【参考】　研究成果の刊行物・別刷り

CENTRIFUGE MODEL TESTS ON INSTABILITY OF AUTOMOTIVE PILE DRIVERS

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ABSTRACT: The automotive pile driver is a piece of large-scale construction machinery. This machinery is used for ground improvement and foundation work. In recent years, there have been some reports of accidents in which the machinery overturned. In this study, a 1/25 scale model of an automotive pile driver was made to clarify the mechanism making the pile driver unstable, and centrifuge tests were performed. The load of each axle and the behavior of the model were measured in a centrifuge test. The grounds used with the model are two types of urethane foam with different strengths, with conditions imitating the uniform ground and non-uniform ground. As a result, the response acceleration did not have a significant difference due to differences in ground conditions. On the other hand, the effect of the ground condition was different in the axle load, and it was possible to evaluable the instability of the automotive pile driver when self propelling.

INTRODUCTION

The automotive pile driver (hereinafter referred to as the machinery) is mainly used for the foundation work of high-rise buildings and ground improvement. A photograph of the automotive pile driver is shown in Photo 1. This machinery is frequently used in urban areas. Recently, there have been accidents in which this machinery has overturned. In cases where the machinery topples, the risk to the lives of workers is not only a problem but this can also block trunk roads etc., having a great impact on society. Investigation revealed that overturning accidents of this machinery often occur during relocation to another pile. There are two factors in the background of the overturning of the machinery. One is structural instability stemming from a high center of gravity, and another is the ground where the machinery is set up being too soft. It is necessary to conduct a quantitative assessment of the fluctuation in the ground contact pressure while the machinery is running.

In this study, a 1/25 scale model of the automotive pile driver was made to clarify the mechanism of the instability of the pile driver during self propelling, and centrifuge

Photo 1. Automotive pile driver

Photo 2. Automotive pile driver model

tests have been performed. In the experiment, the behavior of the model when self propelling was measured by installing an accelerometer, and the load placed on the each axle of the model was measured to investigate the instability of the automotive pile driver.

This paper presents the safety factor of bearing capacity that is necessary to prevent the overturning of the machinery.

OUTLINE OF THE AUTOMOTIVE PILE DRIVER MODEL

The automotive pile driver model (hereinafter referred to as the model) was made by referring to the machinery subject to overturning accidents in the past. Table 1 shows a comparison between the specifications of the actual machinery and the model. The gross weight of this machinery is 539kN (55ton), and it is medium-sized in terms of this kind of machinery. The centrifuge tests were conducted at 25 g. This is the reason for the 1/25 scale mode. The positions of the motor, reduction gears, and battery of the

Table 1. Comparison of the specifications of the actual machinery and the model

		Automotive pile driver			
		original		model (1/25 scale)	
Center of gravity		Horizontal x(m)	Vertical y(m)	Horizontal x(mm)	Vertical y(mm)
Lower part (crawler)		-0.83	1.43	6.5	2.7
Upper part	body・leader	3.35	12.42	213.0	198.8
	auger・etc.	4.20	15.98	-5.8	32.2
Gross weight		539kN		29.9N (25g in 747N)	
Ground contact pressure (kPa)		101		133	
Velocity (km/h)		1.2 (=33cm/sec)			

model were designed relative to the machinery in terms of the center of gravity. The weight of the model is 29.9N. In a centrifugal field, the weight of the model is increased by up to 25 times. As a result, the ground contact pressure that acts on the crawler can be reproduced with the machinery.

Feedback control of the rotation rate of the motor was carried out to make it possible to hold a straight line. The velocity of the model can be changed by exchanging gears. The model is operated wirelessly. The stability angle of the model can be freely changed by changing the position of the additional weight. This is because the additional weight is loaded into the construction machinery (auger, sand compaction pile, etc.). Ground contact pressure was measured on the crawler by putting the strain gauge on the arm part of each axle, which has a cantilever structure. A calibration test was carried out to investigate the relation between the load and response of strain. As a result, it was confirmed that there were linear relationships in the load and the response of strain even if 300N (30kg) was applied. In addition, the behavior of the model was measured by putting accelerometers in three places (upper part and lower part of the leader, and the body). Photo 2 shows the automotive pile driver model.

MODELING OF THE GROUND

Material

To obtain basic data on the behavior of the model, urethane foam was used for ground in the model. Two types of urethane foam with different strengths are used. One is hard FP15, and another is soft FP30. Table 2 shows the density and hardness of the urethane foams.

Table 2. Density and hardness of urethane foams

	Density (kg/m^3)	Degree of hardness (kPa)
FP15	61	139
FP30	28	50

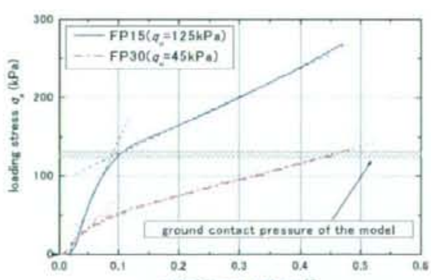


FIG. 1. Bearing capacity test results

Bearing Capacity Tests on Urethane Foam

The bearing capacity tests were performed to investigate the strength characteristics of the two types of urethane foam. This was examined using strain control and the rate of loading is 1 mm/min. The size of the loading plate used for the experiment is

25mm×50mm. Fig.1 shows the relation between loading stress and subsidence ratio (s/D) in which the amount of subsidence (s) is divided by the short side of the rectangle (D) of the loading plate. The q_u value of the intersection of two tangents in front and behind the winding point is defined as the ultimate bearing capacity.

The ultimate bearing capacity of FP15 and the ground contact pressure of the model are almost equal. On the other hand, the ultimate bearing capacity of FP30 is lower than the ground contact pressure of the model.

TEST PROGRAM

Test Apparatus

The test of the performance (operation) of the model was carried out in a centrifuge. Centrifuge testing was performed at the National Institute of Occupational Safety and Health, Japan (JNIOSH). A photograph of the NIIS Mark-II Centrifuge is shown in Photo 3. This apparatus has an effective radius of 2.3m, and the maximum acceleration of gravity is 100g. This is a medium-sized centrifuge compared to others in the world. As in other centrifuges, it has a main shaft, a drive unit, two arms, two swinging platforms, a signal and power supply interface and a control box. However, its arms are asymmetrical, which is its special feature.

