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ABSTRACT

In order to clarify the mechanical behaviors of sand grounds induced by various loadings including sea wave forces, traffic vibrations and earthquake etc., a series of model tests were carried out on model structure-ground system by using the two-dimensional plane strain soil box apparatus. It was found that; (1) the lateral flow behavior of ground depends strongly on settlement performance of a structure, (2) the bearing capacity of ground may be evaluated by a failure envelope which is depicted in M-V-H plane irrespective of the difference in loading conditions and (3) the stability of sand ground-structure system can be assessed on the basis of a parameter V_{δ}/V_{ρ} which quantifies the lateral flow deformation.

INTRODUCTION

It is important for evaluating the stability of ground-structure system to accurately understand the relationships among settlement performance of a structure, lateral flow deformation behavior in a ground and failure mode. However, experiment study on the characteristics of the ground failure which is induced mainly by flow deformation is rather limited due to that estimating of deformation in a ground beneath a structure is very difficult.

In this study, a series of model tests were performed to explore the deformation behavior in a sand ground bearing a structure under several loading conditions. Based on test data obtained from model tests, an evaluation method on the stability of ground-structure system is also proposed.

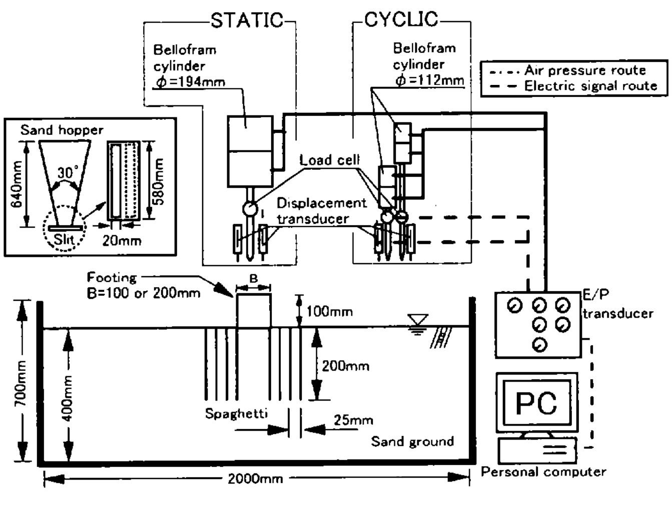

Fig. 1. Test apparatus

TEST APPARATUS

Figure 1 shows the whole view of apparatus developed by Miura et al (1995). The soil container was 2000mm in length, 700mm in depth and 600mm in width, and its front wall was made of a reinforced glass to observe the deformation of sand ground.

A model ground was constructed by pluviating Toyoura sand (ρ_s=2.65g/cm^3, ρ_{dmax}=1.648g/cm^3, ρ_{dmin}=1.354g/cm^3 and D_{50}= 0.18mm) through air into the soil box to a depth of 400mm. A sand hopper used in this study can easily control the density of the ground (Miura et al.1995). The relative densities adopted are 50 and 80%. After construction, water is permeated into the ground from eight porous disks on the soil box bottom. The water level is raised to 5mm from the surface of the sand ground.

A model rigid structure is 100 or 200mm in breadth, 100mm in height, 580mm in length and 13.2kg in mass, and its bottom surface is made rough by attaching the sand-paper (G120).

The cyclic and static loading systems consist of bellofram cylinders, displacement transducers and load cells. A series of model tests were controlled automatically by a personal computer. During tests, the static or cyclic loads and the vertical and horizontal displacements of a model structure are recorded in the control unit.

DEFINITIONS OF DEFORMATION

In order to quantify the deformation behaviors of ground-structure system, settlements (S_{VL}, S_{VR}) and horizontal displacements (S_{HL}, S_{HR}) illustrated schematically in Fig.2 are derived geometrically from the measurements (Y_L, Y_R) at the crown of model structure. The major values between S_{VL} and S_{VR} or S_{HL} and S_{HR} are defined as S_{Vmajor} and S_{Hmajor}, respectively. Lateral deformation in sand ground is also measured by using eight strands of spaghetti (diameter is 1.9mm) vertically inserted at 25mm intervals in the ground (Miura et al.1999).

