# Dynamic consolidation test in centrifuge

## L'essai de consolidation dynamique en centrifuge

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SYNOPSIS Dynamic consolidation or heavy tamping was simulated in a centrifuge to obtain basic data of ram penetration into the ground and deformation of a sandy ground under a variety of tamping conditions. The model ground was designed as a semi-cylindrical column, the center of which was tamped by a ram. The vertical front face of the model ground contacts a glass plate through which the ground deformation was observed. Main conclusions are : 1) ram penetration was in proportion to the square root of the number of ram blows and 2) was governed by ram momentum, 3) ground deformation due to ram penetration was rather limited in a spherical zone around the bottom of tamping hole, and 4) the increase in ground density was governed by the total tamping energy.

## INTRODUCTION

In Japan, there have been many cases where dynamic consolidation was successfully applied to improve sandy and gravely grounds. However, the work conditions in the current design procedure, such as ram mass, ram drop height, number of blows at a tamping point and distance between tamping points, have been determined only empirically, because field instrumentations and measurements such as settlement gage, inclinometer, pressuremeter and dynamic sounding have not yet produced sufficient data to clarify the ground behavior under this violent tamping method.

In such situation, we have recently started a series of centrifuge model test of dynamic consolidation (Takada et al 1987, Mikasa et al 1988, Ohshima et al 1988) to obtain basic data to serve for the optimum design of this ground improving method under given conditions. The effects of tamping conditions (ram mass, drop height and number of blows) and ground conditions (kind of soils, soil density and ground water level) on the ground improvement are being studied.

This paper discusses the ground behavior under tamping together with some findings in relation to the ram penetration into the ground. The deformation and compaction of the ground as a whole are also referred to.

## TEST APPARATUS

The prototype ground is assumed as an axi-symmetrical cylindrical column, half of which is simulated in a semi-cylindrical column, 30cm in diameter and 20cm in height. The vertical cross-section of the model ground including its center axis is supported by a glass plate, through which the ground deformation can be observed. To observe the ground deformation clearly, ram blows are given to the ground surface through a short semi-cylindrical wooden penetration rod, weighing 13.5g, placed at the center of the ground surface (Fig.1). The inertia of this rod was ascertained not to affect test results (Mikasa et al 1988).

The specimen box is made of aluminum alloy, in which a semi-circular steel cylinder, 15cm in radius and 25cm in height, is installed to hold the model ground. The front face of the model ground is supported by a tempered glass plate, 10mm thick, which again is covered and guarded by a tempered composite glass plate (10mm + 0.5mm vinyl film + 6mm) built in a rigid aluminum frame.

As an effective measure to eliminate the friction between the glass plate and the soil, the glass plate was coated with a wet thin agar film. This film also served as a base on which cross markers are pasted and a grid is printed by spraying color paint through a 8mm mesh (cf. Fig.6).

The ram is wound up by an electric motor by means of a string to a predetermined height, and then automatically released to drop along a guide perpendicular to the model ground till it blows the penetration rod. The ram hanger, after releasing the ram, is kept wound up till it contacts the upper limit switch, which makes the motor rotate reversely. Then the hanger descends till it contacts the lower limit switch, which makes the hanger hold the ram and be wound up again. The penetration of the rod is measured visually by the help of a strobo-flash.

The centrifuge is Mark 5 in Osaka City University having a 2.56m nominal radius rotor driven by a 22KW induction motor; the maximum centrifugal acceleration being 200g. The rotation is controlled by means of frequency control.