. Fig. 2 shows the outline of the centrifuge model test. The size of the soil container is 920mm in length, 465mm in height, and 450mm in width. To prevent the wind from influencing it when experimenting, the whole unit was covered with a windshield cowl. The velocity of the model was measured with a wire-type displacement sensor. In this study, each axle was defined from the front wheel as FS (Front Sprocket), FR (Front Roller), CR (Center Roller), RR (Rear Roller), and RS Rear Sprocket).

Photo 3. NIIS Mark-II centrifuge

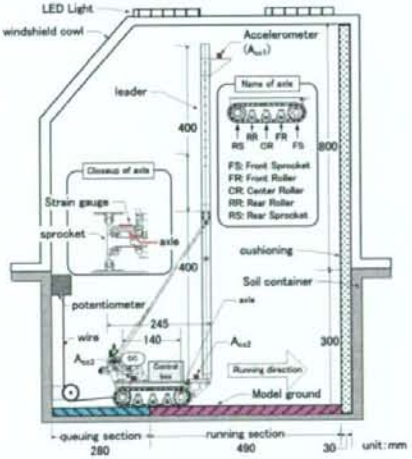
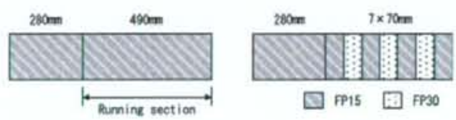


FIG. 2. Outline of the centrifuge test

Test Condition

The stability angle of the machinery should be five degrees or more according to the standard of Japan. In addition, the stability angle when running is ten degrees or more according to the British Standard. Therefore, the experiment was performed on the condition of a stability angle of fifteen degrees.

The model grounds are the two types shown in Fig 3. One is "the uniform ground" that using F15 and imitates the ground where strength is uniform. Another is "the alternating ground" using an alternating combination of FP15 and FP30 in bands 1/2 of the crawler length, and imitates the non-uniform ground. The model was made to run after centrifugal acceleration had been increased up to 25g.



(a) Uniform ground (b) Alternating ground

FIG. 3. Model grounds

TEST RESULTS

Typical Test Results

Fig.4 and Fig.5 show typical test results of the uniform ground and the alternating ground. The data shown in figure is a result for after 150mm when the entire band is in the running section. The velocity of the model was constant and it was about 30cm/sec. The acceleration shown in figure is the direction of travel. The acceleration data in the

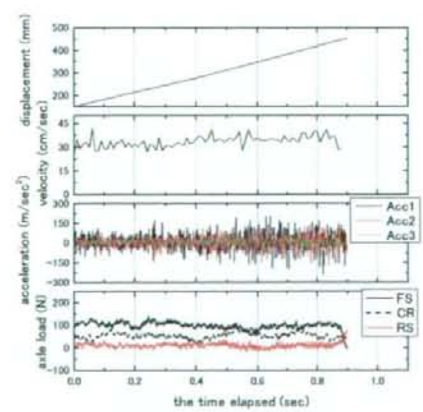


FIG. 4. Typical test results of the uniform ground

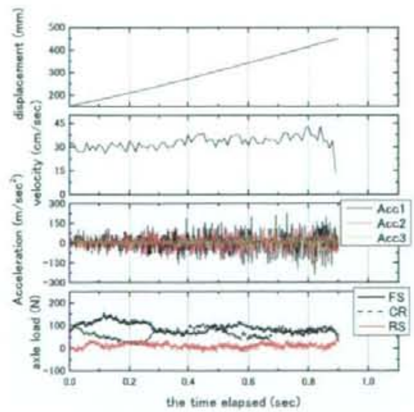


FIG. 5. Typical test results of the alternating ground

upper part of the leader was defined as Acc1, the lower part was defined as Acc2, and the body part was defined as Acc3. When accelerations are compared, Acc2 and Acc3 are almost equal regardless of the ground condition. In contrast, Acc1 is slightly larger than others. It was clarified that Acc1 was amplified by the leader. Meanwhile in the result of the axle load, the load of the front wheel is larger and the overturning moment more impactful than the rear wheel. In the case of the uniform ground, each axle load is almost constant. On the other hand, in the case of the alternating ground, the increase and decrease of the axle load on the front wheel side is especially large.

Frequency Analysis of Acceleration

Fig. 6 shows the result of the Fourier transform after conversion from the model scale into a full scale. The dominant frequency is seen in about 2Hz for both the uniform ground and the alternating ground. This is an influenced by structural unevenness of the crawler. In the case of the alternating ground, the dominant frequency is seen in about 0-2Hz. Therefore, the model shakes for a longer period.

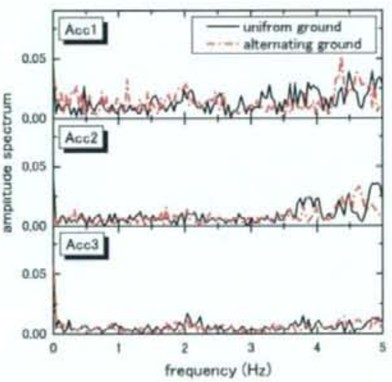


FIG. 6. Frequency analysis of acceleration

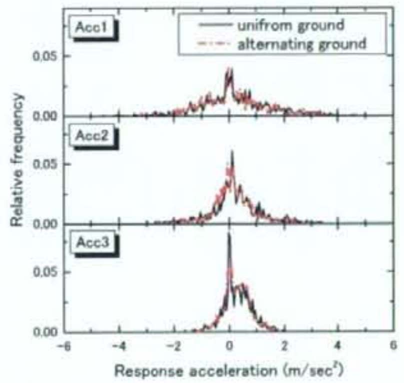


FIG. 7. Frequency distribution analysis of acceleration

Frequency Distribution Analysis

Fig. 7 shows the result of frequency distribution analysis of response acceleration. The frequency distribution analysis was carried out in 0.005g steps. There was no significant difference when the uniform ground was compared with the alternating ground. As mentioned above, there were no differences in the results of the Fourier transform and the frequency distribution analysis at the response accelerations.

