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SIMILARITY LAW IN MODEL GROUND TESTS WITH FOCUS ON SHEAR MODULUS UNDER LOW CONFINING STRESS

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Abstract

It is popular that model ground tests concerning dynamic problems are conducted under 1g gravitational condition. In those model tests, the similarity law is very important to predict the actual behavior of the real ground. Experimental results, where shear moduli of soils are proportional to the square root of confining stress (here, this is referred to as “square root law of *G*”), have been frequently available for making a similarity law. This experimental assumption is mainly examined in soil element tests under quite high confining stress comparing with small model ground tests. However, there is little data concerning the shear modulus under extremely low confining stress because of the difficulty of soil element tests under low confining stress conditions. Therefore, shear modulus was estimated under low confining stress conditions using bender elements (BE) not only in the triaxial tests but also in the model ground in this study. Moreover, the shear wave generated by plate hitting is also used to evaluate the shear modulus of soil in the model ground.

The shear moduli at various confining stress level are measured using BE and plate hitting in soil container and triaxial tests. There was a good agreement in the shear moduli obtained from the BE tests using the triaxial apparatus and the soil container. However, the shear moduli obtained from the plate hitting method were larger than those from the BE tests. Finally, it was demonstrated that the assumption of “square root law of *G*” is roughly established under low confining stress although small difference appears in the type of experiments.

Keywords: low confining stress; shear modulus; similarity law

1. Introduction

Small model tests were usually conducted for seismic ground problems because of many limitations such as labor, expense, time and space, although prototype should be used ideally. In the model tests of this kind, similarity law used is important factor to simulate the actual ground behavior. A similar similarity law has been established by many researchers in 1g gravitational shaking table tests [1, 2, 3]. An important soil property, which is that shear modulus G is proportional to square root of confining stress (referred to as "the square root law of G"), is used in the similarity law. This fact "the square root law of G" has been empirically obtained from soil element tests [4]. The problem is that the square root law of G was tested only under high confining stress level (larger than 20 kPa) and little data exists under extremely low confining stress level. Therefore, shear modulus was calculated from the shear wave velocity ($G=\rho V_s^2$) under low confining stress conditions such as overburden soil of several centimeters. Here, three methods were used: those are plate hitting, bender elements (BE) in triaxial tests and BE in soil container. Moreover, reliability of the data obtained from the three methods was also discussed in the paper.

2. Testing methods

2.1 Soil and sample preparation

Soil used is Onahama sand whose physical properties and grain size distribution are shown in Fig. 1. Air pluviation method was used for sample preparation. Here, air-dried Onahama sand was poured from a certain drop height through a sieve at each layer of 2 cm thickness for triaxial specimens and of 5 cm thickness for model ground in the soil container. At each layer, the sand was compressed vertically to obtain a sample with relative density of 60%.