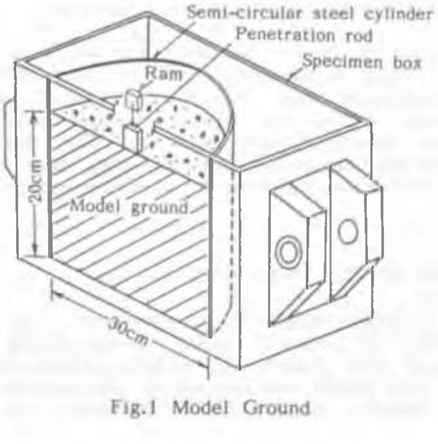


Fig.1 Model Ground

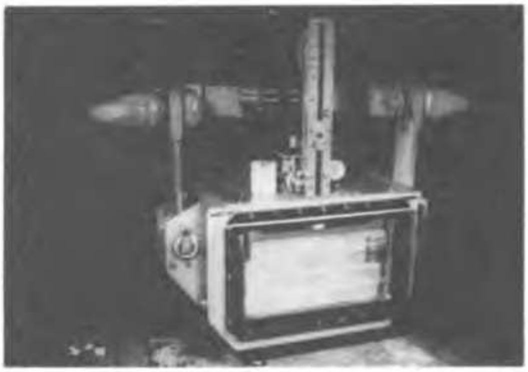


Fig.2 Model Setup

Table I Test Conditions and Results

| $E_I$ | $m_p \times H_p$ | $A_p$ | $D_r$ | $N_{p3}$ | $E_t$ | $m_p \cdot v_p$ | $N'_{p3}$ | $\frac{m_p \cdot v_p}{A_p} \sqrt{N'_{p3}}$ |
|---|---|---|---|---|---|---|---|---|
| 100 tfm | 20t×5m | 4 m² | 78% | 85 | 8,500 tf·m | 198.0 t·m/s | 96 | 485.0 tm/s/m² |
| 200 | 10t×20m | 〃 | 78 | 78 | 15,600 | 198.0 | 94 | 479.9 |
| | 20t×10m | 〃 | 72 | 49 | 9,800 | 280.0 | 49 | 490.0 |
| | 40t×5m | 〃 | 78 | 31 | 6,200 | 396.0 | 25 | 495.0 |
| 400 | 16t×25m | 〃 | 70 | 30 | 12,000 | 354.2 | 30 | 485.0 |
| | 20t×20m | 〃 | 74 | 23 | 9,200 | 396.0 | 24 | 485.0 |
| | 40t×10m | 〃 | 76 | 15.5 | 6,200 | 560.0 | 12 | 485.0 |
| | 80t×5m | 〃 | 73 | 7 | 2,800 | 792.0 | 6 | 485.0 |
| 800 | 40t×20m | 〃 | 75 | 7 | 5,600 | 792.0 | 6 | 485.0 |
| | 80t×10m | 〃 | 76 | 4.5 | 3,600 | 1120.0 | 3.5 | 523.8 |
| 400 | 20t×20m | 9.8 | 76 | 157 | 62,800 | 396.0 | 157 | 507.3 |

$E_I$ : Energy per one blow ($=m_p \cdot g \cdot H_p$)
$A_p$ : Cross sectional area of ram
$N_{p3}$ : Number of blows for 3 m penetration
$E_t$ : Total energy ($=E_I \cdot N_{p3}$)
$m_p v_p$ : Ram momentum ($=m_p \cdot \sqrt{2 \cdot g \cdot H_p}$)
$N'_{p3}$ : Corrected $N_{p3}$

Fig.2 shows a setup of the model ground and the ram operating device.

## SOIL PROPERTIES

The prototype material was assumed as a blasted and crushed soft rock with a small fraction of fine particles, a candidate material for the enormous fill of Kansai International Airport, which is now being constructed in Osaka Bay. The model material, therefore, was chosen as a clean sand finer than 2mm, mixed with a weathered granite, 75% finer than 0.075mm, by 5.4% at dry mass. Its uniformity coefficient is 3.2 and maximum dry density is 1.69t/m³ at the optimum water content of 8.1%. The minimum dry density is 1.36t/m³, which was determined as follows: air dried soil is poured in a very loose state to 10cm in depth in a cylinder of 12cm in diameter, loaded by a 960g brass disc and saturated slowly from its bottom.

## MODEL PREPARATION AND TEST PROCEDURE

The model ground, 20cm thick, was prepared in four layers, each being compacted by a ram at the optimum water content; the number of blows and ram mass were determined from preliminary compaction tests to obtain the desired density. During compaction, the front face of the model ground was covered by a hard aluminum alloy plate, which, after compaction, was replaced by the glass plate coated with agar film on which markers and grid were prepared as already explained. Then, the ram operating device and the penetration rod were installed.

The model set up in the centrifuge was put in a predetermined centrifugal acceleration field for about 10min allowing the settlement under its selfweight before ram blows were applied. During test, number of blows, penetration of the rod and ground surface settlement were recorded and photographs were taken. All the tests were terminated when the penetration came to 3m in the prototype scale.

