MECHANICAL PROPERTIES OF SAND SUBJECTED TO DYNAMIC LOAD BY SHALLOW FOOTING

by

Jinichi Takeda* and Hiroyuki Tachikawa**

Synopsis

This paper deals with the effects of loading rate on the bearing capacity, modulus of subgrade reaction of sand etc. subjected to vertical and diagonal load of shallow footing. The experiments were carried out on several kinds of sand, dense and loose, air-dried and saturated, at the loading rate ranging from about 10^{-4} kg per sq cm per sec to about 10^{2} kg per sq cm per sec. The footing used was a cylinder with the diameter of 15 cm, made of steel. Load applied and settlement of footing were measured electrically.

Introduction

The investigation on the dynamic properties of soil lying under buildings subjected to seismic oscilation is nowadays one of the most important problems in earthquake engineering. There are many investigations, on this subject, based on the experiments of unconfined compression or triaxial compression by single transient load or vibratory load. They were performed by Prof. Casagrande,[1] Prof. Seed[2] and many other authorities. Besides these investigations, the important results on the bearing capacity of soil during vibration are obtained by Prof. Mogami,[3] Prof. Okamoto[4] and other authorities,[5] however, there are still many problems left to be solved in this scope.

The authors, three years ago, intended to study the strength behavior of sand subjected to nonvibratory dynamic load by shallow footing, and carried out a series of experiments for this investigation, using sand box and footing model to which the load was applied vertically and diagonally. In the experiments conducted at various loading rates on several kinds of sand, load-settlement curves, bearing capacities, moduli of subgrade reaction etc. were obtained in relation to the sinking rate of footing. As to the consideration of earthquake, this paper describes the results of experiments conducted at the loading rate lees than about 10^{2} kg per sq cm per sec, though the experiments are carried out to the rate of about 10^{4} kg per sq cm per sec.

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Method of Test

In order to apply the loads, the solid lever arm connected to dynamic testing machine, which is designed for the high speed tests of structures and building materials and is driven by high pressure oil, was used in the tests. The apparatus for this investigation is shown in Fig. 1. The sand box sued was 1.5 m square and 1.35 m deep, and was observantly filled with sand to the height of 1.2 m. On the center of the sand surface a cylindrical footing model of 15 cm diameter and of 20 cm height, made of steel, was vertically placed and was connected to loading rod which served as a dynamometer too through wire strain gages bonded to stem of it. The footing model, loading rod and accessaries of them which are ready for the test have initial load of 0.366 kg per sq cm in total on the underlying sand through the bottom of the footing model. So they were kept on sand for about 30 minutes before each test. A steel girder, strongly built, was fastened to the upper frame of sand box. The loading rod in regulated direction and four potentiometers, two sets of pair, was installed on the steel girder for measuring of settlement of footing. The potentiometers were also connected to the footing at the ends.

The data of load and settlement of footing obtained in the tests were photographed with a polaroid camera on a six elements cathode ray oscilloseope.

The study includes two series of tests, one is the test which was performed by applying vertical load and the other diagonal load which incline at 30° to the vertical. And each series is devided into several kinds of tests by density and water content of sand used. They are shown in Table 1.

The dense air-dried sand, in the Table, was filled in 15 cm layers and was vibrated by a 0.5 hp concrete vibrator after each layer had been placed. Though the loose air-dried sand was also filled in 15 cm layers, it was dealt with the definite number of times of blows with the weight of 12.5 kg instead of the vibration in dense air-dried sand.

In the case of the saturated sand, both dense and loose, only the upper layer of it was made by the same way as in the air-dried sand and water was fully poured in the box before every tests, then the water floating above the surface of sand was drained off for preparing the tests.

The sand used is a uniform Sagami River sand, physical properties of which are shown in Table II. The relative density of sand in the Table, is the average values measured before each test carried out on the prepared sand.

In the tests, the loads were applied at the loading rates of three stages ranging from those of standard tests of bearing capacity of soil recommended by A.I.J. to about 10^2 kg per sq cm per sec, except the standard tests in saturated loose sand and in the tests of Series 2.

The rate of loading and the rate of sinking of footing were taken by mean values of them within the settlement of footing of 2 mm.