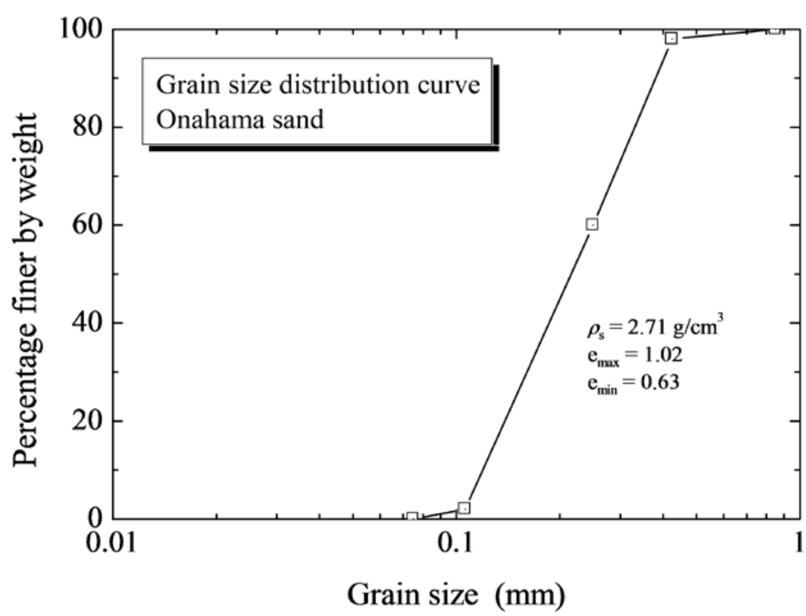


Fig. 1– Physical properties and grain size of Onahama sand

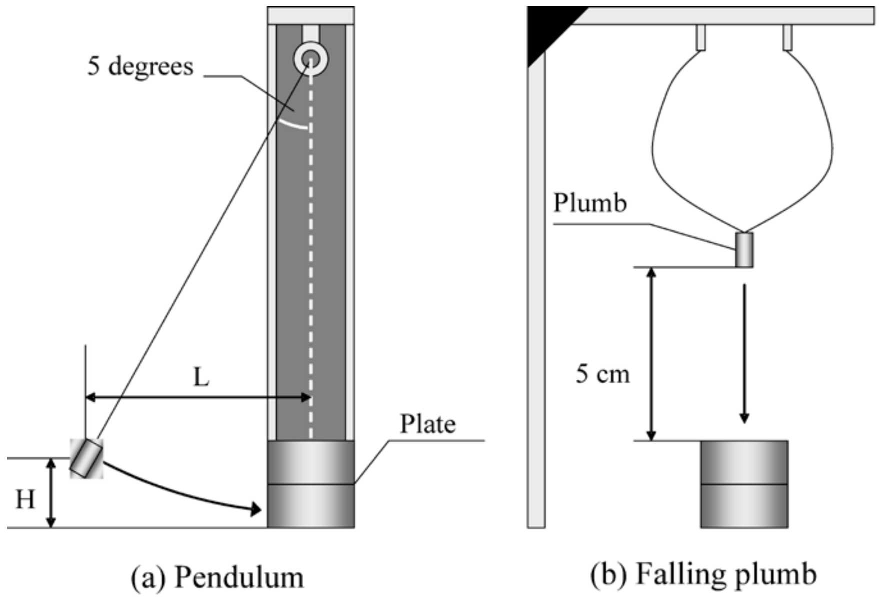


Fig. 2– Plate hitting method: (a) pendulum, (b) falling plumb

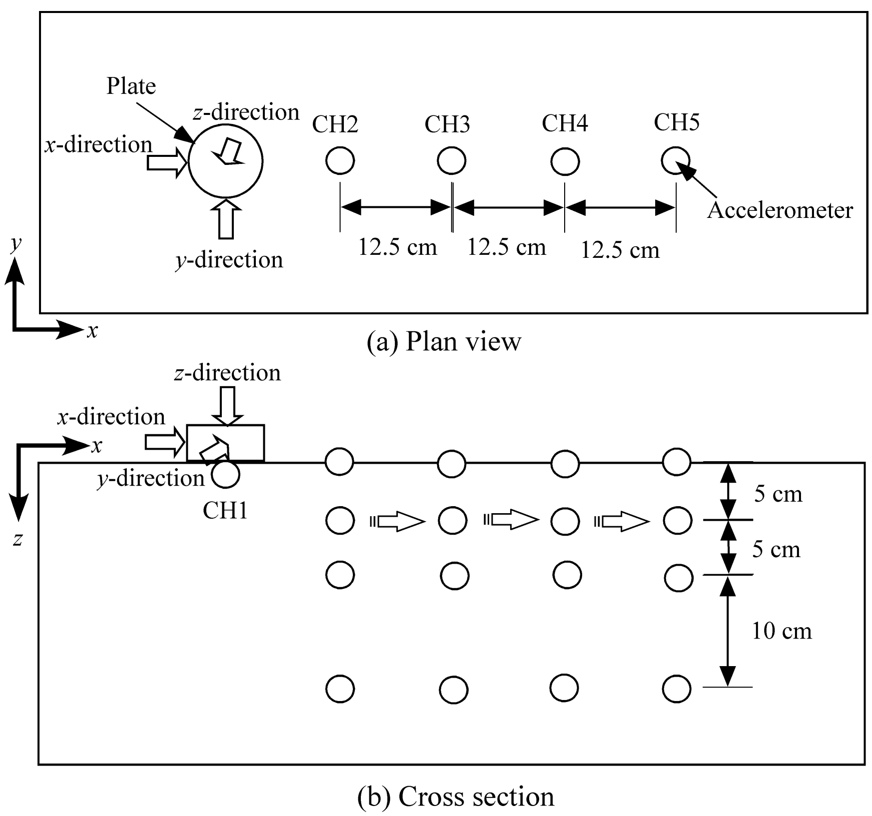


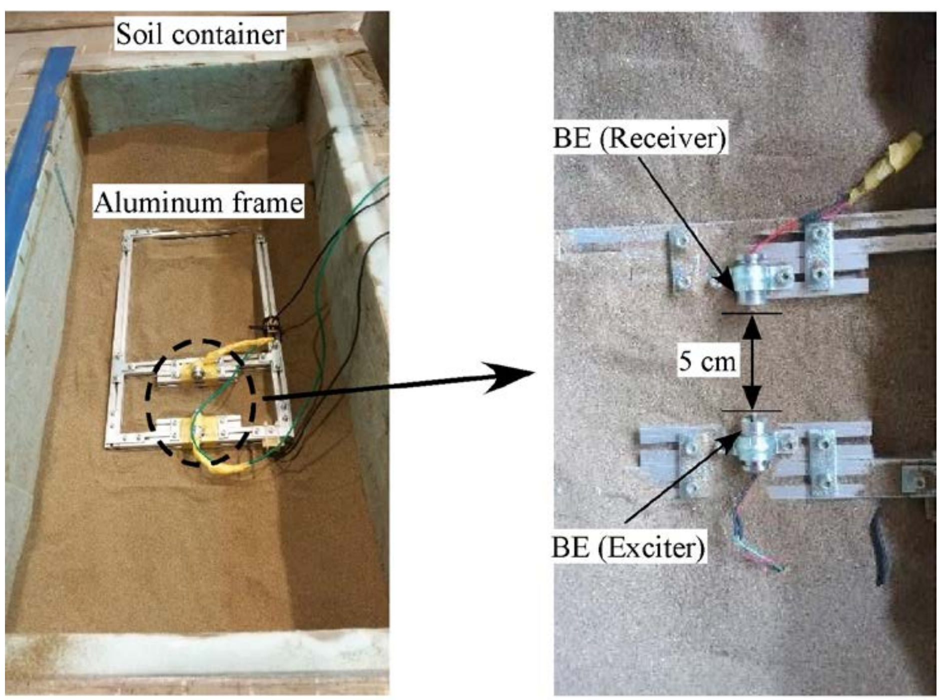
Fig. 3– Arrangement of accelerometers

2.2 Plate hitting method

Model ground was made using dry Onahama sand (D_r=60%) in a soil container whose dimensions are 100 cm length, 50 cm width and 50cm depth. A metal plate, which is 90 mm height and 40 mm diameter, was placed on the surface of the model ground. Impulse wave was generated by hitting the plate using a metal plumb, which has 13 mm height, 14 mm diameter and 25 g mass. A pendulum as shown in Fig. 2 (a) was used for the excitation in *x* and *y*-directions. The plumb was fallen from a certain height for the excitation in *z*-direction (Fig. 2 (b)). Accelerometers of piezoelectric type were placed with 12.5 cm distance on the ground surface and were embedded in the ground with 5 cm, 10 cm and 20 cm depth as shown in Fig. 3. Although wave will propagate diagonally, transmitting distance was assumed as the distance between adjacent accelerometers in the same depth for simplicity. Then, wave velocity V_s was calculated by taking an average of V_s at three adjacent distances of the same depth (Fig. 3).

