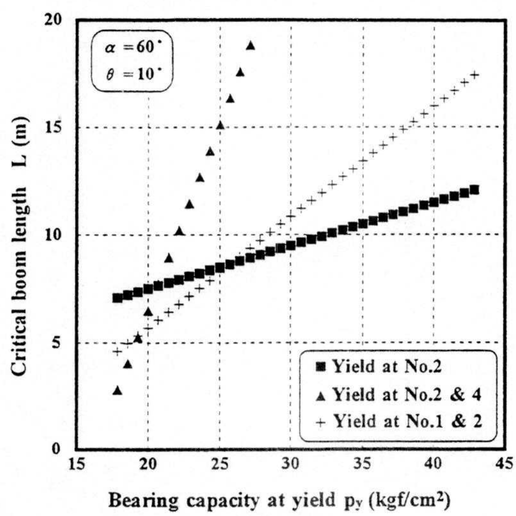

Fig.17 Effect of p_y and tipping conditions on L (α=60deg, θ=10deg, 1kgf/cm²=98kN/m²)

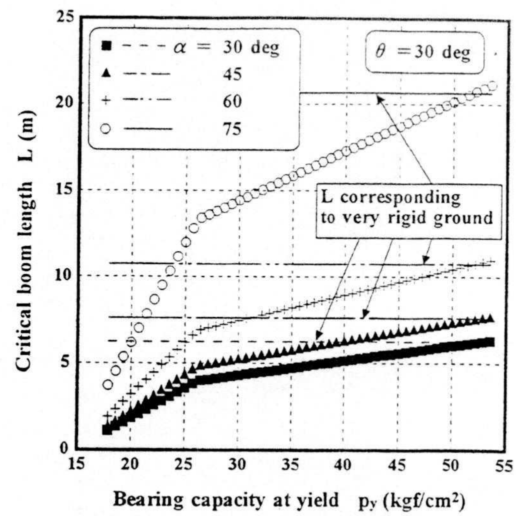

Fig.18 Total evaluation of tipping conditions (1kgf/cm²=98kN/m²)

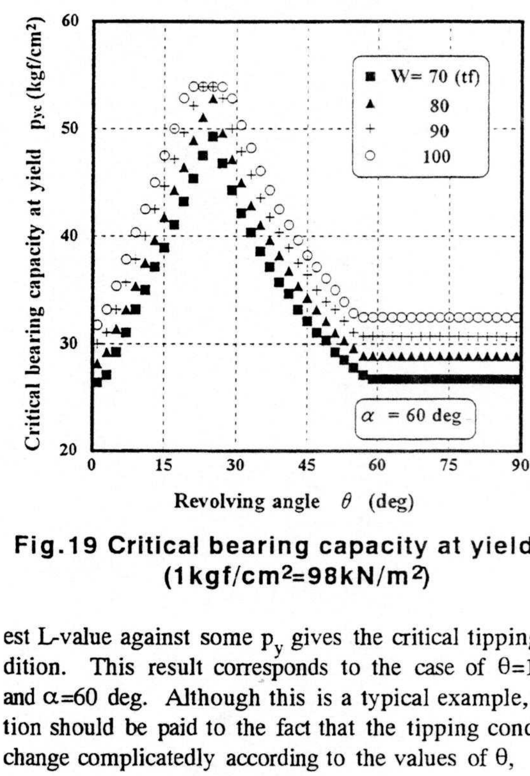

Fig.19 Critical bearing capacity at yield p_{yc} (1kgf/cm²=98kN/m²)

shown in Fig. 16 as a typical example. The analysis was carried out for the cases of α=30, 45, 60, 75 deg. It could be seen that the tendency changes at about p_y=34kgf/cm² (333kN/m²). As mentioned before, this is because the tipping condition with the greatest effect depends on p_y, that is, the equation giving the tipping condition was changed at about 333kN/m². The change of the tipping conditions is mainly determined by θ, for example when θ=90 deg, L is only determined by Eq.(7) irrespective of α-values. Of course this result does not consider the case of very rigid ground.

Fig.17 shows the case in which the three tipping conditions are all concerned with the tipping. The smallest L-value against some p_y gives the critical tipping condition. This result corresponds to the case of θ=10 deg and α=60 deg. Although this is a typical example, attention should be paid to the fact that the tipping conditions change complicatedly according to the values of θ, α and p_y.

d) Total evaluation of tipping conditions

The actual tipping of a truck crane happens according to the easiest tipping condition. The effect of the possibility of ground failure on the tipping conditions is therefore considered next.

Fig.18 shows the relationship between the critical boom lengths and p_y. In this figure, θ is 30 deg (kept constant) and α is altered 30, 45, 60 and 75 deg against this θ-value. Some breaking points were observed at about p_y=26kgf/cm^2 (255kN/m^2). When p_y was beyond about 54kgf/cm^2 (510kN/m^2), the tipping corresponding to the case of very rigid ground would occur before the tipping due to ground failure. This p_y was defined as the critical bearing capacity at yield, p_{yc}. If θ is constant, p_y which gives the breaking point in Fig.18 does not depend on the α-values.

Fig.19 shows the relationship between p_{yc} and θ. In this figure, four kinds of lifting weight from 70 to 100 tf (0.63-0.98MN) were used in the calculation. p_{yc} showed peak values at about θ=25 deg for any W-values and showed constant values for θ more than 60 deg. Accompanied by the increase of W, the gradient of p_{yc} became smaller within θ=20-30 deg, but the overall tendency is similar irrespective of W-values. Since the tipping due to ground failure is relatively apt to happen when θ is less than 60 deg, attention must be paid to this from the viewpoint of safety management.

The analytical results or the considerations mentioned in this paper depends strongly on the truck crane considered in this paper, but the methodology of this paper would be effective for other kinds of truck cranes.

4. Conclusions

This study dealt with the alarm system of truck crane when a truck crane is overturning. Especially the proposed system was expected to work well when ground failure is possible. The main conclusions obtained from this study are as follows:

(1) An alarm system which can predict the ground failure under almost realtime conditions was proposed based on the measurement of the relationship between the loading stress and the settlement at the outrigger pontoons. The system could yield the correct alarm signal according to the degree of danger against the tipping of the miniature truck crane, and the degree of danger showed good correspondence with the overturning phenomena of the truck crane.

(2) The analysis of the tipping conditions considering ground failure was carried out for an actual truck crane. The effect of the bearing capacity at yield, the revolving angle and the boom angle of the upper etc. on the tipping of the truck crane was investigated and the quantitative effect was made clear.

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