A newly developed 'Compacted Bulb Foundation' and its bearing characteristics

L'ampoule compact fondation récemment développé et les caractéristiques de sa capacité portant

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ABSTRACT: The heavy tamping produced a heavily compacted soil mass beneath the tamping point. This bulb shaped soil mass can be directly used as a spread foundation of middle size structures. A series of centrifuge model test of 'Compacted Bulb Foundation Method' was carried out to investigate the bearing capacity of the compacted bulb under various tamping conditions. Main conclusions are as follows: 1) bearing capacity and modulus of subgrade reaction of compacted bulb are twenty times or more and ten times larger than untamped fresh ground, respectively, 2) bearing capacity depends on the ram mass per unit base area, 3) a ram having larger base area relative to the loading area produces lager bearing capacity.

RÉSUMÉ: Une 'Méthode de fondation de bulbe compacté', récemment developpée et sescaracteristiques de capacité portante. Une série d'essais de modèles centrifugés de la 'Méthode de fondations de Bulbe Compacté' a été executée pour étudier la capacité portante d'un bulbe compacté sous plusieurs conditions. Les principales conclusions sont: 1) La capacité portante ultime et le coeficient de réaction horizontale ont été, respectivement, cent fois ou plus et dix fois plus grandes dans le bulbe compacté que dans un sol non pilonné. 2) Sa capacité portante a été dépendente de la masse du mouton par unite d'aire de base. 3) Un bulbe compacté a eu une capacité portante majeur lorsque pilonné par un mouton avec surface de base plus grande que la surface chargée.

1 INTRODUCTION

The authors have investigated the compaction mechanism of heavy tamping by centrifuge models and field tests. The heavy tamping produces a compacted soil mass beneath the tamping point. This bulb shaped soil mass compresses the surrounding soil and the size of the compacted area grows as shown in Figure 1 (Oshima and Takada 1997, 1998). If the ram blows are concentrated at this point, a heavily compacted bulb will be formed. This bulb can be used as a spread foundation. So the authors intended to investigate the bearing characteristics of this 'Compacted Bulb Foundation' (Oshima et al. 1997) under various conditions such as ram mass, ram base area, number of blows, loading plate area and soil density.

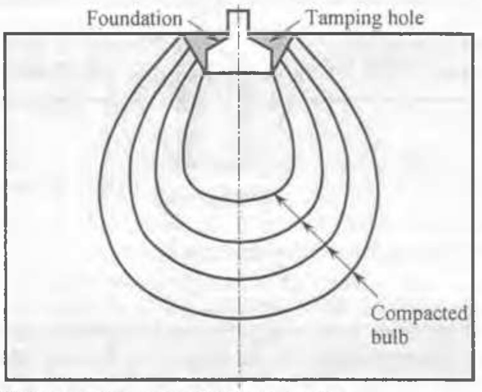

Figure 1. Illustration of compacted bulb foundation.

2 CENTRIFUGE MODELS AND TEST PROCEDURES

The model ground is square column of 30 cm in length, 29 cm in width and 24 cm in height as shown in Figure 2. This ground corresponds to the prototype ground of 30 m in length, 29 m in width and 24 m in height in the centrifugal acceleration field of 100 *g*. The nominal rotor radius of the centrifuge is 2.56 m.

The model material is a sandy soil passing the 2 mm sieve containing fine fractions of 6.4 % with the uniformity coefficient of 3.4. The maximum and minimum dry densities are 1.73 and 1.41 t/m^3, respectively. The model ground was compacted to the initial relative density of 35 % with an initial water content of 4 %. This water content is the maximum value at which the pore water does not migrate downward under 100 *g*. The model grounds with relative density of 50, 65 and 80 % were also employed to obtain the relationships between initial density and bearing capacity of untampted fresh ground. The model ground was allowed to settle under its selfweight at 100 *g* for 1 hour.