Fig. 8 shows frequency distribution analysis results for the axle loads. In this study, the load acting on each crawler is divided by the weight of the model to define the load distribution ratio. There is little subsidence caused in the crawler because the ultimate bearing capacity of the urethane foam and the ground contact pressure of the model are almost equal in the uniform ground. Therefore, the maximum relative frequency of each axle showed comparable results. On the other hand, there is a difference in the distribution shape of I_{fr} when each axle is over alternating ground, and the front axle load is distributed widely. For that reason, the influence by the effect of the ground condition at the axle load where strength changes periodically appear.

Fig.9 shows the comparison between the theoretical value and the experimental value. The theoretical value of the ground contact pressure was calculated as established in the Japan Industrial Standards (JIS). The numerical expression is the same as in the British Standard. The mean and standard deviation are shown in figure. When the means are compared, the theoretical value and the average of experimental value are almost equal for both the uniform ground and the alternating ground. The error bar indicates two standard deviations (2σ). In a comparison of the uniform ground and the alternating ground, the standard deviation of the alternating ground is larger. The short-term safety factor of the foundation work is 1.5 in Japan. In addition, the same safety factor is adopted in CIRIA. For the biggest FS of the axle load, both the uniform ground and the alternating ground fall below the safety factor threshold of 1.5. Accordingly, it is

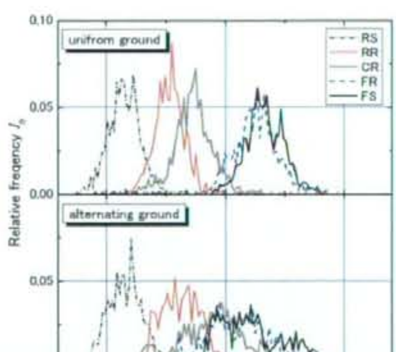


FIG. 8. Frequency distribution analysis of axle load distribution ratio

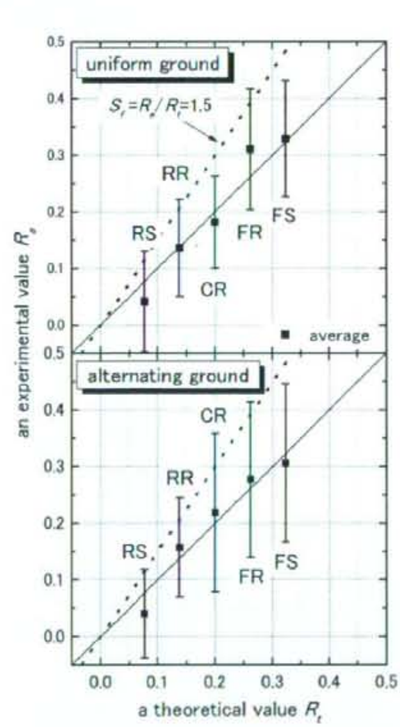


FIG. 9. Comparison between the theoretical value and the experimental value

thought that a safety factor of 1.5 is appropriate. However, FS and RS, tensile force acts on the crawler part when running, and bending-torsion force acts on the axle part. This is due to the effect of a structural problem in the axle part. Therefore, there is a problem where this is underestimated compared with the actual load. There are plans to improve the structure of the axle part examine it in the future.

CONCLUSIONS

The following conclusions were obtained on the centrifuge model test results performed on two types of the model ground:

(1) The acceleration did not result in any marked difference due to differences in the ground condition. On the other hand, there was a clear effect of the ground condition in the axle load, and it was possible to evaluate the instability of the model.

(2) The average of the experimental value of axle load was almost equal to the theoretical value.

(3) Two standard deviations in the frequency distribution analysis of the axle load were for a safety factor of roughly 1.5 or less. Therefore, it is thought that the safety factor for the bearing capacity of the ground must be at least 1.5 or more.

REFERENCES

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CIRIA, 2003, *Crane stability on site*, SP131, pp.48.

N. Horii, K. Itoh, Y. Toyosawa and S. Tamate (2006), "Development of the NIIS Mark-II geotechnical centrifuge" *Proceedings of the 6th international conference on physical modeling in geotechnics*, vol.1, pp.141-146.

A Case Study on the Overturning of Drill Rigs on Construction Sites

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ABSTRACT: Drill rigs are large pieces of construction machinery used to build pile foundations and to improve the ground stability. Crawlers comprising the lower base enable the machines to propel themselves. A tall leader given in the upper structure provides top heavy weight distribution. Sufficient bearing capacity and flatness are required in the bearing ground to keep the machinery stable without any tilts while it is propelling itself. Nevertheless, overturning often occurs at constructions. This study focuses on the phenomenon of ground instability causing machines to overturn. A drill rig weighing 372.5kN and with a leader 15.9m tall overturned on a building construction site. This machinery moved within the site to the positions required for building the diaphragm walls. This paper, firstly, summarizes operations prior to the accident. Secondly, the equilibrium condition of the machinery was calculated to clarify the stability, and the pressure acting on the ground through the crawlers was estimated. Ground properties were also investigated to assess the potential risk of failure in bearing ground. Finally, problems with the stability of drill rigs are discussed.

INTRODUCTION

Some drill rigs and similar machinery for piling and ground improvements are propelled by crawlers on both sides of the lower base carrier. Such machinery must be kept near horizontal on the bearing ground when moving if the derrick is raised. Nevertheless, accidents have often occurred due to overturning of drill rigs in Japan as well as in countries throughout the world. Ground penetration by crawlers was observed in many cases where actual overturning occurred as shown in Fig 1.

While the safety regulations for drill rigs worldwide prescribe the stability angle as the allowable tilt in the machinery, the ground is assumed to be sufficiently stiff and firm. The necessary ground conditions for setting up drill rigs are not specifically prescribed in the regulations.

This study examines the phenomenon of ground instability causing the drill rigs to overturn. A case study on an accident was carried out to investigate the problems with stability in terms of the bearing ground. This paper, firstly, summarizes the outline of operations prior to the accident. Secondly, the equilibrium condition of the machinery was calculated to clarify the stability, and the pressure acting on the ground through the crawlers is estimated in accordance with the regulations (British Standards Institution (1996a and 1996b) and Japanese Standards Association (2007)). The bearing capacity of ground is investigated to make sure the potential risk of overturning. Finally, problems with the stability of drill rigs are discussed.

FIG.1. Overturning of a drill rig in construction site.

