ABSTRACT

The aim of this study is to design economically foundations which are subjected to large lateral forces such as unsymmetrical earth pressure or seismic inertia force of superstructure by using grid form soil improvement wall used as liquefaction prevention of soft ground. The proposed way is to add dents and bumps to the head of the soil improvement and unite concrete foundation with it for lateral force transmitting. Lateral resistance of the joint is studied theoretically and experimentally. The results show the performance of the joint is more than 1.5 times larger than the no dent and bump joint under same contact pressure and the proposed calculation formula is valid.

Keywords: soil improvement, lateral resistance, model test, limit equilibrium method

1. INTRODUCTION

The aim of this study is to design economically foundations which are subjected to large lateral forces such as unsymmetrical earth pressure or seismic inertia force of superstructure by using grid form soil improvement wall. The grid-form soil improvement wall, which has been developed as liquefaction prevention of soft ground at first, has so high shear stiffness and strength for resisting the forces. In this study, we propose a mechanical joint of transmitting the forces to the head of grid-form soil improvement by adding dents and bumps and propose a calculation formula of predicting an ultimate lateral resistance of the joint and examined a cyclic loading test to confirm shear failure of the joint and the validity of the proposed calculation formula. Fig.1 shows a concept of this system.
2.2 Prediction of ultimate lateral resistance

There are two resistance factors at the joint. One is shear resistance force of the bumps of the improved soil, the other is frictional resistance force or adhesion between improved soil and concrete foundation. However the adhesion is excluded from consideration for err on the side of caution.

Lateral resistance of the bump is expressed as Eq. (2) derived from failure criterion of improved soil Eq. (1) and equilibrium of forces on the slip line (see Fig. 3.),

\[ \tau_l = 0.3 \cdot F_s + \sigma'_n \tan \phi' \]  \hspace{1cm} (1)

\[ R_{cs} = P_t \tan(\alpha + \phi') + \frac{0.3 \cdot S \cdot F_s}{\cos \alpha (1 - \tan \alpha \tan \phi')} \]  \hspace{1cm} (2)

where, \( \tau_l \) is the shear strength of improved soil, \( F_s \) is the design strength, \( \phi' \) is the angle of internal friction and \( \sigma'_n \) is the normal stress on the slip line. \( R_{cs} \) is the ultimate lateral resistance force per bump. \( P_t \) is the vertical load acting on a shear resistance area. \( S \) is the shear resistance area and is expressed as follows.

\[ S = l / \cos \alpha \times D \]  \hspace{1cm} (3)

\[ l = \min(l_n, \frac{H}{\tan \alpha}) \]  \hspace{1cm} (4)

where, \( D \) is the width of improved soil, \( l \) is the length of the shear resistance area, \( l_n \) is the length of the bump, \( H \) is the height of the bump.

Meanwhile, the frictional resistance force \( R_{cf} \) is express as Eq. (5) using the coefficient of friction \( \mu_s \).

\[ R_{cf} = \mu_s \cdot P_f \]  \hspace{1cm} (5)

where, \( P_f \) is the vertical load by superstructure acting on a frictional resistance area. When \( P \) is defined as the total vertical load by superstructure and \( P_f \) and \( P_s \) are defined as the vertical load acting on the frictional resistance area and the shear resistance area respectively and \( L \) is the distance between the bumps, Eq.(6) and Eq.(7) are established.

\[ P = P_f + P_s \]  \hspace{1cm} (6)

\[ P_s = \frac{1}{L} \cdot P, P_s = \left(1 - \frac{1}{L}\right)P \]  \hspace{1cm} (7)

The ultimate lateral resistance of the joint \( R_s \) is sum of shear resistance and frictional resistance and multiplied by the number of bumps \( n \). It is expressed as Eq. (8).

\[ R_s = \mu_s \cdot P_f + P_s \tan(\alpha + \phi') + \frac{0.3 \cdot n \cdot S \cdot F_s}{\cos \alpha (1 - \tan \alpha \tan \phi')} \]  \hspace{1cm} (8)

In the calculation, the angle \( \alpha \) is only an unknown quantity. The angle \( \alpha \) and \( R_c \) in eq.(8) are obtained through searching for the angle to minimize \( R_c \).

3 CYCLIC LOAD TEST

3.1 Experimental procedure

The test setup is illustrated in Fig.4. This loading apparatus can apply arbitrary lateral and vertical force to a specimen under the rotational constraint. A specimen is 600mm in length, 300m in width and 80mm in height and is fixed between an upper concrete plate and a lower concrete plate. The load incremental of a step is one third of the calculated ultimate lateral resistance and the each step loading is repeated twice. After three steps, the control method was changed from the load control to the displacement control as the displacement amplitude of a new step was two times than one of the previous step. Table 1 shows materials of the improved soil. Adhesion between the improved soil and the concrete plate was eliminated.