Figure 3 shows the ram operating device. This device drops the model ram to the center of the ground surface and lifts it automatically to predetermined height by means of an electric motor. Ram blow period is around one minute. The model rams are cylindrical wooden columns having a diameter of 2.26 cm and masses of 10, 20, 40 and 80 g. These model rams correspond

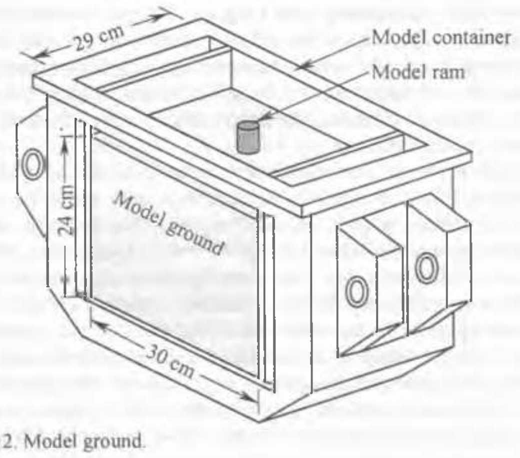

Figure 2. Model ground.

to prototype ram masses, m, of 10, 20, 40 and 80 t with a ram base area, A_R, of 4 m^2. The ram mass of 40 t having a base area of 8 m^2 was also employed. The prototype drop height, H, is 20 m in all cases.

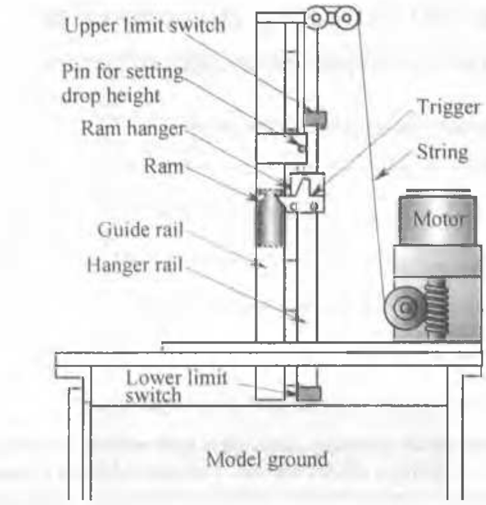

Figure 3. Ram operation device.

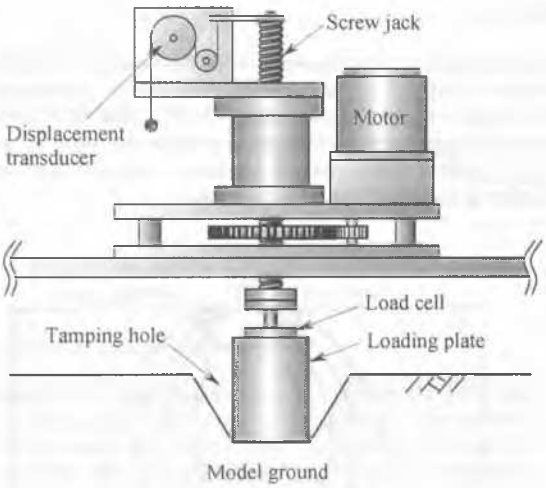

Figure 4. Loading device for bearing capacity.

After tamping, the bearing test was made at the center of the tamping hole produced by tamping. The loading device is a screw jack type as shown in Figure 4. The loading plates are cylindrical columns. Their prototype base area, A_S, are 1, 2, 4 and 8 m^2. The loading rate is 2 mm/min. The preliminary tests showed that the loading rate ranging 1 to 4 mm/min did not change the test results. Although the stress in the ground induced by tamping is released when the centrifuge stops after tamping to replace the ram operating device to the loading device, this stress release did not substantially affect the bearing characteristics (Takada et al. 1998).

Table 1 shows test conditions described in the prototype scales in a 1 *g* gravity field. Ram drop height, *H*, in the centrifuge is rectified so that the ram has the same velocity when it tamps the ground as in the 1 *g* gravity field (Mikasa et al. 1989).

As a preliminary test, the bearing tests of untamped fresh ground were made for different relative densities and for different loading plate areas. After each 20 ram drop was applied to the ground, the tamping hole was back-filled with the same soil as the model ground; this procedure is usually employed in the actual field work to avoid the difficulty of lifting the ram in the deep tamping hole. This set of ram blows and back-filling was called a 'pass' procedure. As a main series of tests simulating the pass procedure was carried out for different number of passes, N_P, and different ram masses, *m*. A series of continuous tamping without the pass procedure was also carried out for different numbers of blows, N_B. In addition, a case of different ram base areas was conducted.

Table 1. Test conditions.