2.3 BE in triaxial test

The shear wave velocity was measured using a pair of bender elements installed in the top cap and the pedestal, after the initial consolidation, stress loading, and unloading processes. The input signal was a single sinusoidal wave with half-amplitude of 10 V and frequency of 15 kHz. The distance for traveling was estimated as the tip-to-tip distance. The traveling time was estimated using the start-to-start method considering a zero-crossing line. Confining stress, which is isotropic mean effective stress, was varied from 10 kPa to 600 kPa. The case, where the specimen is self-standing with the support of the brass mold without cell pressure, was also conducted.



(a) Whole view (b) Bender elements

Fig. 4– Setting of BE in soil container

2.4 BE in soil container test

Model ground was made in the same soil container with the plate hitting test whose inside dimensions are 50 cm in height, 50 cm in width and 100 cm in length. A pair of bender elements, which are exciter and receiver, was installed in an aluminum frame (Fig. 4). In preliminary tests, shear wave velocity was examined in two cases where piezo ceramic plates in BE are respectively set to bend vertically and horizontally. The input signal was a single sinusoidal wave with half-amplitude of 90 V and frequency of 15 kHz. The distance for traveling was estimated as the tip-to-tip distance. The traveling time was estimated using the start-to-start method considering a zero-crossing line. If vertical stress and horizontal stress are different each other, the shear wave velocities obtained from vertical bending of BE and horizontal bending of BE will be different [5]. However, results of the preliminary tests were almost the same in both cases of vertical bending and horizontal bending. Therefore, piezo ceramic plates in the BE were set to bend in vertical direction in this study. The frame was embedded in the model ground at certain depth (5, 10, 20, 30, 35, 40, 45 cm). Reason is unclear, but we could not get the clear received wave at 5 cm depth. Therefore, data at 5cm depth was removed in the study. Although distances between BE's were set at 5, 10 and 20 cm, only results of 5 cm distance were used because the clearest received waves were obtained.

3. Test results

3.1 Plate hitting method

Starting points of arrival waves are read from acceleration records, as shown in Fig. 5. Although the amplitude becomes small at larger distance from the exciter, the arrival wave can be still recognized. From the average shear wave velocity, the shear modulus was calculated at each depth.

Figure 6 indicates the relation between shear modulus and confining stress. The plotted data are average value at each depth estimated from horizontal distance between accelerometers. Although the reason is not obvious, the shear modulus is independent of confining stress in the cases of excitation in z direction. In those cases, it is considered that surface wave analysis should be conducted because the waves transmitted at various depths are classified by the frequency of the waves according to the theory of surface wave. On the other hand, more liner relation is roughly achieved between logarithm of G and logarithm of confining stress in the excitations of x and y directions. The power numbers of the relations are respectively 0.65 and 0.51 in x and y excitation directions. The difference in the power number of 0.65 and 0.51 might be engendered from the error of the experiments. Although, the accelerometers on the surface were embedded in 1 cm deep, the vertical (overburden) stress calculated from 1 cm depth is too small for accurate discussion. Therefore, additional data should be collected at deeper than 5 cm.

3.2 BE in triaxial test

Time history of voltage obtained from input signal and receiver BE are shown in Fig. 7. To estimate shear wave velocity, time difference was calculated from the starting points.

The relation between shear modulus estimated from the BE in triaxial test and confining stress is depicted in Fig. 8. "No cell pressure" in the figure indicates that shear wave was measured in a specimen supported by a brass mold without cell pressure. Overburden pressure at middle height of the specimen was used as the confining stress in this case. Transmitted time might become short because the wave propagates through the brass mold. However, the effect of brass mold hardly seen in the result (Fig. 8). The power number of the relation is 0.45, which is close to the ideal value of 0.5.