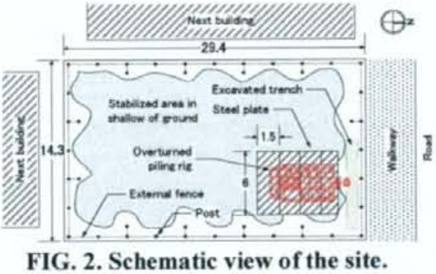


FIG. 2. Schematic view of the site.

FIG.3. Preliminary trench excavation.

SITE CONDITIONS IN THE ACCIDENT

An eight stories apartment house was being constructed at the site as shown in Fig 2. Diaphragm walls were selected as the foundation type in this construction. An external fence supported by posts was installed in the site to protect the adjacent buildings. Fig.1 shows an overturned drill rig to discuss in this paper from an incident that occurred in Japan in 2004. The drill rig comprised three augers in the leader and hit a car parked beside the site. Two workers were severely injured in this accident. Ground penetration by a crawler was clearly observed.

Soft clay was overlaid by sandy subsoil down to a depth of 0.7m. Shallow soil was stabilized by mixing with cement to increase the bearing capacity in advance. Though preliminary theoretical calculation indicated that thickness of 1.0m of stabilization was required to support heavy machinery, the actual stabilization was only performed to 0.7m due to difficulty mixing in the clay. Therefore, the bearing capacity was lower than the required value. In addition, existences of both the fence and the supporting posts disrupted the stabilization. Consequently, the bearing capacity in this around area was smaller than that of other areas. It seems that insufficient of bearing capacity was one cause of the accident.

A small trench, 0.9m in depth and 0.8m in width, was excavated by a backhoe in the north area prior to building the diaphragm wall as shown Fig 3. This trench excavation was carried out as preliminary preparation to indicate the positions of drilling columns and to prevent the overflow of mixing mud. However, the depth of the trench was deeper than 0.7m of the designed value. The deeper trench reduced the bearing capacity near the walls, and made the drill rig unstable. This was also considered to be another cause of the accident.

PROCESS PRIOR TO THE ACCIDENT

Table 1 shows the process of constructions at the site prior to the accident. Shallow soil stabilization was carried out as one of the preliminary preparations to increase the bearing capacity to ensure the machinery is kept nearly horizontal during self-propelling. The drill rig was assembled the previous day. Placing steel plates at the site was also required to support the heavy machinery.

Preliminary trench excavation started at 9:00 in the morning. Since a buried water pipe was broken at the excavation, however, the trench was submerged at 10:00. A site manager called up the water supply office to inform them of the trouble with water pipes. Running water was stopped by water supply personnel at 11:30. The remaining preparations were resumed soon after completion of the repairs even though the bearing ground softened due to the exposure to water.

Table 1. Process of the constructions prior to accident

Process		Contents of work
Before		Shallow soil stabilization by cement
Previous day		Assembling the drill rig in the site.
Day of the Accident	8:00	Meeting.
	9:00	Started preliminary preparations such as excavation of small trench and placement of the steel plates.
	10:00	A buried water pipe was broken at the trench excavation.
	10:05	Started pumping the water from the submerged trench
	10:45	Water department officials arrived
	11:30	Water leakage stopped
	11:45	Water pipe was repaired. Trench excavations and placing the steel plates were resumed.
	12:15	Completion of the preparations.
	13:00	The Drill rig moved toward to the position for excavation.
	13:10	Overturned near the trench

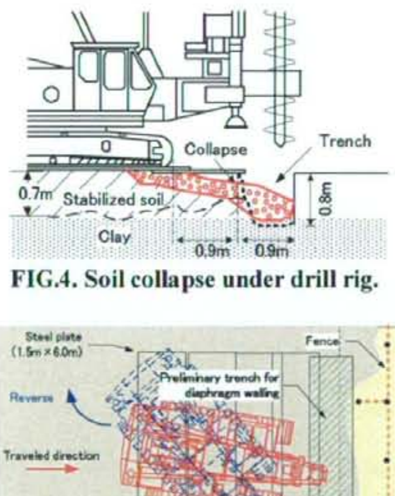


FIG.4. Soil collapse under drill rig.

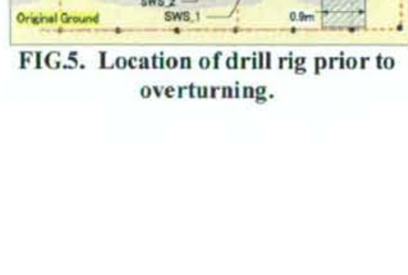


FIG.5. Location of drill rig prior to overturning.

The drill rig moved to the north east position to build the diaphragm walls as shown in Fig 4. However, the machinery was tilting slowly when it had reached a distance of 0.9m offset from the trench. An operator who observed the tilt quickly reversed the travel and turned the upper structure right as shown Fig 5. The increment of tilt in the machinery accelerated due to collapsed soil, and the machinery finally overturned as shown in Fig 1.

STABILITY OF THE DRILL RIG

Stability angle

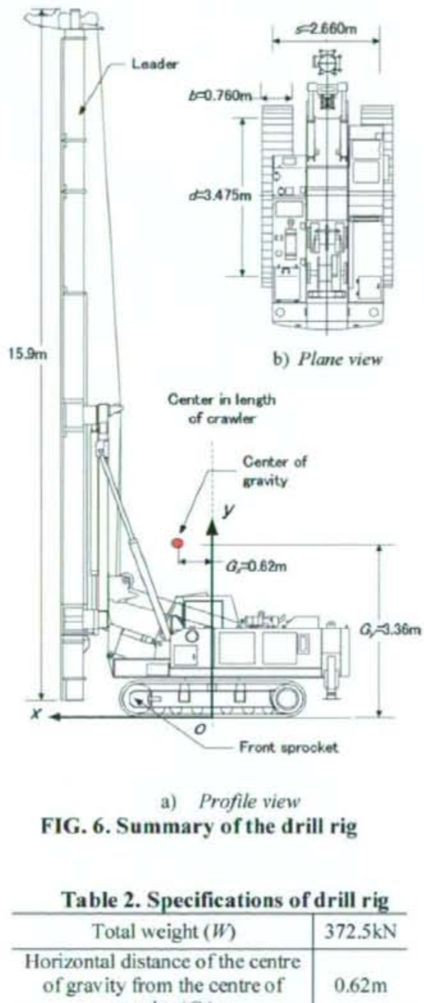
Fig 6 shows a summary of the drill rig with a leader 15.9m in length and 372.5kN in total weight (W). Since the x axis and the y axis are defined as shown Fig 6, the origin (O) is positioned at the horizontal center of the crawler on the ground surface. Coordination of the center of gravity in horizontal axis (G_x) and vertical axis (G_y) was calculated to investigate the stability of the machinery. Table 2 summarizes the specifications of the drill rig.