Based on the above measurements, deformation volumes V_δ and V_ρ shown in Fig.2 are also calculated. V_δ and V_ρ are the lateral deformation area of the spaghetti deformed and the settlement area of the model structure, respectively (see the shaded area in Fig.2). The deformation behaviors of sand ground-structure system are discussed by using of those parameters.

TEST PROCEDURES

The following model tests are conducted on the soil box apparatus.

Static Loading Test Series (SCL,SEL)

This test was performed under central or eccentric loading conditions. In these tests referred to SCL or SEL, monotonic vertical load P_V with loading rate of 0.3kN/m^2/min is applied to model structure as shown in Figs.3 (a) and (b). The values of eccentricity e/B adopted are 0, 0.15, 0.3, 0.4, 0.5. e and B mean the distance from loading ram to the center of model structure and the structure breadth, respectively.

Cyclic Loading Test Series (CCL,CVL,CEL)

To examine the effect of difference in loading conditions on deformation behaviors of sand ground, a series of cyclic loading tests were carried out.

·Cyclic central loading test (referred to CCL) : The cyclic loads (P_{VR}, P_{VL}) with a period of 4s were applied simultaneously to the model structure by using two vertical loading rams (see Fig.3 (c)).

·Cyclic vertical loading test (CVL) : The cyclic loads (P_{VR}, P_{VL})