Results of Tests Loaded Vertically

The applying rates of loads, the sinking rates of footing, load-settlement curves and bearing capcites of sand were directly obtained from the records of tests. And from the load-settlement curve, the moduli of subgrade reaction $k_{s0.5}$ and k_s which were defined as the slope of tangent at the point corresponding to load of 0.5 kg per sq cm and the slope of a line drawn from the initial point through the point represented by the load of one half of bearing capacity on the load-settlement curve respectively, were measured. The bearing capacity, in this paper, was assumed the load corresponding to the settlement of 20 mm tentatively, unless the load-settlement curve had an apparent apex which was usually defined as bearing capacity.

As the settlement of footing increased, in the tests of dense air-dried sand conducted at the various loading rates the swelling that was accompanied by the failure of sand was observed in sand surrounding the footing (Fig. 2). Though such swelling of sand was not observed in the other tests, the remarkable decrease of pore water in sand around the footing, which was defined as dilatancy was observed on saturated sand, especially on dense saturated sand after the test (Fig. 3).

Load-Settlement Curves.

In each kind of the tests conducted at various loading rates, the load-settlement curves had the tendency in which the load corresponding to the given settlement of footing increased according to the increment of loading rate (or sinking rate of footing). Fig. 4 is the examples of load-settlement curves drawn in relation to the sinking rate of footing. The loose saturated sand, as shown in Fig. 5, took the behavior of yield at the initial stage of the tests in which the maximum loads made no great difference in all tests of this kind performed at the various loading rates.

In the tests with the dense saturated sand conducted at the highest loading rates, the load-settlement curves indicated a considerable difference from that in the other tests, which might be due to the water content.

Bearing Capacity.

The relations of all tests between the bearing capacity and the sinking rate of footing are shown in Fig.6. The bearing capacities of dense sand, both air-dried and saturated, increased with the increment of sinking rate of footing, exceedingly in the latter. On the other hand, the loose sand, in spite of the water content, did not indicate the distinct increase of bearing capacity in the range of sinking rate of footing conducted in the tests. Here, the bearing capacity of loose saturated sand, however, was measured at the yield point in initial stage of the tests.

Moduli of Subgrade Reaction.

The moduli of subgrade reaction $k_{s0.5}$ and k_s obtained from the tests are drawn in Fig. 7 and 8 respectively in relation to the sinking rate of footing. The ratios of them to the average values obtained from the tests conducted at the sinking rates of footing in the standard tests of bearing capacity of soil recommended by A.I.J. are indicated in Fig. 9 and 10 respectively.

The moduli of subgrade reaction $k_{s0.5}$ and k_s took considerable larger values at the higher sinking rate than at the lower sinking rate, and the ratios to the average values of them in standard tests were approximately expressed by a linear relation of logarithms of sinking rates of footing. In the case of $k_{s0.5}$, the ratio was almost independent of the kinds of the tests, and gave the increase of nearly 35 per cent for every increment of ten times in sinking rate of footing.

Relation Between the Loading Rate and Sinking Rate of Footing.

The effects of speed of applying load on bearing capacity, moduli of subgrade reaction of sand etc. were observed on the basis of sinking rates of footing, as shown in previous figures, and the same tendencies of them were obtained on the basis of loading rates too. The loading rates corresponding to the sinking rates of footing in the tests are approximately obtained from the diagram in Fig.11.

In addition to such use, this figure allows to draw an approximate relation between the loading rates $\dot{\sigma}$ and sinking rates of footing $\dot{u}$ which is represented by;

$$\dot{\sigma} = a(\dot{u})^b \qquad \text{..............(1)}$$

where a and b are constant in each kind of the tests. The ratio $\dot{\sigma}/\dot{u}$ is just identical with the modulus of subgrade reaction in initial stage of the test and the relation almost supports the previous results that the modulus of subgrade reaction in the tests loaded dynamically took a value increasing proportionately with the logarithm of sinking rate of footing (or loading rate).

Results of Tests Loaded Diagonally

Since this study were conducted as a preliminary tests of sand subjected to inclined footing load, only the load inclined at 30° to the vertical and applied to the center of footing was dealt with. Analysis of test results were carried out with the same way as the tests loaded vertically, and as the settlement of footing the vertical component of displacement was measured in the same direction as of the applied loads.

In all tests, the maximum load was obesrved at the settlement of footing less than 10 mm in which the footing still kept the base almost horizontal. In most loose sand, two peaks of load were found untill the footing was turned over during the tests, as shown in Fig. 12.

Bearing capacity obtained in dynamic tests did not indicate a distinct difference from the results of static tests (Fig. 6) and it was considerably smaller than the values obtained in the tests loaded vertically.