Safety regulations prescribe structural requirements in terms of the stability angle as allowable tilt of drill rigs. Table 3 shows comparison of the stability angles between Europe and Japan. The European Norm (British Standard Institution (1996a) and (1996b)) prescribes the stability angles in both EN996 of "Piling equipment - safety requirements" and EN791 of "Drill rigs – safety". EN996 describes that a stability angle of 5 deg must be provided in the drill rigs as minimum requirement. 8 deg is also written for propelling on job sites. EN791 also describes the stability angles those shall not be less than 10 deg in any direction when moving and not be less than 5 deg under any other conditions. The stability angle of 10 deg also includes a margin for the effects of the inertia forces from acceleration, braking and swaying of the drill rigs. The Japanese Ministry of Health, Labor and Welfare prescribes a stability angle of 5 deg in the Ordinance on Occupational Safety and Health as a minimum value. The Society of Materials Science, Japan (2002) recommends two sets of values in connection with the stability angles that are 7 deg when drilling and 9 deg when self-propelling.

Larger values in the stability angle at self-propelling are introduced in both regulations since an increase of instability takes the effect of the inertia forces by into account. The stability angles were calculated by giving consideration to the specifications of machinery as shown in Table 4. The stability angle in forward (θ_{sf}) means a tipping angel where the center of gravity turns above the front sprockets due to tilt, and this value is derived by Eq.(1). The stability angle in lateral (θ_{sl}) is also obtained by Eq.(2). Both 18.4 degrees for θ_{sf} and 21.6 degrees for θ_{sl} are greater than 10 deg of the limitation by EN791. Hence, the drill rig overturned even though sufficient stability was provided in the machinery. Accordingly, it was ascertained that a collapse of the bearing ground was the main cause of the accident.

Pressures acting on the ground

EN791 and EN996 define five types of distributions in the pressures acting on the ground through the crawlers as well as JIS A 8509-1 by the Japanese Standards Association(2007) . These distributions are specified by the position of a single load (e) as shown in Table 5. A value of e is the same as that of G_x introduced above. The maximum pressures acting on the ground (σ_2) are obtained by the equations given.



a) *Profile view*
FIG. 6. Summary of the drill rig

Table 2. Specifications of drill rig

Total weight (W)	372.5kN
Horizontal distance of the centre of gravity from the centre of crawler (G_x)	0.62m
Vertical distance of the centre of gravity from ground surface (G_y)	3.36m
Length of contacting area on crawler (d)	3.475m
Width of crawler (b)	0.76m
Tread between crawlers (s)	2.660m

Table 3. Comparison of the stability angle in safety regulations

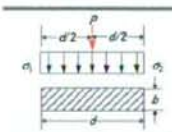
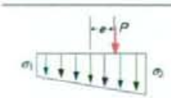
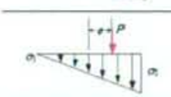
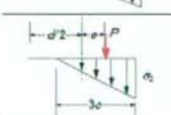
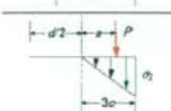
	Stability angles (deg)
EUR	Usually 5 Either 8 (EN996)or 10 (EN791) at self-propelling
JPN	5*

* 7 (at the drilling) and 9 (at self-propelling) are recommended by the Society of Material Science, Japan (2002).

Table 4. Calculation of the stability angle

	Forward	Lateral
Calculating formula	$\tan\theta_{sf} = \frac{d-2G_x}{2G_y}$ (1)	$\tan\theta_{sl} = \frac{s}{2G_y}$ (2)
Stability angle (deg)	θ_{sf}=18.4	θ_{sl}=21.6

Table 5. Calculation of maximum ground pressure under crawlers

Load and stress diagram	Position of the single load P	Ground pressure
	e=0 P in the middle	$\sigma_1=\sigma_2=P/bd$
	$e<d/6$	$\sigma_1 = \frac{P(1-6e/d)}{bd}$ $\sigma_2 = \frac{P(1+6e/d)}{bd}$
	$e=d/6$	$\sigma_1=0$ $\sigma_2=2P/bd$
	$e>d/6$ $c=d/2-e$	$\sigma_2=2P/3bc$
	$e=d/3$	$\sigma_2=4P/bd$

A value of e and a value of d were 0.62m and 3.475m in the drill rig, respectively. The relationship between e and $d/6$ is derived as Eq.(3). Consequently, σ_2 is calculated by Eq.(4).

$$e > \frac{d}{6} \qquad (3)$$

$$\sigma_2 = \frac{2P}{3bc} = 146(kPa) \qquad (4)$$

where the single load (P) is substituted by a value of $W/2$.

As the steel plates were sheeted on the ground surface, the actual pressure acting on the ground was smaller than the value of σ_2.

Bearing grounds are assumed to be sufficiently stiff and firm. Safety regulations don't consider the machinery becoming unstable by tilt with an increase of differential settlement in the crawlers. However, this settlement increases the pressure acting on the ground by an increase in the overturning moment due to the machinery tilting. Accordingly, the values of the actual pressure acting on the ground become greater than the values suggested by the regulations where the machinery tilts due to settlement of crawlers.

Supported ground conditions

Swedish weight sounding tests (SWS) were carried out to investigate the distribution of stiffness at the two positions of SWS_1 and SWS_2 shown in Fig.5. The N value is well known as an index to classify the ground stiffness. N-value means the number of blows in standard penetration tests that are carried out in boreholes during site investigations. The procedure is specified in BS1377. The N value is interpreted by Eq.(5) and Eq.(6) depending on soil materials.