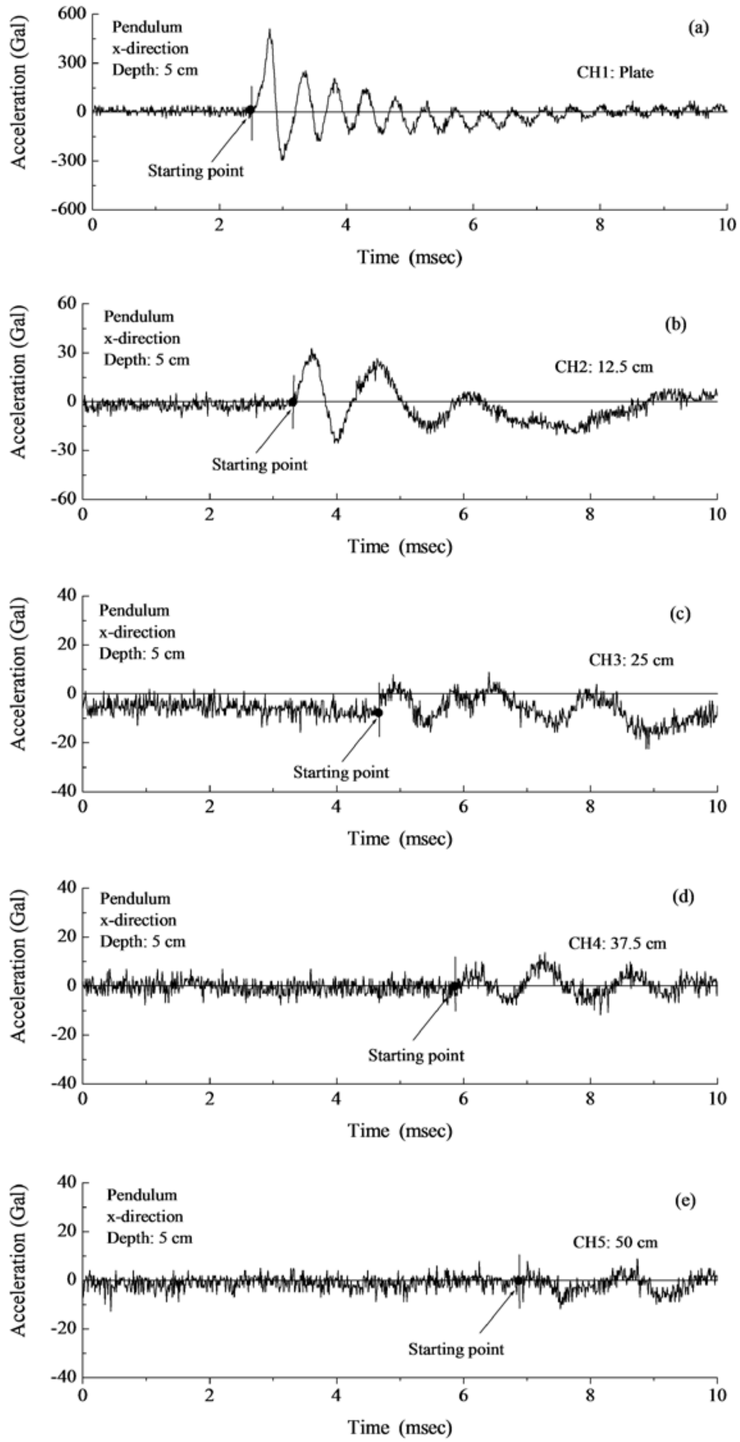


Fig. 5– Time history of accelerations (Plate hitting)