Modulus of subgrade reaction $k_{s0.5}$ was obtained from the tests, and is shown in Fig. 7. It was observed to be nearly independent of the sinking rate of footing.

Conclusion

From the results of these tests, the following conclusions are drawn:

On the vertical loading tests:

(1) The bearing capacities, which have a meaning here of the yield value or the load at the settlement of footing of 20 mm, increased considerably with the sinking rate of footing (or loading rate) in dense sand, both air-dried and saturated. On the contrary, they were observed to be almost independent of the sinking rate of footing in loose sand.

(2, The moduli of subgrade reaction $k_{s0.5}$ and k_s were found to increase nearly proportionately with the logarithm of sinking rates of footing in all kinds of tests.

(3) The relation between the loading rate and the sinking rate of footing in these tests, was approximately represented by equation (1).

On the diagonal loading tests;

The bearing capacities were observed to be nearly independent of the sinking rate of footing and to be considerably smaller than that of vertical loading tests in spite of the dense or the loose.

Acknowlodgment

The authors wish to express the deepest apreciation to Prof. Katsuta for valuable advice and encouragement. Grateful acknowledgment is also made to Mr. Yaguchi and Mr. Takanezawa for the continued assistances in this study.

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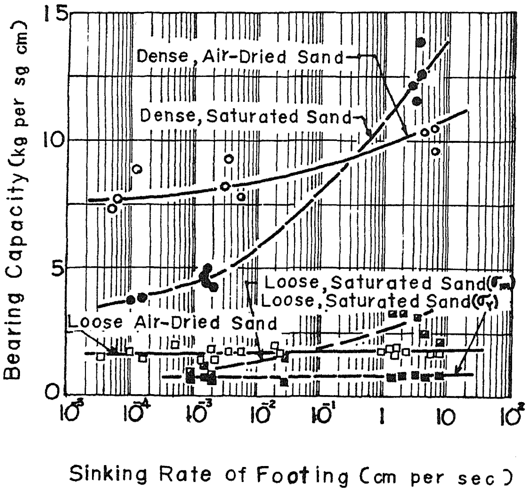


Symbols		
Dense, Air-Dried Sand		○ ○
Dense, Saturated Sand		● ●
Loose, Air-Dried Sand		□
Dense, Saturated Sand	(σ_m)	▨
	(σ_Y)	■

σ_m = Footing load at the settlement of 20 mm.

σ_Y = Footing load at initial yield point.

Fig. 1. Effect of Sinking Rate of Footing on Bearing Capacity of Sand.

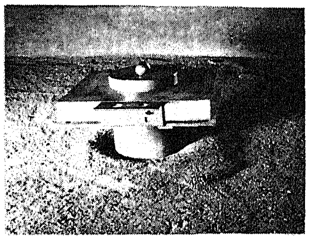


Fig. 2. Failure of Dense, Air-Dried Sand. (Sinking rate of footing = 0.63×10^{-4} $^{cm}/_{sec}$)