<Sand> $N_i = 0.002W_{sw} + 0.067N_{sw}$ (5)

<Clay> $N_i = 0.003W_{sw} + 0.050N_{sw}$ (6)

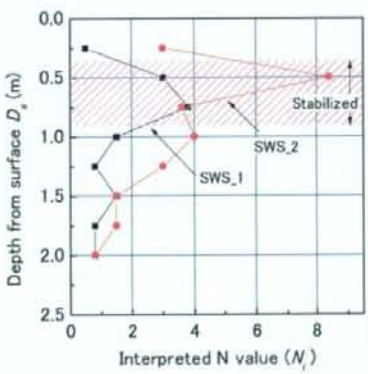


FIG.7. Relationship between the interpreted N values (N_i) and depth (D_s)

where N_i is the interpreted N value, W_{SW} is the value of the loading weight, N_{sw} is the equivalent number of caracole required to penetrate 1m in depth.

Fig 7 shows the relationship between depth (D_s) and N_i. Since SWS_2 shows higher value than SWS_1, the bearing capacity of ground is lower in the northeast corner. Both curves show the existence of a stabilized layer between 0.2m and 0.9m. Soft clay was deposited below 1m so N_i decreased rapidly. A likely difference in measured N_i was the water seepage by the broke water supply line.

DISCUSSIONS ON PROBLEMS WITH STABILITY

Hazards in the ground

Various hazards usually exist in constructions. Since drill rigs are large pieces of machinery, their overturning causes serious damage to the surroundings of the sites as well as inside the site.

Two problems existed in the construction.

1) Existence of both fences and supporting posts disturbed stabilization near their boundaries. Hence, the bearing capacity was lower in this area.
2) Insufficient stabilization thickness reducing the bearing capacity.

In addition, another three problems made the bearing ground unstable.

1) Bearing capacity near the walls was reduced because the depth of the trench was deeper than the designed value.
2) A broken water pipe caused the excavated trench to be submerged. Water seepage made the bearing ground soft.
3) Soon after the completion of repairs, the remaining works were resumed without confirmation of the stability.

Safety requirements for the stability of sites

Safety regulations commonly assume that sufficient bearing capacity is provided in the ground of construction sites. Meanwhile, either pilings or ground improvements were conducted on sites where the bearing capacity is insufficient for supporting facilities. Therefore, various stabilization methods such as deep soil mixing and the installations of pile foundations are used to support the structures. Accordingly, the drill rigs must move over unstable ground on construction sites.

Tamate et al. (2005) investigated the mechanism of the overturning of the mobile cranes. Top heavy distribution in both the mobile cranes and drill rigs induce potential instability. Four outriggers support mobile cranes while hooking the load. Mobile cranes become quite unstable where the outriggers rapidly penetrate the surface due to the brittle failure in the bearing ground.

CIRIA (2003) recommends three sets of safety factors in terms of bearing capacity (F_s) as follows. F_s of 1.5 is the absolute minimum and should only be used where ground conditions have been accurately identified under the guidance of an experienced geotechnical engineers. F_s of 2.0 is adequate for most situations. F_s of 3.0 is more normally used for permanent works for foundations and will give a conservative size of foundation area. It should be used for outrigger foundations where little ground information is available, where soils are variable or where minor settlements could be critical to a precision lifting and placing operation.

Theoretical calculations were carried out by Tamate et al (2006) to learn about the relationship between the probability of safety for overturning (P_{ss}) and F_s. P_{ss}>0.984 at F_s=3 resulted whereas P_{ss}>0.802 at F_s=1.5 in particular ground that induces rapid outrigger penetration. Accordingly, it is ascertained that safety for overturning can be easily ensured by using F_s=3 to prevent any ground penetration by outriggers.

Drill rigs propel by themselves whereas mobile cranes stand still in the positions they perform hooking operations. The potential risk of the overturning by the differential penetrations in the crawlers due to failure in the bearing ground is unclear. In addition, flatness of the surface and variation of the stiffness cause a swaying motion, and thus inertia forces are generated. Accordingly, drill rigs are considered to be quite unstable by the inertia forces due to sway during self-propulsion. It was confirmed that further study is needed to specify the safety requirements in terms of the bearing ground.

CONCLUSIONS

A case study on the overturning of drill rigs on construction sites was discussed to address problems with stability. The conclusions are summarized as follows:

1) Top heavy structure is provided in drill rigs during propelling by themselves. Sufficient bearing capacity is required to support the machinery safely. The case introduced to illustrate overturning occurred due to penetration by the crawlers because of a failure of the bearing ground. Hence, sufficient capacity must be provided to keep drill rigs stable in the bearing ground.
2) Safety regulations worldwide prescribe the stability angles as allowable tilt by the overturning moment. By contrast, the bearing ground is assumed to be sufficiently stiff and firm. Safety requirements on bearing ground are not prescribed in the regulations.
3) Calculation procedures regarding the pressures acting on the ground are specified in the regulations. Nevertheless, the values obtained are generally lower estimated because the tilts in drill rigs induced by differential settlement in crawlers are not considered.
4) Drill rigs propel themselves in sites while mobile cranes stand still in their positions during hooking operations. Inertia force caused by sway during propelling makes drill rigs more unstable than mobile cranes. Accordingly, the potential risk of the overturning increases for drill rigs.
5) Safety requirements for bearing ground are necessary to prevent the overturning of drill rigs and similar foundation machinery. Clarification of the relationship between characteristics of instability of the drill rigs and properties of the bearing ground needs to be addressed in further studies.

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原著論文

実大走行実験によるくい打機の不安定化挙動の解析†

堀　智仁[*1]　玉手　聡[*1]

基礎工事用大型車両系建設機械（以下，「くい打機」という）は，上部旋回体と下部走行体で構成される大型の建設機械である．毎年，この種の機械の転倒災害が数件発生している．原因の多くは設置地盤の支持力不足にあるが，その背景にはくい打機がトップヘビーな構造を有しながら自走することと，この機械が設置される施工現場が軟弱であることの2つの要因がある．本研究では，くい打機の自走時不安定化メカニズムを明らかにすることを目的に，実機を用いた実大走行実験を実施した．実大走行実験では機体の3箇所に3成分の加速度計を設置して，直進およびカーブの2つの条件で走行挙動を計測した．その結果，走行時のくい打機の応答加速度には，長周期的な揺れが確認された．また，カーブ走行では応答加速度に増加が見られ，くい打機が不安定化した際の特徴的な傾向が計測によって明らかになった．