## RAM DROP HEIGHT IN CENTRIFUGE

In a 1/n scaled model in an imaginary stationary ng gravitational field (e.g. on a big planet), during the free fall from a drop height $H_m$ ($=H_p/n$, where $H_p$ is the prototype drop height on the earth), the ram would gain the same velocity as that of the prototype ram in a 1g gravitational field. In a centrifuge, however, the released ram, for an observer outside the centrifuge, flies at a certain velocity along a straight line tangent to the circle on which the ram has been rotating and will not fall normal to the model ground. Thus the ram must be guided in the radial direction to resist the Coriolis force.

The ram drop height should be determined taking into consideration that the centrifugal forces at both the ram release radius, $r_1$, and the ram blow radius, $r_2$, are different. In a centrifuge rotating at $\omega$ rad/s, a ram having a mass $m_m$ at a radius r is subjected to a centrifugal force of $m_m r \omega^2$. During the movement along the guide from $r_1$ to $r_2$, the model ram gains a kinetic energy increment $m_m \omega^2 (r_2^2 - r_1^2)/2$, which should equal to the kinetic energy of the ram having prototype velocity, $v_p$, at the moment of ram blow, that is $m_m n g H_p/n$. Thus the ram release radius, $r_1$, is expressed by

$$r_1 = \sqrt{r_2^2 - (2g/\omega^2)/H_p} \qquad (1)$$

In the present model tests, the radius $r_2$ was taken at the top of the penetration rod. The increase of $r_2$ in Eq.(1) due to ram penetration was neglected, and $r_1$ was kept constant throughout the test.

## ON RAM PENETRATION

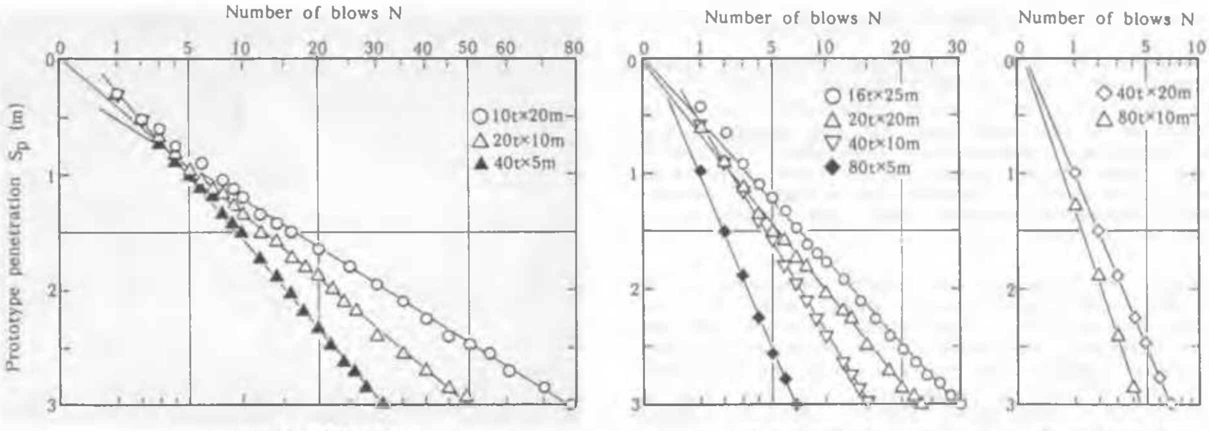
Since preliminary "modeling of models" test series proved the validity of the similarity rule for the centrifuge test of dynamic consolidation (Mikasa et al 1988), all test results obtained in 75g in this paper will be presented in prototype scale using the similarity rule:

length : $L_p = 75\,L_m$, area : $A_p = 75^2 A_m$
volume : $V_p = 75^3 V_m$, mass : $m_p = 75^3 m_m$
potential energy : $E_p = 75^3 E_m$

where subscript p and m designate prototype and model, respectively.

Table I is the list of the present test series conducted under the following conditions: nominal relative density of the ground is 75%; centrifugal acceleration is 75g; prototype ram diameter, $D_p$, is 2.25m, ram base area, $A_p$, is 4m² and final ram penetration, $S_p$, is 3m.

Figs.3(1), (2) and (3) show ram penetration, $S_p$, against the number of blows, N (in square root scale), for the three cases where prototype kinetic energies per one blow, $E_I$,



(1) $E_1$=200 tfm (2) $E_1$=400 tfm (3) $E_1$=800 tfm

Fig.3 $\sqrt{N}$-$S_p$ Relations for Different One Blow Energy, $E_1$

are 200, 400 and 800tfm, respectively. All $\sqrt{N}$-$S_p$ relations are linear as conformed to many field measurements. From these figures, we find that a combination of larger ram mass and smaller drop height under the same kinetic energy of one blow requires less number of blows and smaller total energy to produce a certain penetration.