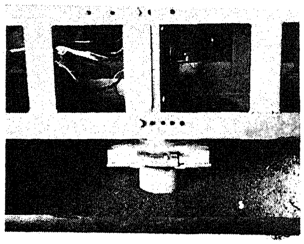
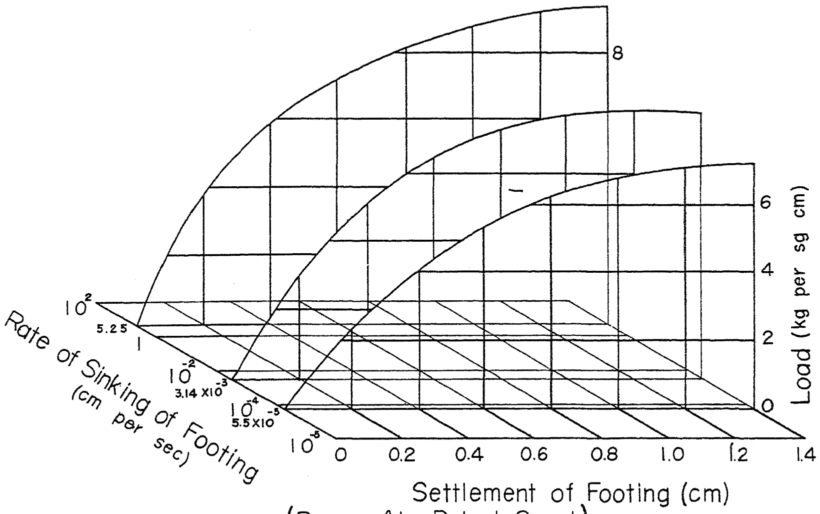
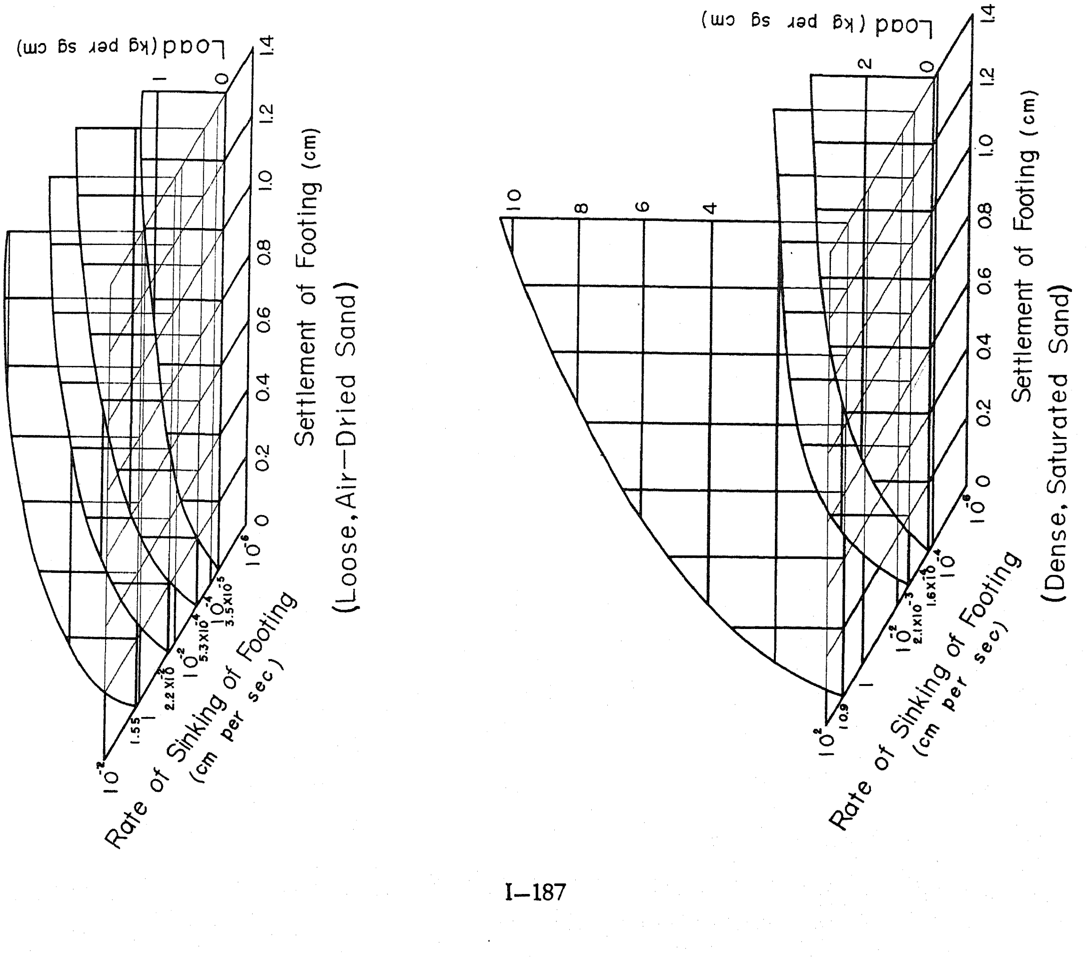


Fig. 3. Surface of Dense, Saturated Sand After Test. (Sinking rate of footing = 1.65×10^{-3} $^{cm}/_{sec}$)



(Dense, Air-Dried Sand)

Fig. 4. Examples of Load-Settlement Curve at Various Sinking Rates.