キーワード: くい打機，実大実験，自走時挙動，施工安全

1　はじめに

くい打機は地盤の改良工事や基礎工事に用いられる大型の建設機械である．過去に発生した災害を調査すると，自走中における転倒が年間数件発生している．この転倒による被害は，現場内のみならず，その周辺にも及び，マスメディアでも大きく報道されている．

くい打機の上部旋回体には長尺なリーダー等が備わり，トップヘビーな状態で自走する．しかし，施工現場を自走するくい打機が「どのように」，そして「どの程度」不安定化するのかは未解明な問題である．

そこで本研究では，くい打機の安定度と走行地盤の支持力条件の違いが揺動と接地圧力分布に与える影響の解明を試みている．

本報告は，その第一段階として調査した国内外の安全規則に関する比較と，実大のくい打機を用いた自走実験から明らかになった揺動特性について述べる．

2　くい打機の転倒防止に関する国内外の関係規則

1)　国内の規則

くい打機の転倒を防止するために2つの規則等が定められている．その一つは，車両系建設機械構造規格[1)]であり，建設機械が備えなければならない安定度を機種毎に定めている．ここで，安定度とは，機械が最も不利となる状態において，傾けても転倒しない角度を表し，前後左右について満足しなければならない値である．表1に機械が備えるべき安定度を示す．くい打機が有するべき安定度は5度である．この値はブル・ドーザーのそれに比べて小さく設定されており，構造的に不安定なことがわかる．

もう一つは，労働安全衛生規則第173条[2)]であり，「軟弱な地盤において施工する場合には，敷板等の使用による沈下防止のための措置を講じなければならない」と記述されている．しかしながら，設置地盤の具体的な要件については示されていない．そのため，安定設置の判断は事業者に委ねられているのが現状である．表2は事業者が独自に定めた基準[3)]の一例である．作業時と走行時の安定度について異なる値を設定するとともに，構造規格の基準値に比べ1.4～1.8倍の値が用いられている．また，地表の勾配については1/100以内の平坦性と支持力安全率1.5以上の確保を使用基準に定めている．

表1　機種と安定度

機種	くい打機	ブル・ドーザー
安定度	5度	35度

表2　事業者が定めた使用基準の例

安定度	作業時：7度
	走行時：9度
地盤床・地盤の勾配	1/100以内に整地し平坦性を保つ
支持力条件	安全率：1.5

2)　ヨーロッパの安全基準

くい打機に関するヨーロッパの基準について調査した結果，ヨーロッパの関係各国の基準が1996年に統一され，以下の2つの欧州規格が示されていた．

(1)　EN-996(1996)-Piling equipment- Safety requirements

EN-996[4)]では，くい打機が有するべき安定度を，施工時と休止時に分けて，それぞれを3つに分類して，4つの荷重成分に対する部分安全率と機体の安定度を表3の通り示している．

(2)　EN-791(1996)-Drill rigs- safety

EN-791[5)]には，自走時と作業時の2つの状態についてくい打機の安定度を「移動中は，前後左右に対して10度以上を有し，その他の状況は5度以上を有しなければならない．このときの安定度10度は，加速時と停止時の動的な力の作用による影響の余裕も含んでいる」と記述されている．

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表 3 荷重状態と部分安全率

状態		作業荷重	旋回荷重	風荷重	動的荷重	安定度
施工時	作業中	1.1	1.1	1.1	1.1	5 度
	自走中	1.1	1.1	1.1	1.1	8 度
	停止時	1.1		1.1	1.1	5 度
休止時	風荷重が作用	1.0		1.3		5 度
	リーダーが起立状態	安定モーメント>1.1×転倒モーメント				
	リーダーが低い状態					5 度

3) 日本とヨーロッパの法令規則の比較

表4にくい打機の安定度に関する日本とヨーロッパの基準の比較を示す．表に示すように，日本とヨーロッパでは走行時の安定度に違いが見られ，ヨーロッパの安定度の基準は日本よりも厳しく，詳細に記述されていることがわかった．しかしながら，くい打機の設置地盤に関する要件については，国内外の規則にその詳細が示されておらず，設置地盤の支持力要件の検討は急務であると考えられる．

表 4 安全規則の比較

	安定度			
	安全基準		推奨値	
	施工時	走行時	施工時	走行時
日本	5度	5度	7度	9度
ヨーロッパ	5度	8 及び 10度	不明	不明

3 実大走行実験地盤の概要

1) 実験現場

くい打機の自走時挙動解析を行うために，実大走行実験を行った．実験現場は東京国際空港国際線地区エプロン等事業が行われているエリアの南西部である．

本実験では走行路の地盤条件と機体に生じる挙動の関係を明らかにするために，水準測量と平板載荷試験を実施した．その後，走行路に敷鉄板を敷設して，くい打機を自走させた．機体に生じる加速度応答は後述する 3 箇所で計測を行った．

2) 水準測量

水準測量は 1.8m 間隔の格子状に測点を設定し，128 地点（4×32）について計測を行った．基準点の地盤高を 0m とした時の高低差を図 1 に示す．走行路には緩やかな起伏が見られる．高低差は最大で約 10cm と小さく，ほぼ平坦な地盤である．図中の BC1～BC3 は後述する平板載荷試験の実施位置である．

3) 現場密度試験

走行路地盤密度を砂置換法 [6]により調査した．試験に用いた砂は豊浦砂である．表 5 に試験結果を示す．No.1 は平板載荷試験を実施した BC1 の近傍における結果であり，No.2 は BC2 の近傍における結果である．No.1 と No.2 を比較すると，乾燥密度と含水比の値に差が見られる．図 2 に試験孔から採取した試料の粒度分布を示す．No.1 は No.2 に比べ全体的に左上に位置しており，No.2 よりも粒径が小さく，粘土分やシルト分を多く含んでいる．以上の結果から，走行路の土質は箇所によってやや異なることがわかった．

表 5 現場密度試験の結果

試料名	土粒子密度 ρ_s(g/cm^3)	湿潤密度 ρ_t(g/cm^3)	乾燥密度 ρ_d(g/cm^3)	含水比 w(%)
No.1	2.685	1.531	0.922	66.0
No.2	2.675	1.670	1.389	20.2