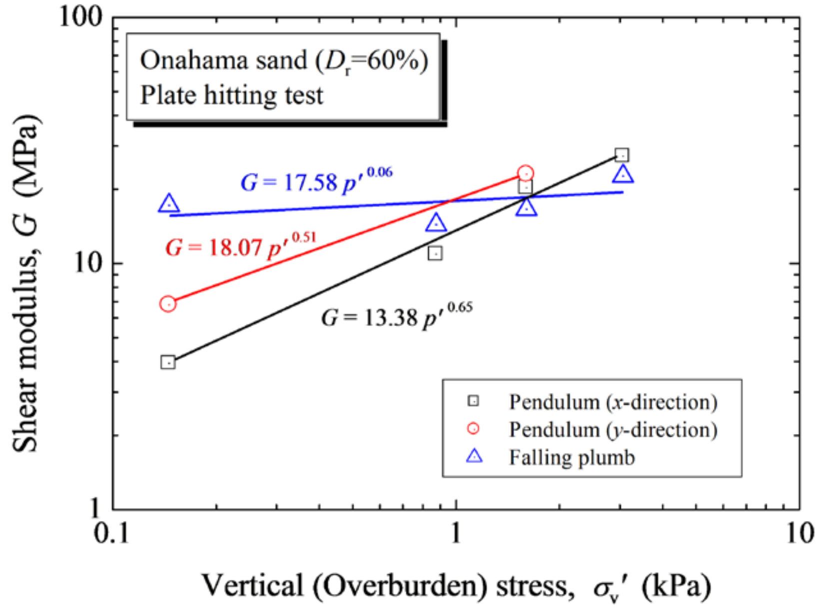


Fig. 6– Relation between *G* and vertical (overburden) stress (Plate hitting)

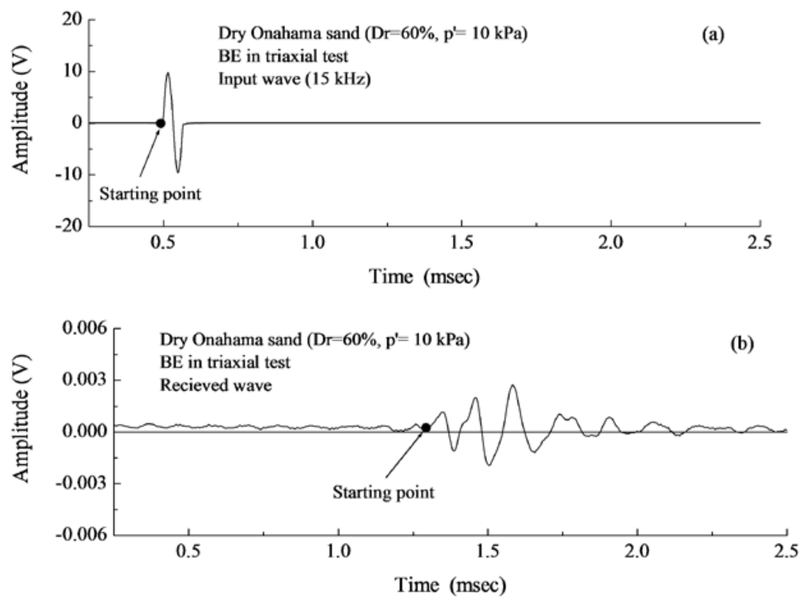


Fig. 7– Time history of voltage (BE in triaxial test)

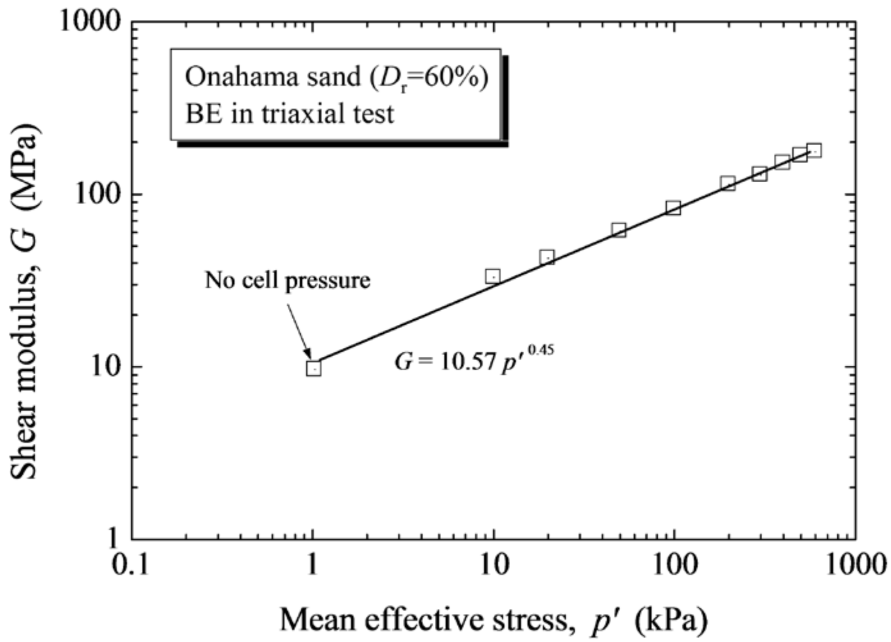


Fig. 8– Relation between G and mean effective stress (BE in triaxial test)