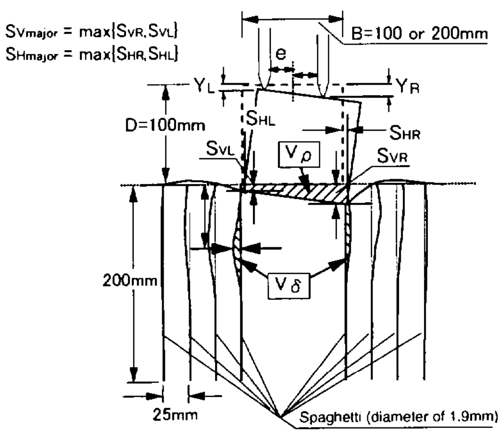

Fig.2. Definitions of deformation in this study

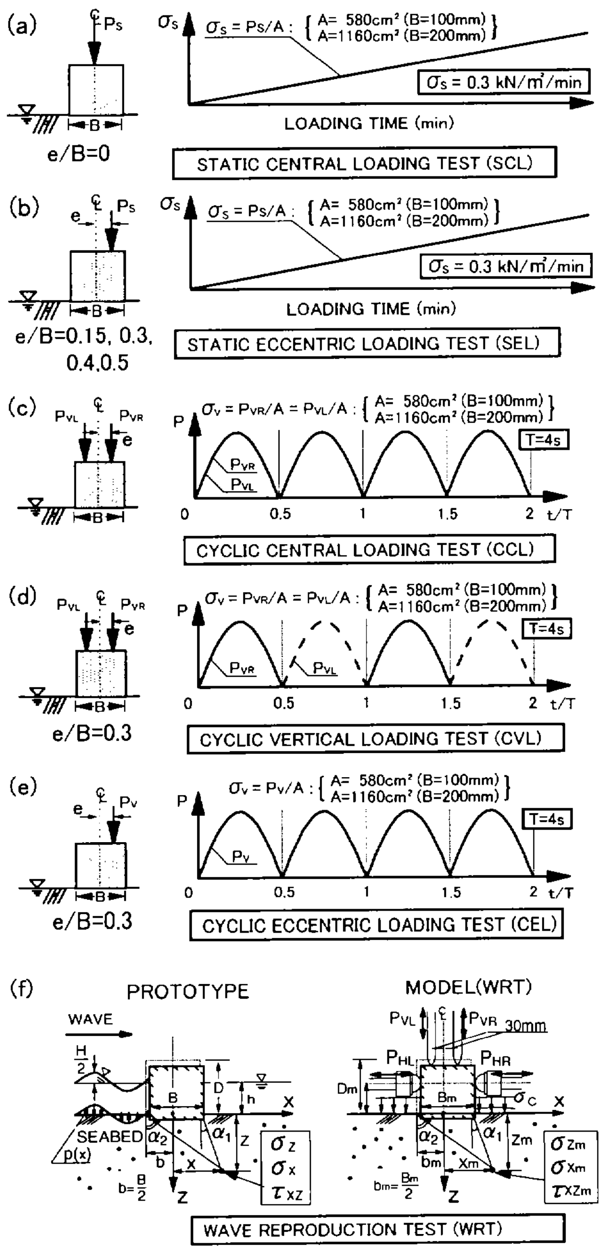

Fig.3. Test procedures: (a)SCL, (b)SEL, (c)CCL, (d)CVL, (e) CEL tests and (f) WRT

were given alternately to the model structure with a period of 4s (see Fig.3 (d)).

·Cyclic eccentric loading test (CEL) : The cyclic eccentric load P_{VR} or P_{VL} with a period of 4s was applied to the model structure, as shown in Fig.3 (e).

The eccentricity e/B at CVL or CEL test is 0.3.

Wave Reproduction Test (WRT)

To simulate stress conditions at an element of ground bearing a structure in the maritime field, model tests as depicted in Fig.3 (f) were also performed. In-situ stress conditions may be reproduced by appropriately combining vertical loads (P_{VL}, P_{VR}), horizontal loads (P_{HL}, P_{HR}) and an oscillating water pressure σ_O based on the following relationship (Miura et al. 1999);

$$\left\{\frac{\sigma_z}{\sigma_{z\,max}},\frac{\sigma_x}{\sigma_{z\,max}},\frac{\tau_{xz}}{\sigma_{z\,max}}\right\}=\left\{\frac{\sigma_{zm}}{\sigma_{zm\,max}},\frac{\sigma_{xm}}{\sigma_{zm\,max}},\frac{\tau_{xzm}}{\sigma_{zm\,max}}\right\} \qquad (1)$$

where { σ_Z, σ_X, τ_{XZ} } are vertical stress, horizontal stress and shear stress. σ_{Zmax} denotes the maximum value of vertical stress induced during one period of a wave propagation. The suffix m also indicates the stresses in model tests. This test is regarded as the model test simulating the maritime field.

TEST RESULTS AND DISCUSSIONS

Static Loading Test (SCL and SEL)

In order to reveal the effects of differences of structure breadth B and the eccentricity e/B on bearing capacity, Fig.4 shows the results of SCL and SEL tests in terms of the static loading stress σ_S(=P_S/A, A is the base area of the structure) versus the major settlement normalized to the structure breadth, S_{Vmajor}/B. From this figure, it is obvious that the bearing capacity decreases with the increase of e/B. The rate of decrease in the bearing capacity due to the increasing of e/B also becomes remarkable with the increase of B. This fact indicates that Meyerhof's theory (Meyerhof 1953) is suitable for evaluating the bearing capacity behavior of ground subjected to eccentric loads.

Figure 5 is arranged on the relationship between N_γ value by De Beer (1965) and e/B. N_γ means the normalized ultimate bearing capacity ($2\sigma_{su}/\gamma_d \cdot B$). σ_{su} and γ_d are the ultimate bearing capacity and the unit dry weight of ground, respectively. In this study, the ultimate bearing capacity is determined by the peak value on the stress-settlement relationship that the plastic wedge zone in the ground is clearly observed beneath the structure. As shown in Fig.5, N_γ value decreases noticeably with the increase of e/B despite of difference in ground density or structure breadth. In particular, these tendencies are extended due to that the effective structure breadth B' (=B/2-e) increases. Therefore, as many