(Loose, Air-Dried Sand)

(Dense, Saturated Sand)

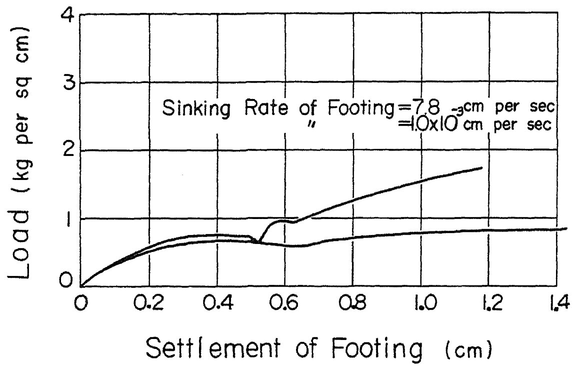
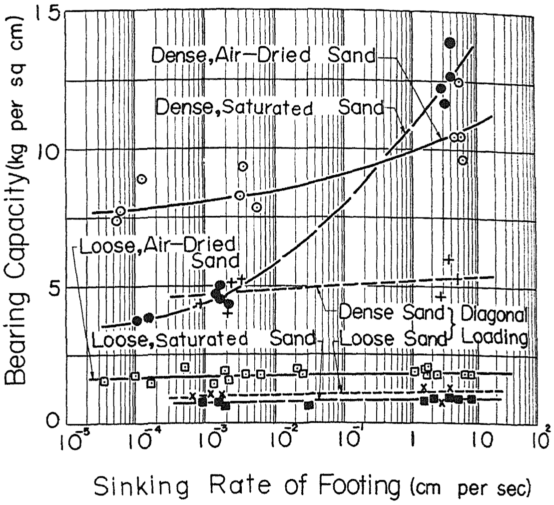


Fig. 5. Examples of Load-Settlement Curve: Loose, Saturated Sand.



Symbols :		Test in Vertical Loading	Test in Diagonal Loading
Dense Sand	Air-Dried Sand	○	+
	Submerged Sand	●	
Loose Sand	Air-Dried Sand	▫	x
	Submerged Sand	▪	

Fig. 6. Effect of Sinking Rate of Footing on Bearing Capacity of Sand.

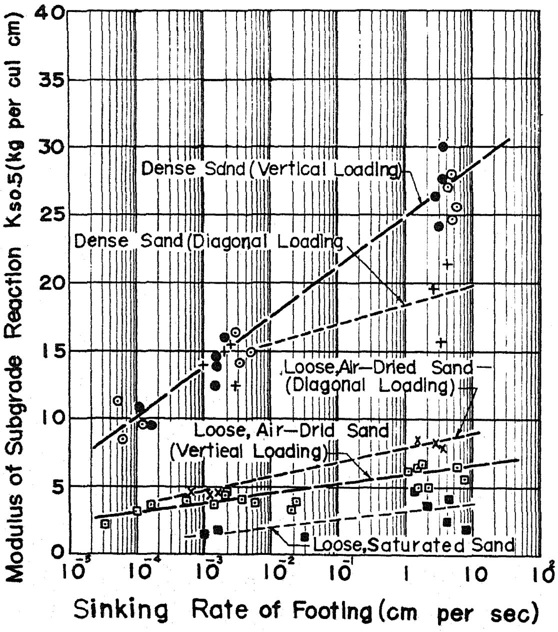


Fig. 7. Effect of Sinking Rate of Footing on Modulus of Subgrade Reaction $k_{s0.5}$.

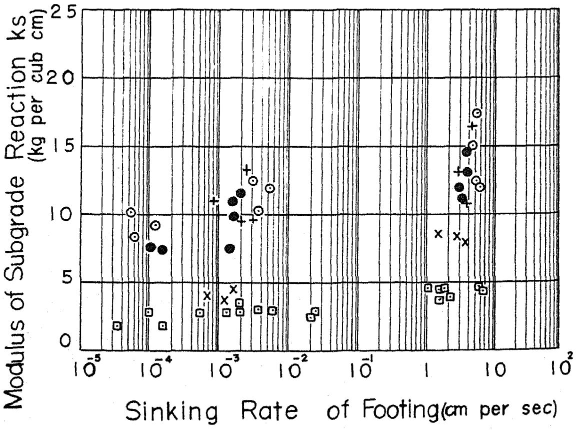


Fig. 8. Effect of Sinking Rate of Footing on Modulus of Subgrade Reaction k_S .