Fig.4 shows the total energy required for $S_p$=3m, $E_t = m_p g H_p N_{p3}$, plotted against ram drop height for different ram mass. Since $E_t$ does not change appreciably for a certain ram mass, the number of blow to get $S_p$=3m changes almost inversely proportional to ram drop height. The total energy to get $S_p$=3m, $E_t$, is much influenced by the ram mass.

Fig.5 shows three sets of $\sqrt{N}$-$S_p$ relations, each set having the same ram momentum at blow, most of which appear in Figs.3(1)-(3), but corrected taking the intersection of $\sqrt{N}$-$S_p$ straight lines with the $S_p$=0 line as N=0. Corrected N values for $S_p$=3m, $N'_{p3}$, are presented in Table I. The increase of ram momentum two times decreases the number of blows to get $S_p$=3m one-fourth. Therefore the value $m_p v_p \cdot \sqrt{N}$ is constant irrespective of ram mass and drop height. The ram momentum for the unit area of ram base multiplied by square root of number of blows for $S_p$=3m, $(m_p v_p/A_p)\cdot\sqrt{N_{p3}}$, presented in Table I, shows the same value of 485 $tm/s/m^2$ for all the tests with a few exceptions. These results, together with the linear $\sqrt{N}$-$S_p$ relation, bring forth the following relation:

$$S_p = \alpha\cdot(m_p v_p/A_p)\cdot\sqrt{N}$$
$$= \alpha\cdot\sqrt{2g}\,(m_p/A_p)\cdot\sqrt{H_p N} \qquad (2)$$

where α is a constant depending on the ground conditions. In the present tests, α is determined as follows:

$$3\ [m] = \alpha\cdot 485\ [tm/s/m^2]$$
$$\therefore\ \alpha = 6.2\cdot 10^{-3}\ [(m^2/t)s] \qquad (3)$$

Eq.(2) shows that ram mass is the predominant factor in ram penetration followed by both drop height and number of blows.

## GROUND DEFORMATION

Fig.6 shows a view of a tested model ground of $D_r$=75% under the conditions: centrifugal acceleration is 75g; $D_m$=3cm ($D_p$=2.25m); $m_m$=47.8g ($m_p$=20t); $H_m$=29.8cm ($H_p$=20m). The part of the ground that deformed appreciably by ram penetration is rather limited in a small spherical zone around the bottom of the tamping hole, about $4D_m$ in depth. This pattern of ground deformation was always ob-

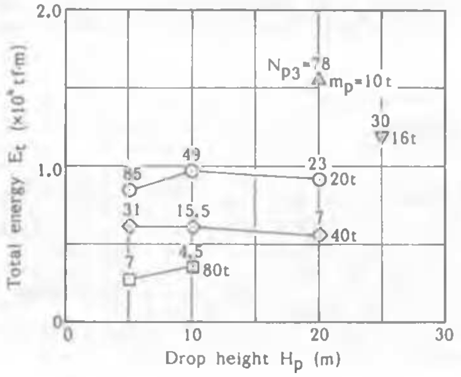


Fig.4 Relation of Total Energy and Drop Height for Different Ram Mass

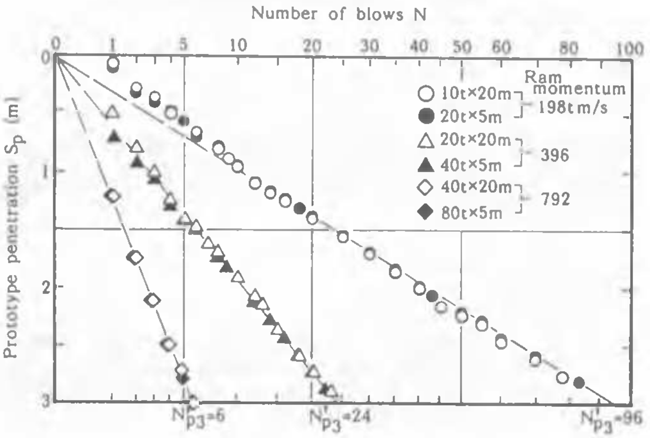


Fig.5 $\sqrt{N}$-$S_p$ Relations for Different Ram Momentum served irrespective of ram mass or drop height.