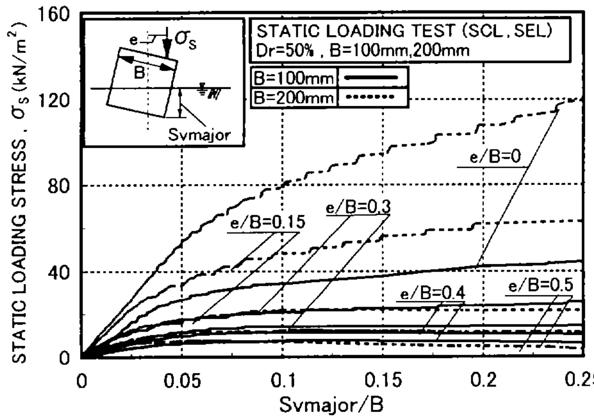

Fig.4. Bearing capacity-settlement relationships for SCL and SEL tests (Dr=50%)

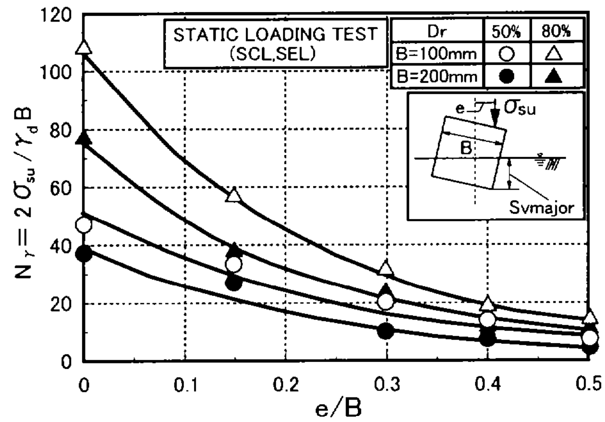

Fig.5. Relationships between N_γ and e/B

researchers have described (e.g. De beer 1965, Yamaguchi et al. 1976, Oda et al. 1979), the effect of base size of structure on the bearing capacity is considerably significant for evaluating the bearing capacity characteristics of ground-structure system.

Figures 6 (a) and (b) depict lateral deformations of sand deposits with movements of model structure at S_{Vmajor}=10mm for SCL and SEL tests. The pattern of lateral flow deformation varies from settlement performance of structure. For instance, the sand bed deforms symmetrically in SCL test, but the lateral deformation develops asymmetrically in SEL test.

On the basis of test data obtained from Fig.6, the lateral deformation behaviors of grounds are investigated. The relationships between soil volume ratio V_δ/V_ρ and S_{Vmajor}/B for Dr=50, 80% are shown in Figs.7(a) and (b). In spite of the difference of structure breadth, V_δ/V_ρ values increase rapidly until S_{Vmajor}/B reaches to 0.05~0.1, and thereafter becomes a constant. The ultimate value of V_δ/V_ρ which is defined at S_{Vmajor}/B=0.25 varies with difference in settlement performances from 0.7 (SCL test) to 0.8(SEL test). The reason for which V_δ/V_ρ on SEL test becomes higher value than that on SCL test may be that V_δ increases with e/B.