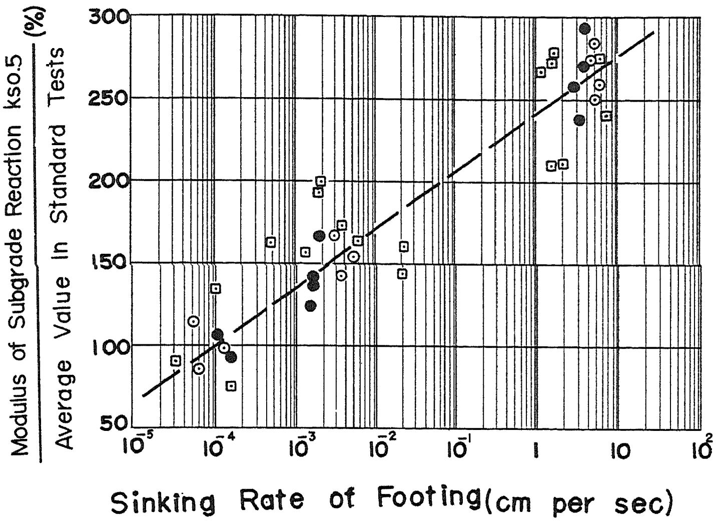


Fig. 9. Effect of Sinking Rate of Footing on Ratio of $k_{s0.5}$ to Average Value in Standard Test.

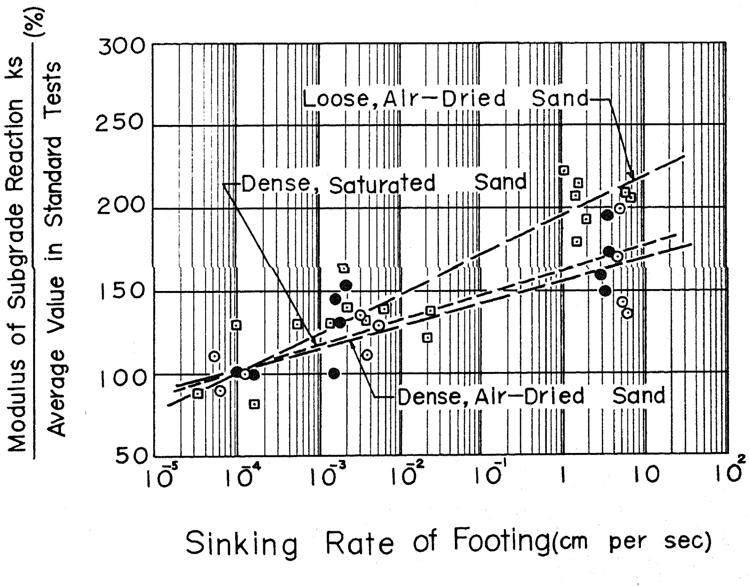


Fig. 10. Effect of Sinking Rate of Footing on Ratio of k_s to Average Value in Standard Test.

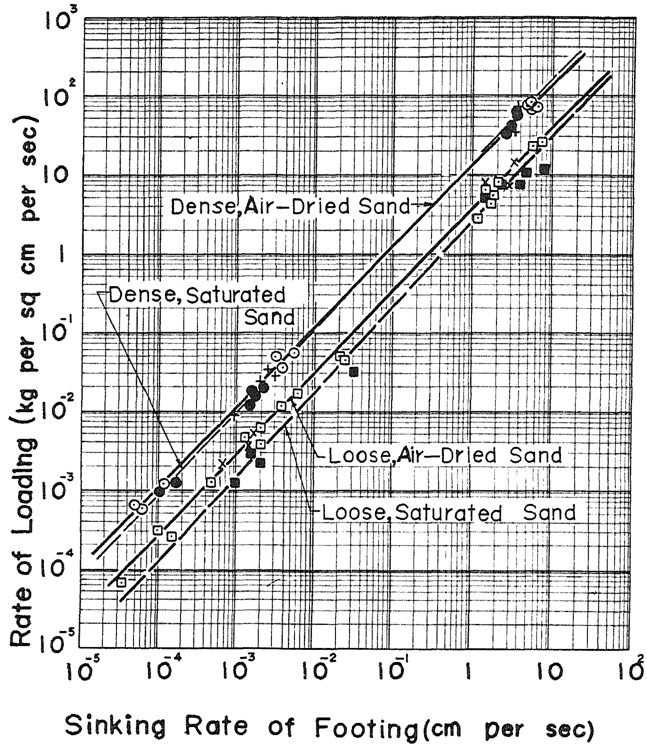


Fig. 11. Relation Between Loading Rate and Sinking Rate of Footing.