Fig.7 compares the ground surface settlement at $S_p$=3m before and after a test in which $m_p$=20t, $H_p$=20 m and $A_p$=4m² with that by a static penetration test using penetration rod of the same shape and area $A_p$=4m². The dynamic penetration generated a considerable settlement over the whole model ground which must have been produced by the shock or vibration due to tamping, whereas the static penetration generated much less settlement except near the penetration rod.

Fig.8 shows the plots of the volume reduction of the ground against the total tamping energy when the ram penetration reached 3m. The volume reduction was obtained by integrating the ground surface settlement including the volume of tamping hole and subtracting the settlement by selfweight consolidation before tamping (around 7.5cm in prototype scale). The figure indicates that the volume reduction depends on the tamping energy rather than on the ram momentum; no tendency is found that larger ram mass or larger ram momentum works effectively to compact the ground in spite of the clear effect of those factors on ram penetration. The factors governing the ground compaction besides the total compacting energy are difficult to be specified from Fig.8, and should be looked for in further studies.

## CONCLUSIONS

The test results lead to the following conclusions:
1) Ram penetration into the ground always shows linear relationship to the square root of number of ram blows.
2) The ram mass per unit area of ram base is the predominant factor on ram penetration into the ground. The number of blows vs. ram penetration relationship is determined by the ram momentum at blow.
3) Predominant factor on ground compaction is the applied total energy.
4) The part of the ground that compacted remarkably by ram penetration is rather limited in a small spherical zone around the bottom of the tamping hole, but an appreciable overall ground settlement was also observed, in contrast to the static penetration that caused settlement only around the penetration rod.

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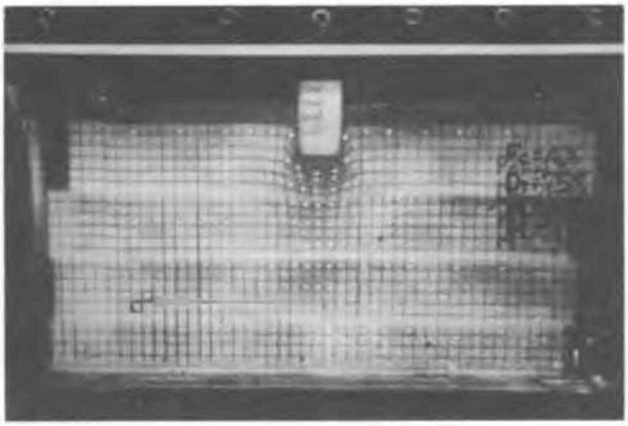
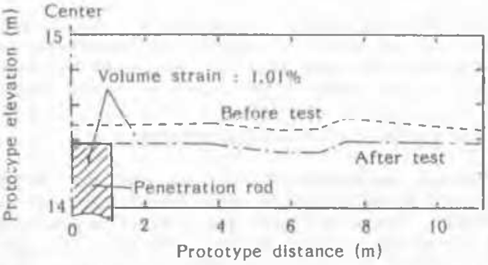
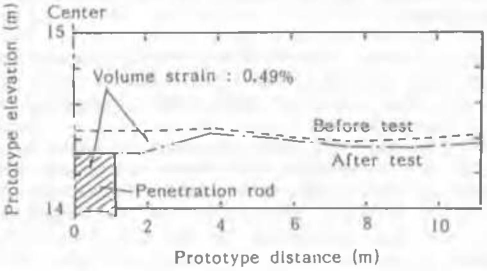


Fig.6 Ground Deformation



(1) Dynamic Compaction



(2) Static Penetration

Fig.7 Comparison of Ground Settlement

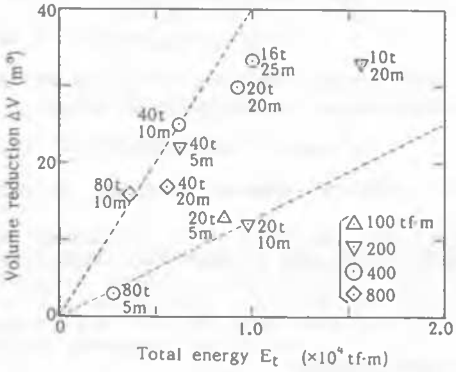


Fig.8 Relation of Total Energy and Volume Reduction of Ground