3.3 BE in soil container test

Figure 9 representatively shows records of voltage obtained from BE and assessment of arrival time of the wave to estimate shear wave velocity. Although the starting point of received wave is not obvious, small disturbance appears in the received wave (Fig. 9 (b)). Then, this reading leads to a good agreement with the results of the BE in triaxial test.

Figure 10 shows the G and confining stress relations obtained from the BE in container test. The power number of the relation is 0.53, which is very close to the ideal value of 0.5.

4. Discussion

All data obtained from the plate hitting method (except for plumb falling method), BE in triaxial test and BE in soil container test are plotted in Fig. 11. Here, the confining (overburden) stress was defined as the vertical (overburden) stress calculated from the depth and dry density of the sand in the soil container test (plate hitting and BE in soil container tests). But in the BE in triaxial test, the confining (overburden) stress coincides with the mean effective stress because of isotropic stress condition. The values of G obtained from the plate hitting method are slightly larger than those obtained from the BE in triaxial test and BE in soil container test. The reason is considered that although only horizontal distance was used for calculation of V_s, shorter distance will exist considering diagonally transmitted wave. However, this assessment is difficult because V_s is bigger at larger confining stress.

When the results from the BE in triaxial test are compared with those from the BE in soil container test, the good connectivity and agreement was obtained in the results between two cases. This indicates that BE tests are very useful for estimation of shear modulus under low confining stress conditions.

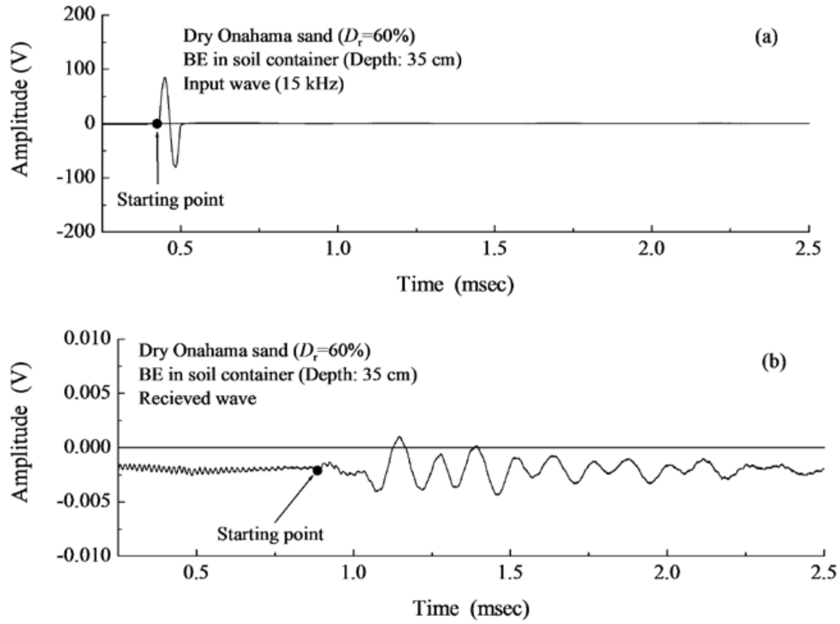


Fig. 9– Time history of voltage (BE in soil container test)