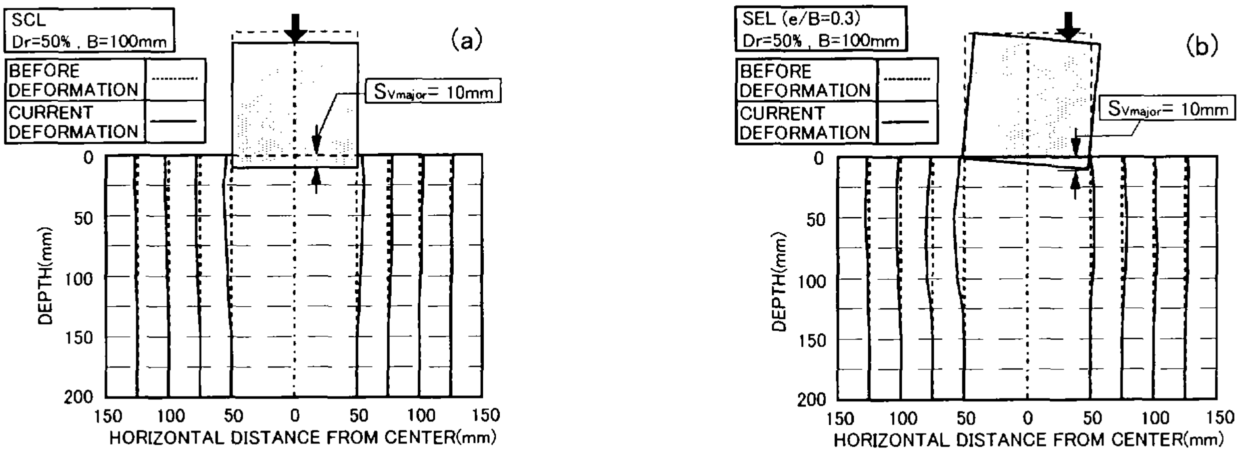

Fig.6. Lateral flow deformations of ground-structure system: (a) SCL, (b) SEL

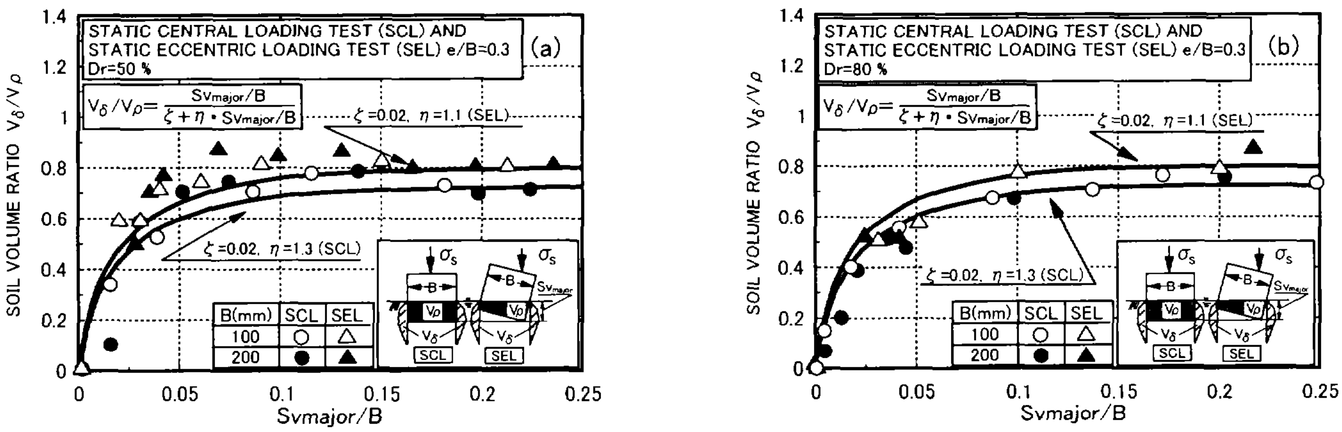

Fig.7. Relationships between V_δ/V_ρ and S_{Vmajor}/B : (a) Dr=50%, (b) Dr=80%

V_δ/V_ρ-S_{Vmajor}/B relationship can be expressed as follows,

$$V_\delta/V_\rho = (S_{Vmajor}/B)/(\zeta + \eta \cdot S_{Vmajor}/B) \tag{2}$$

where ζ and η indicate V_δ/V_ρ at the initial and at the infinity of S_{Vmajor}/B, respectively. ζ and η for SCL test are 0.02 and 1.3, and for SEL test 0.02 and 1.1.

Therefore, it may be said that deformation parameter of V_δ/V_ρ adopted in the present study evaluates the deformation behavior of ground without the base size effect.

In order to confirm the validity of soil volume ratio V_δ/V_ρ, the relationships among bearing capacity, V_δ/V_ρ and S_{Vmajor}/B are shown in Fig.8. Bearing capacity vs. V_δ/V_ρ relationship corresponds well with S_{Vmajor}/B vs. V_δ/V_ρ relationship. From this fact, it can be pointed out that soil volume ratio V_δ/V_ρ are available for estimating the mobilization behavior of bearing capacity.