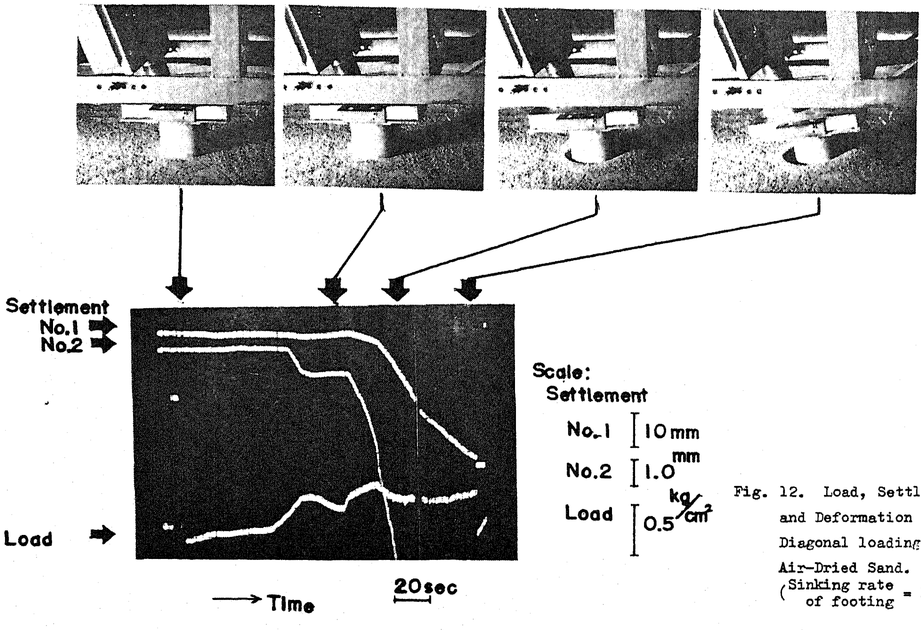


Fig. 12. Load, Settlement Record and Deformation of Sand in Diagonal loading Test of Loose, Air-Dried Sand.
(Sinking rate of footing = 1.65 x 10^{-3} cm/sec)

TABLE I

PROGRAM OF TEST

Test Series	Sand Used	Load Applied
1——A	Dense, Air-Dried Sand Loose, Air-Dried Sand	Vertical Load
1——B	Dense, Saturated Sand Loose, Saturated Sand	
2	Dense, Air-Dried Sand Loose, Air-Dried Sand	Diagonal (Oblique) Load

TABLE II

PHYSICAL PROPERTIES OF SAND USED

Coefficient of Uniformity		3.78
Specific Gravity		2.59
Water Content of Air-Dried Sand		1.95
Void Ratio	Dense, Air-Dried Sand	0.54
	Loose, Air-Dried Sand	0.62
	Dense, Saturated Sand	0.58
	Loose, Saturated Sand	0.63
Relative Density	Dense, Air-Dried Sand	77%
	Loose, Air-Dried Sand	53%
	Dense, Saturated Sand	68%
	Loose, Saturated Sand	50%

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BY J. TAKEDA AND H. TACHIKAWA

QUESTION BY: J.A. DEAKER - NEW ZEALAND

1. Work at the University of Canterbury has indicated that the results of small scale static loading tests on sands are not compatible with the results of large scale tests. A comparison of the results in this paper with tests on footings up to 30 cm in diameter would be valuable.

2. The smooth curves of the load settlement graphs even for the case of slow rate of loading seem surprising as results of static tests invariably show a distinct failure position regardless of whether the type of failure is a general shear failure (slip circle) or local shear failure. Would the authors suggest that the type of failure for dynamic loads is tending to be different from these two types envisaged by Terzaghi and Meyeroff and others? A comparison of the results with those theories would be helpful.

COMMENT BY: R.F. SCOTT - U.S.A.

Changes in bearing capacity at various loading rates were caused by pore pressures generated, and are therefore functions of relative density, permeability of sand and pore fluid. At high rates, and dense soil, cavitation probably occurs, giving an upper limit to the bearing capacity.

AUTHORS' REPLY: 1. Bearing capacity of saturated sand.

The bearing capacity of saturated sand subjected to a footing load was affected in some degree by the sinking rate of the footing. The cause of this could possibly be the changes in the rate of generation and dissipation of pore water pressure in sand grains, as indicated by Professor R.F. Scott and Dr. N.N. Ambraseys. However, besides these, there are other views that the frictional resistance of the sand grain matrix is dependent on the sinking rate of the footing, and that the frictional resistance of water being pushed away by the sinking footing has some effects on the bearing capacity of sand at a high sinking rate.