Object	D_r (%)	m A_R H	N_B	N_P	A_S
Ground Density	35 50 65 80	Untamped ground			4m²
Loading plate base area	35	Untamped ground			1m² 2 4 8
Number of passes	35	20t, 4m², 20m	20	1 2 3 4 5	4m²
Number of blows	35	20t, 4m², 20m	40 60 80	1	4m²
Ram mass and base area	35	10t 20t 40t 80t 4m², 20m	20	4	1m² 2 4
		40t, 8m², 20m	20	4	1m² 2 4 8

m : ram mass, A_R : ram base area, H : ram drop height, N_B : number of blows, N_P : number of passes, A_S : loading plate base area

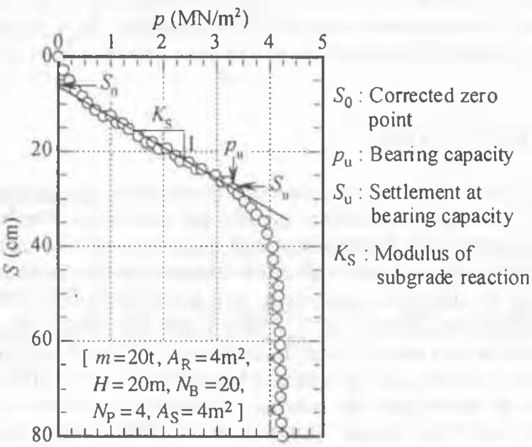

Figure 5. Interpretation of test result.

3 TEST RESULTS AND DICUSSIONS

3.1 *Interpretation of test result*

Figure 5 shows an example of bearing test result presenting a relation between load intensity and settlement, $p - S$. Although the early stage of $p - S$ relation was a straight line, the initial stage was concave. This was considered to be caused by soft soil deposition collapsed from the wall of tamping hole during tamping. Thus, the $p - S$ relation was corrected on the assumption that $p - S$ relation in the early stage is a straight line; the corrected zero point is S_0 as shown in Figure 5. The deviation point of the $p - S$ curve from the straight line is defined as a bearing capacity, p_u, and corresponding settlement (corrected), S_u. The slope of this straight line is defined as a modulus of subgrade reaction, K_S ($= p_u / S_u$).

3.2 *Untamped ground*

Figure 6 shows $p - S$ relations of untamped fresh ground of relative densities of D_r = 35, 50, 65 and 80 %. In the figure K_S values are presented, and p_u points are shown by arrows ↓. Both K_S and p_u values increase remarkably as the relative density increases. Figure 7 shows $p - S$ relations of untamped ground of D_r = 35 % for A_S = 1, 2, 4 and 8 m^2. Four $p - S$ curves show the same $p - S$ relation irrespective of the loading plate area under

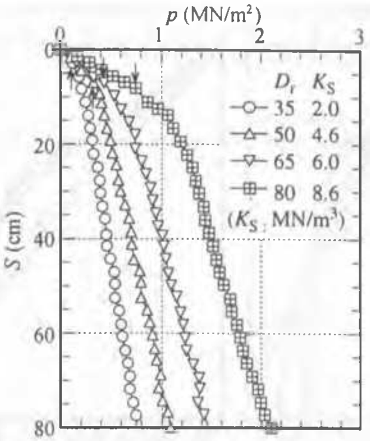

Figure 6. Effect of ground density on $p - S$ relation of untamped ground ($A_S = 4$ m^2).

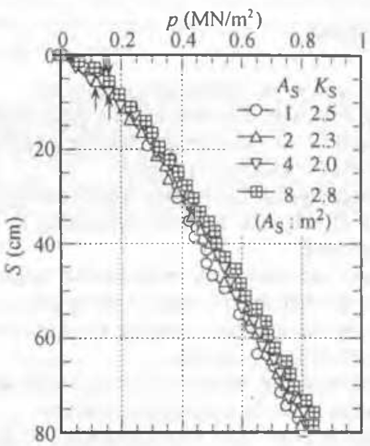

Figure 7. Effect of loading area on $p - S$ relation of untamped ground ($D_r = 35$ %).

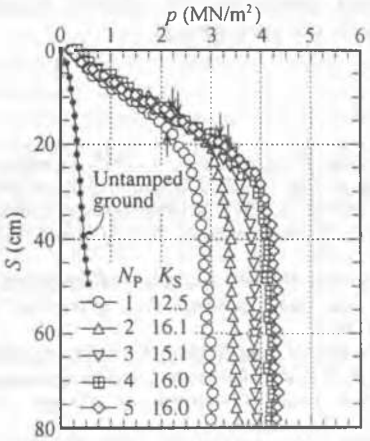

Figure 8. Effect of number of passes on $p - S$ relation ($m = 20$ t, $A_R = 4$ m^2, $A_S = 4$ m^2).

this axisymmetrical condition, although it is derived theoretically that the larger loading plate area generates the larger bearing capacity.