Cyclic Loading Tests and Wave Reproduction Test (CCL, CVL, CEL and WRT)

As mentioned in above, fundamental data on deformation

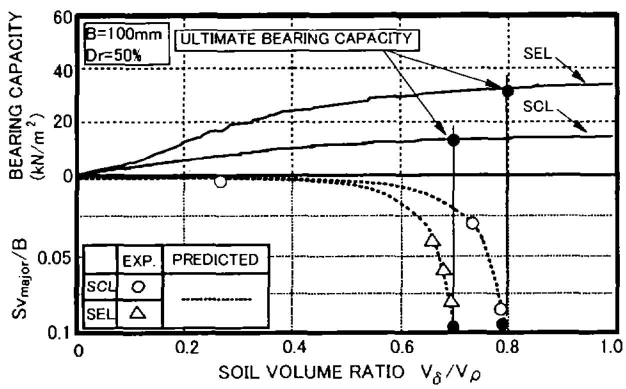

Fig.8. Relationships among V_δ/V_ρ, bearing capacity and S_{Vmajor}/B

behavior of the grounds subjected to static loadings can be obtained. The mechanical behaviors of sand grounds subjected by cyclic loadings such as earthquake, sea wave force and traffic vibration were also investigated. Figure 9 represents the results of cyclic loading tests for B=100 or 200mm at Dr=50% in terms of the cyclic loading stress σ_V (= P_{VL} or P_{VR} /A: A is the base area of structure) versus the number of loading cycles Nc required to S_{Vmajor}/B of 3, 5, 10%. Cyclic strength behaviors observed in model ground are very similar to those in the element test such as cyclic undrained triaxial test. Variations in loading cycles due to difference of structure breadth exist at the same cyclic stress σ_V. A similar tendency is also obtained for Dr = 80%. These results indicate that the scale effect in the bearing capacity extremely significant for estimating the stability of structure-ground system subjected to cyclic loadings.

Figure 10 exhibits the results of wave reproduction tests (WRT, Dr=50% and 80%) in terms of the relationships between wave height H or corresponding moment at the center of structure and number of loading cycles Nc. Wave condition is T=10s and h=15m, and structure breadth B and height D in the field are 20m. It is apparent that the strength behavior of sand ground subjected to cyclic loading such as wave force has the similar tendency to that of CVL test.

The relationship between V_δ/V_ρ and S_{Vmajor}/B on each test is shown in Fig.11. Similar tendencies to the behaviors observed in the static loading tests (SCL, SEL tests) can be found in the figure. Namely, there are the unique relationships between V_δ/V_ρ and S_{Vmajor}/B. To reveal the variations in the development of V_δ/V_ρ due to the difference in loading conditions, Table 1 exhibits ζ and η in Eq. (2) on each test. ζ and η for

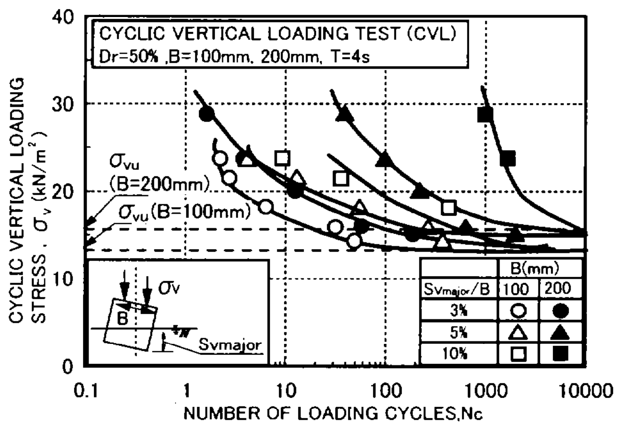

Fig.9. Cyclic loading stress versus number of loading cycles for CVL tests with B = 100mm and 200mm