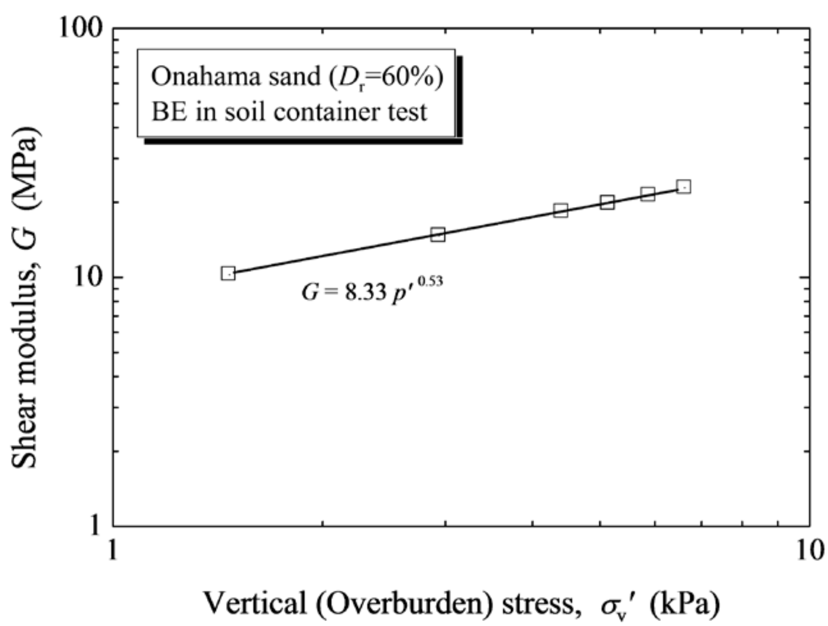


Fig. 10– Relation between G and vertical (overburden) stress (BE in soil container test)

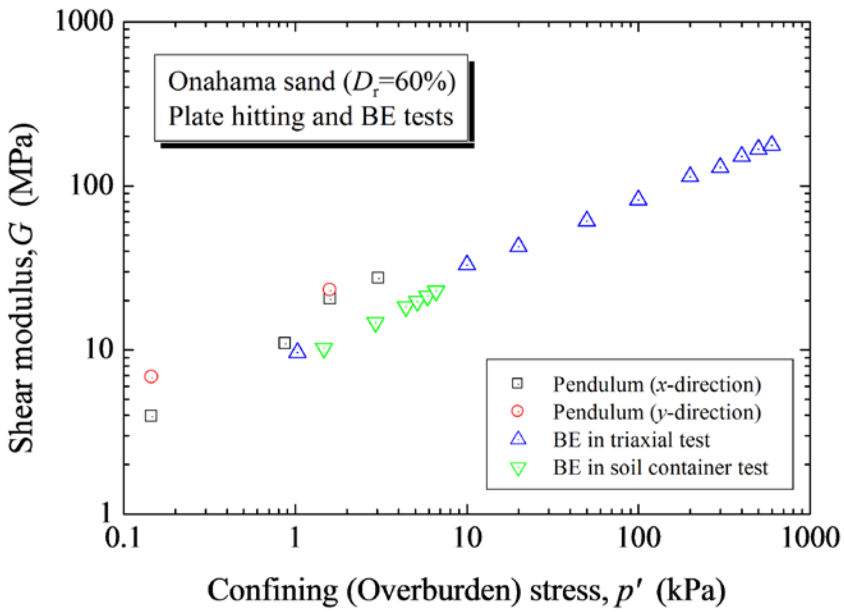


Fig. 11– Relation between G and confining stress (All tests)

5. Conclusions

The G was measured at low confining stress conditions to verify a suitable similarity law of small ground model tests for dynamic problems. The results obtained from the study are summarized as follows:

1. In the BE tests using soil container, good data were obtained only the conditions of BE distance of 5cm and soil depth of over 10 cm.

2. In the plate hitting method, the G was larger than those obtained from the BE in triaxial tests and the BE in soil container tests. It might be insufficient to consider only horizontal distance as transmitting path with ignoring diagonal path.

3. There was a good agreement in the G from the results of the BE tests using the triaxial apparatus and the soil container. Moreover those relations nearly obeyed the square root law of G.

According to the results where the square root law of G can be completed even in low confining stress conditions, the existing similarity law [1, 2, 3] is satisfied in wide range of scale of the model ground.

6. Acknowledgements

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7. References

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