3.3 *Pass tamping and continuous tamping*

Figure 8 shows $p - S$ relations of the ground tamped by means of pass procedure of $N_P = 1$ to 5 ($m = 20$ t, $A_R = 4$ m^2 and $N_B = 20$). In this figure, $p - S$ relation of the untamped fresh ground of $D_r = 35$ % which appears in Figure 6 is presented for comparison. The bearing capacity, p_u, of tamped ground increases drastically over 20 times than that of the untamped fresh ground and the modulus of subgrade reaction, K_S, also increases 10 times. The

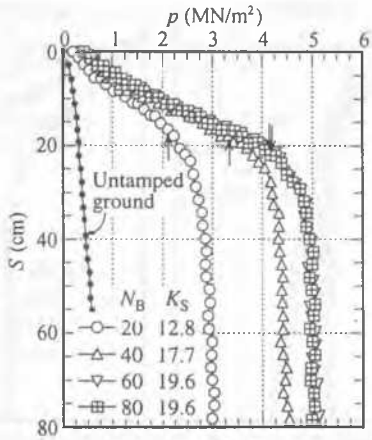

Figure 9. Effect of number of blows on $p - S$ relation ($m = 20$ t, $A_R = 4$ m^2, $A_S = 4$ m^2).

K_S value is even larger than $K_S = 8.6$ MN/m^3 of untamped ground of $D_r = 80$ % as shown in Figure 6. The p_u value increases with the increase of N_P, but this increase almost terminates at $N_P = 5$. The increase of K_S values with the increase of N_P is rather small.

Figure 9 shows $p - S$ relations of the ground continuously tamped to $N_B = 20$, 40, 60 and 80. The case $N_B = 20$ is identical to the case $N_P = 1$ in Figure 8. Continuous tamping procedure produces larger bearing capacity than the pass tamping procedure when compared at the same total ram tamping ($N_B = 20 \cdot N_P$). This is because in the continuous tamping procedure the bottom of the tamping hole is much compacted than that in the pass tamping procedure where the tamping hole is often back-filled with new soil, moreover the continuous tamping produces deeper tamping hole, which also contributes to the larger bearing capacity due to larger depth of embedment.

3.4 *Loading plate area*

Figure 10 (1) to 10 (4) show $p - S$ relations for loading plate of $A_S = 1$, 2 and 4 m^2 on the grounds tamped by rams of $m = 10$, 20, 40 and 80 t with the same base area of $A_R = 4$ m^2.

The $p - S$ relations of the untamped fresh ground are almost the same irrespective of the loading plate area as shown in Figure 7, while the $p - S$ relations of the tamped ground are dependent on the loading plate area.

In the cases of $m = 10$ and 20 t in Figures 10 (1) and 10 (2), the $p - S$ relations show a general failure mode, and the smaller A_S generates the larger K_S value. In the case of $m = 40$ t in Figures 10 (3), the $p - S$ relations of $A_S = 1$ and 2 m^2 show a local failure mode resulting in a smaller K_S value. The case of $m = 80$ t in Figure 10 (4) generates a local failure mode for all loading plate areas, although the ultimate bearing capacities are large.

This failure mode change as the ram mass increases may be caused by the back-fill volume; the larger ram mass produces the deeper ram penetration resulted in the larger back-fill volume in the pass procedure. The larger back-fill volume causes the back-fill and surrounding soil of the tamping hole less compacted than the case of the smaller ram mass.

In Figures 11, the $p - S$ relations of the ground tamped by the ram having the same mass as and the ram base area twice as large as that in Figure 10 (3). All the $p - S$ relations show a general failure mode, and the lager K_S values than those in Figure 10 (3) are produced. This indicates that the larger ram base area produces the larger K_S value when the ram mass is the same.

3.5 *Modulus of subgrade reaction*

Figures 12 shows relations between the modulus of subgrade reaction, K_S, and the ratio of loading plate area to ram base area, A_S / A_R. In the case where A_S / A_R is 0.25, K_S values occupy a