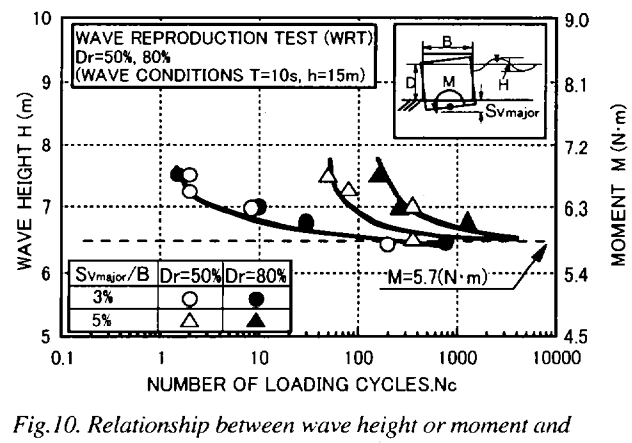

Fig.10. Relationship between wave height or moment and loading cycles in WRT

Table 1. ζ, η on each test

	Dr=50%				Dr=80%			
	B=100mm		B=200mm		B=100mm		B=200mm	
	ζ	η	ζ	η	ζ	η	ζ	η
SCL	0.02	1.1	0.02	1.1	0.02	1.1	0.02	1.1
SEL (e/B=0.3)	0.02	1.3	0.02	1.3	0.02	1.3	0.02	1.3
CVL	0.02	1.1	0.02	1.1	-	-	-	-
CEL (e/B=0.3)	0.02	1.3	0.02	1.3	-	-	-	-
WRT	0.02	5.0	-	-	0.02	5.0	-	-

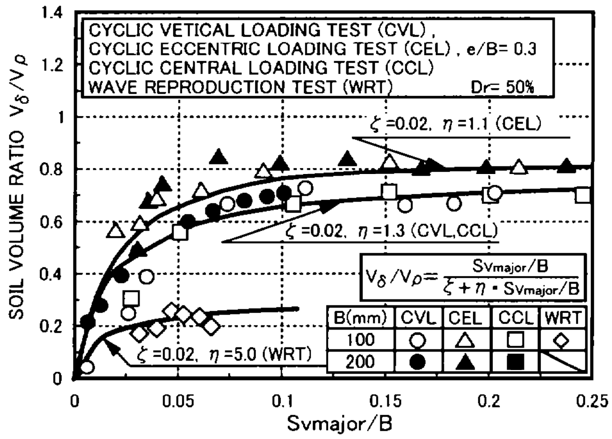

Fig.11. Relationships between V_δ/V_ρ and S_{Vmajor}/B

CCL and CEL tests are the same values to those for SCL and SEL tests, respectively. This fact indicates that the lateral flow behavior are not different from that observed in the static loading tests.

On the other hand, η in WRT denote higher values in comparison with those of the other tests. This reason may be that development of V_δ becomes low due to that the ground failure in WRT is induced at the sliding mode (Miura et al.1999). The change in failure modes attributed to the difference in loading conditions must be accurately estimated. At any rate, it may be said that deformation behavior of ground in the mode of settlement failure depends strongly on the settlement performance of structure.

To estimate the degree of mobilization of bearing capacity in the cyclic loading tests, representative relationships among S_{Vmajor}/B, the normalized loading cycles $N_C/N_{C\ at\ Svmajor=10\%}$ and V_δ/V_ρ are depicted in Fig.12. $N_C/N_{C\ at\ Svmajor=10\%}$ means the loading cycles normalized to the loading cycles at S_{Vmajor}/B=10% for CVL test. The cyclic stress σ_{VU} at which S_{Vmajor}/B lines converge to a critical state is regarded as bearing capacity required to the ground failure (see Fig.9). From this figure, it can be pointed out that there is a proportional correlation between V_δ/V_ρ and the value of $N_C/N_{C\ at\ Svmajor=10\%}$. Therefore, the soil volume ratio V_δ/V_ρ may be useful for evaluating the behaviors of lateral flow deformation of sand ground under cyclic loading conditions.