The former is considered as tho major cause of the rate effects on the bearing capacity of dry sand which was observed in detail in the tests of dense sand and to a lesser extent in the tests of loose sand at the experiments. From the former, it seems to be deduced directly, that the internal friction angle of the sand is dependent on the sinking rate of the footing. However, it is not always correct. Even if the internal friction angle of sand is independent of the rate as observed in triaxial tests conducted by Robert V. Whitman and Kent A. Healey (though there are some questions to apply to the results of experiments as our method is different from that of Whitman and Healey), the resisting force of the sand grain matrix during strain may still be dependent on the rate. This is because the tendency toward an occurrence of the displacement of sand grains decreases as the sinking rate of the footing increases and also the inertia force to move the sand grains becomes appreciable at a high sinking rate. In the case of loose air-dried sand, the bearing capacities did not indicate the distinct rate effect as mentioned above. It is considered that this fact was caused by the contraction accompanied with the strain of the sand grain matrix by load.

In order to explain the rate effects on the bearing capacities of saturated sand, the rate effects on the excess pore pressure, which is generating and dissipating in sand grains, must be considered beside the rate effect on the resisting force of the sand grain matrix. Though it may be doubtful that the rate effect on the resisting force of the sand grain matrix is the same even in the case of saturated sand as in the case of dry sand, this matter is not touched on here. According to the experiments of Whitman and Healy, however, the excess pore pressure in saturated loose sand was generated only at the initial stage of the tests (they observed initial yielding at that stage) and dissipated as soon as the strain increased. We also observed initial yielding in our tests of saturated loose sand at a high sinking rate. Considering this phenomenon and the similarity of stress-strain curves between the two experiments conducted on saturated loose sand, the developments of pore water pressure in our experiments are considered to be similar to those of the experiments of Whitman and Healy. Consequently, in order to explain the behaviour of the bearing capacities of saturated loose sand (bearing capacity means here the footing load at the settlement of 20 mm) which gave extraordinary values at the high sinking rate in our experiments (Fig. 1), the rate effect on the friction of water pushed away by the footing while sinking must be considered as another effect. This rate effect must be allowed for in considering the results of experiments on dense saturated sand also.

2. Application of test results to full scale footing.

The results of experiments carried out with the small footing will probably possess the scale effects in the strain of the sand grain matrix and in developments of pore water pressure etc., so that the application of them to the design of a full scale footing is not right. We wanted to conduct these experiments as the fundamental study of sand under dynamic load and took this method of test as another approach to solve such problems on a full scale footing.

3. The types of failure of sand.

The difference of failure types of sand was not observed clearly between high rate tests and slow rate tests using the sand of almost the same density. General shear failure in dense sand and local shear failure in loose sand took place. In the tests of saturated dense sand, the apparent pattern of general shear failure was not observed on the surface of the sand which dilated somewhat. However, the water which had been contained in the sand surrounding the footing was not found after the tests, and it was supposed that the general shear failure occurred in this case, too. In loose saturated sand, the initial yielding was observed in the beginning of the tests at the high sinking rate as described above, but the difference of failure type was not clearly observed between the tests conducted at high sinking rates and low sinking rates.

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DISCUSSION

BY N.N. AMBRASEYS

The bearing capacity of a circular model footing on saturated sand is controlled by the triaxial shear strength of the sand ($c' = o$, ϕ').

If the rate of loading of the footing is slow enough to allow the excess pore water pressures to dissipate, the sand will behave as a frictional material and its shear strength will be given by:

$$\tau = \sigma_n' \tan (\phi')$$

For a given size of footing and permeability of the sand, there will be a particular rate of loading above which only part of the excess pore water pressures will have time to dissipate. Above this rate, the time of loading will be so short that no drainage of the excess pore pressures can occur, and failure conditions will involve the undrained strength of the saturated sand which will show c_u, $\phi = o$. The shear strength of the saturated sand will be given by $\phi = o$ and

$$c_u = \frac{p' \sin (\phi')}{1 + (2A - 1)\sin(\phi')}$$

where, p' is the effective overburden pressure at a point and A is the pore pressure coefficient. For a strip footing the value of ϕ' will be that obtained from plane strain tests which in general is larger than ϕ' (triaxial).

The time-rate of loading at which the sand begins to behave as a $\phi = o$ material is a function of its permeability and depends on the size of the footing (path of drainage); consequently, the results obtained by the authors for saturated sands are not directly applicable to the full-scale footing.