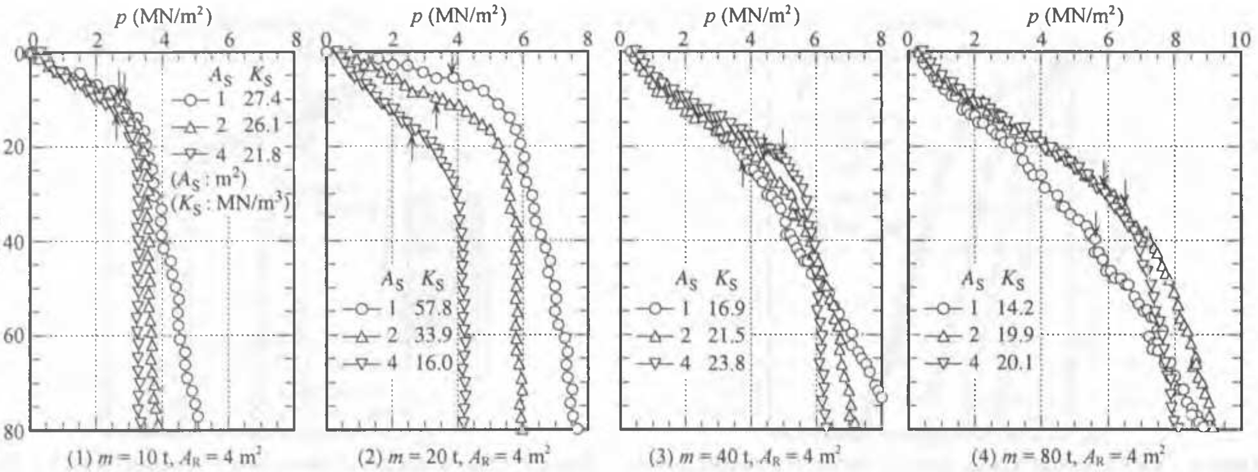

Figure 10. Effect of loading area on $p - S$ relation for different compaction efforts.

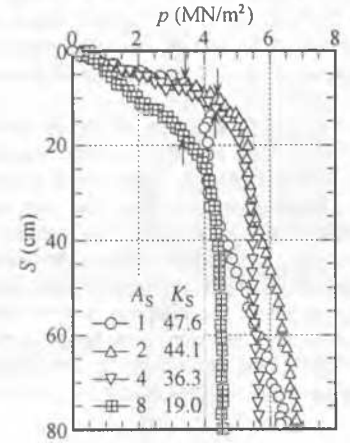

Figure 11. Effect of loading area on $p - S$ relation for $m = 40$ t, $A_R = 8$ m^2.

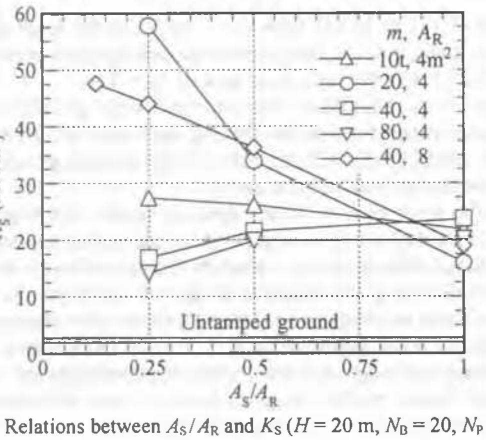

Figure 12. Relations between A_S/A_R and K_S ($H = 20$ m, $N_B = 20$, $N_P = 4$).

wide range; K_S value for m = 20 t is the largest, K_S value for m = 80 t is the smallest. These values converge to around K_S =20 MN/m^3 as the ratio A_S / A_R increases to unity. However, the ram with a larger mass produces slightly larger K_S value where A_S = A_R. These values are very large comparing to those of the untamped fresh ground, which are described by a range of shaded bar determined in Figure 7. Figures 12 suggests that the large ram mass does not always produce high K_S value; there exist the optimum tamping conditions. Figures 12 also presents the relation between K_S and A_S / A_R determined from the test cases where m = 40 t and A_R = 8 m^2 in Figures 11. This relation is similar to the case of m = 20 t and A_R = 4 m^2 except one point. This suggests that the same ram mass per unit base area may produce the same K_S value.

4 CONCLUSIONS

The test results lead to the following conclusions:

1) Loading tests with different loading plate areas on untamped fresh ground in the axisynmetry loading condition show almost the same load – settlement relation.

2) Ram tamped ground generates large bearing capacity and large modulus of subgrade reaction comparing to those of untamped fresh ground.

3) The larger ram base area produces the larger modulus of subgrade reaction when the ram mass is the same.

4) There exist the optimum tamping conditions to obtain the large modulus of subgrade reaction.

5) It is suggested that the same ram mass per unit base area produces the same modulus of subgrade reaction.

The authors believe that this compacted bulb foundation method produces very large bearing capacity under the very simple and economical construction procedures with little excavation, moreover, compaction also prevents liquefaction when constructed on the soft sandy ground.

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