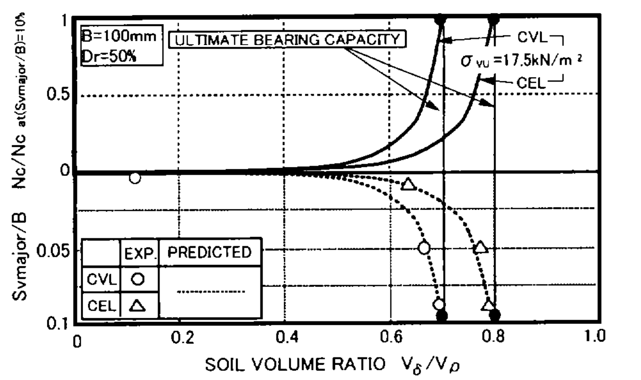

Fig.12. Relationships among V_δ/V_ρ, bearing capacity and S_{Vmajor}/B

EVALUATION OF FAILURE ENVELOPE

Based on the results of model tests, an evaluation method for failure of structure-ground system subjected to various loadings is investigated.

Figure 13 shows the normalized moment M/B vs. vertical load V relationships at the ultimate bearing capacity obtained from SCL and SEL tests or the bearing capacity required to ground failure for CCL, CEL and WRT. M is the moment at the center of structure bottom. The bearing capacity in WRT is determined similarly by the method for CVL tests. From the figure, it must be noted that there are the unique relationships between M/B and V although variation in the shape size of failure envelope exists due to differences of ground density and structure breadth.

Many researchers have widely studied the shape of failure envelope (e.g. Butterfield et al. 1994). The failure envelope is also given by the following expression;

$$H^2+(M/B)^2-a(M/B)H=(V/V_{max}(V_{max}-V))^2 \qquad (3)$$

where, M, V and H are the moment at the center of structure bottom, vertical load and horizontal load, respectively, and a the shape coefficient of failure envelope. The horizontal load H is

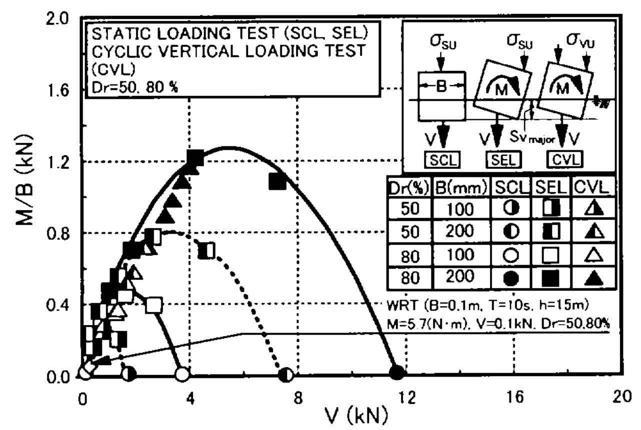

Fig. 13. Failure envelope

zero for SCL, SEL and CCL, CVL tests. V_{max} means the maximum value of the vertical load. The results obtained from a series of model tests satisfy Eq. (3). Therefore, bearing capacity of sand ground can be assessed fittingly by a failure envelope which is depicted in M-V-H plane irrespective of the difference in loading conditions. Furthermore, it may be also said that failure envelope in M-V-H plane is useful for estimation of stability of structure-ground system subjected to cyclic loading conditions such as wave force.

CONCLUSIONS

On the basis of the limited number of model tests, the following conclusions were derived;

1. Lateral flow deformation of sand ground depends strongly on settlement behavior of structure in spite of the difference in loading conditions.
2. Soil volume ratio V_δ/V_ρ adopted in this study can evaluate reasonably the deformation behavior of ground and the mobilization degree of bearing capacity.
3. Failure envelope depicted in M-V-H plane may be used to estimate the stability of structure-ground system under various cyclic loading conditions.

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