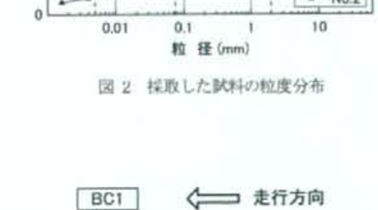

図 2 採取した試料の粒度分布

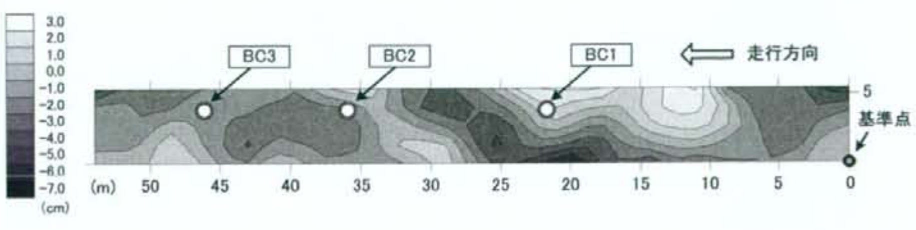

図 1 水準測量の結果

4) 平板載荷試験

走行路の地盤支持力を調べるために平板載荷試験を行った．平板載荷試験は剛な載荷板を介して原地盤に荷重を与え，荷重の大きさと載荷板の沈下量との関係から，ある深さまでの地盤の変形や強さなどの支持力特性を調べるための試験である[7]．本研究では直径 30cm の円形の載荷板を用いた．写真 1 に平板載荷試験の様子を示す．試験はひずみ制御（変位速度 5mm/min）により，図 1 に示す 3 箇所で実施した．図 3 に載荷応力（q_a）と，沈下量（s）を載荷板の直径 D で除した沈下比（s/D）との関係を示す．3 つの曲線に共通して s/D が 0～0.1 の範囲では s/D 増分に対する q_a 増分が大きく，その傾き K_i には一致が見られる．また，曲線は s/D=1.0 付近で屈曲点を示した後，ほぼ単調に増加し明確なピークを示さない．ここで屈曲点前後の 2 つの接線の交点における q_a 値を極限支持力（q_u）と定義し，求めた値は 478～623kPa であった．BC1 地点の極限支持力が低い原因は，前述のとおり BC1 地点は BC2 地点に比べ含水比が高く，粘土分およびシルト分を多く含むためと考えられる．しかしながら，3 地点の q_u は本実験で使用したくい打機の最大接地圧 p_{max}（=196kPa）よりも 2.4～3.3 倍と高く，走行路地盤は十分な支持力を有していた．

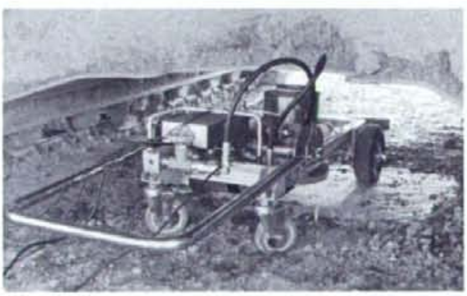

写真 1　平板載荷試験の様子

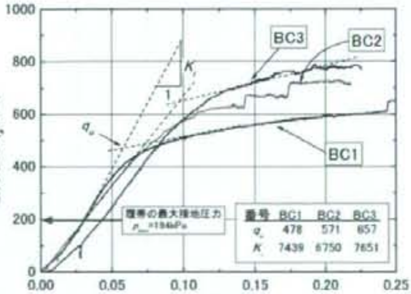

図 3　載荷応力（q_a）-沈下比（s/D）関係

4　実大走行実験

1)　走行実験の概要

実験に使用したくい打機は写真 2 に示すサンドコンパクション用のものであり，全高 27m，総重量 980kN，安定度 17 度，履帯の最大接地圧 194kPa である．機体の 3 箇所に加速度計を設置した．Acc1 はリーダー上部，Acc2 はリーダー下部，Acc3 は履帯支持枠の中央に設置した加速度計である．応答加速度は各箇所において進行方向成分（A_x）と，これと直交する左右方向成分（A_y），上下方向成分（A_z）をサンプリング周波数 100Hz で計測した．加速度計の極性は，A_x は後方，A_y は右，A_z は上が正極となっている．

走行地盤には敷鉄板を進行方向に対して横向きに設置した．この敷鉄板は 1.5m×6m×25mm のものである．実験の走行速度は 1.0km/h（=28cm/sec）である．

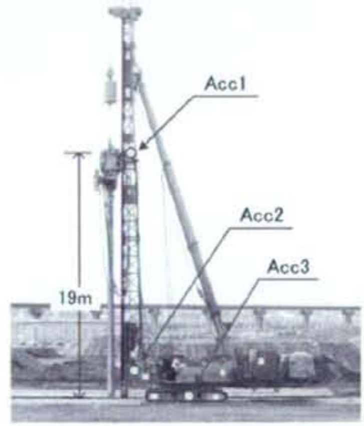

写真 2　実験に使用したくい打機

2)　周辺の振動およびエンジンの振動による影響

実験を行った現場は 24 時間体制で施工が行われており，実験現場の近傍ではサンドコンパクションパイルの施工が行われていた．サンドコンパクションパイルは振動あるいは衝撃荷重を利用して砂杭を造成する工法である．実験現場では数十 m 離れた地点で行われている施工の振動が感じられた．そのため，計測データにはサンドコンパクションパイルの施工によるノイズの影響と，エンジンの稼働によるノイズの影響が考えられる．そこで，エンジンを稼働させた状態での待機中の応答加速度を計測した．図 4 に計測した結果を示す．図中にはリーダー上部（Acc1）とクローラ基部（Acc3）の応答加速度を示した．なお，電気的なノイズの影響を除去するために 5Hz のローパスフィルターを施してある．Acc1 と Acc3 の応答加速度を比較すると，上下方向（A_z），前後方向（A_x）および左右方向（A_y）全てにおいて，Acc1 の応答が大きく，緩やかに増減する傾向が見られる．これは，計測時の風速が 11m/sec と比較的強い風が吹いていたためと考えられる．t=16～23sec に大きな応答が見られる．これは，サンドコンパクションの施工による影響と考えられる．いずれにせよ，待機中の加速度応答の最大振幅は 0.03m/sec^2 であることがわかった．