![Fig. 4. Test setup](image)

| Table 1. Mixing proportions |
|-----------------------------|
| **Materials** | **Soil** | **Cement** | **Water** |
|-------------------|----------|------------|----------|
| silic sand | potter's clay | water | in soil |
| Weight(%) | 64.3 | 7.1 | 14.3 | 7.1 |

| Table 2. Specimens |
|---------------------|
| **Shape of joint** | **Overburden stress** | **Unconfined compression strength** |
|---------------------|
| **No.** | **figure** | **height of bumps** | **number of bumps** | **pressure (kPa)** | **load (kN)** | **(kPa)** |
| No.1 | Bump1 | 20 | 3 | 144 | 26 | 3632 |
| No.2 | Bump1 | 30 | 3 | 144 | 26 | 5337 |
| No.3 | Bump2 | 20 | 2 | 144 | 26 | 3632 |
| No.4 | Bump2 | 30 | 2 | 144 | 26 | 5337 |
| No.5 | Bump2 | 20 | 0 | 144 | 26 | 3632 |
| No.6 | Flat | 30 | 0 | 144 | 26 | 5337 |
| No.7 | Flat | 100 | 0 | 144 | 26 | 5337 |
| No.9 | Flat | 100 | 0 | 144 | 26 | 5337 |

The list of specimens is shown in Table 2 and the shape of specimens is shown in Fig. 5. The experimental variables are shape, number of the bump and dent and vertical load (contact pressure). The Bump1 figure (No.1 ~ No.3) and Bump2 figure (No.4 ~ No.6) are different in shape and number of the bump and dent however they were designed to have same ultimate lateral resistance given by Eq. (8). The Flat figure (No.7 ~ No.9) was examined as a comparison. The strength of specimens was different because the production date of No.1 ~ No.6 was different from that of No.7 ~ No.9.
3.2 Test results

Fig. 6 shows a relation between lateral load and lateral displacement. The displacement of Flat developed into one side because of slipping however the hysteresis loops were stable. The hysteresis loops of Bump1 & Bump2 were similar under same vertical load (No.1 and No.4, No.2 and No.5, No.3 and No.6). The lateral resistances of Bump1 & Bump2 at second cycle were lower than those at first cycle and every hysteresis loop oriented to the maximum lateral load point at experienced maximum lateral displacement until the maximum strength. After that, the reduction of the shear strength occurred and the residual resistances of Bump1 & Bump2 at the last moment were almost same as those of Flat under same vertical load. The displacement at maximum lateral resistance of Bump1 & Bump2 was smaller than that of Flat. It seems to be due to dimensional errors in production and elasto-plastic deformation of the bumps and dents.

Fig. 7 shows relations between the vertical
displacement and the lateral displacement of upper concrete plate in Bump1. When vertical load was given to a specimen, the right side of vertical displacement of No.1 was increased clearly. The both sides of vertical displacements of No.1 tended to increase with the lateral displacement. The vertical displacement difference between both sides of No.1 means the specimen was rotated. Little rotation occurred in No.2 and No.3.

Fig.8 shows a relation between the maximum lateral load and vertical load of Flat. And the results of (Hamada et al., 2014) are added in this figure. These values had a proportional relation with the vertical load. The coefficients of friction were calculated to be about 0.8 in our experiment and 0.6 to 1.0 in (Hamada et al. 2014).

Fig.9 shows the maximum values of the experiment of Bump1 & Bump2 and theoretical values calculated by Eq. (8). The lateral resistances of Bump1 & Bump2 were larger than those of Flat under same vertical load. The equivalent coefficients of friction were calculated to be 1.2 ~ 3.0.

The coefficient of friction is 0.6 and the internal friction angle is 30° in the calculation. In consideration of the dispersion, the minimum value is adopted for safety prediction. The experimental maximum lateral resistances of No.1 and No.4 were smaller than the theoretical value. It seems that we couldn’t completely eliminate the rotation of specimens under low vertical load (see Fig.7 (a)). However the theoretical values agree with the maximum values of the experiment at No.2, No.3, No.5, and No.6 under enough vertical load. Therefore the calculation formula is reasonable.

4 PRACTICAL EXAMPLE

An example is shown below. The 17-story residential building, which is 15.50m in width, 88.50 in length and 41.65m in height above the ground surface, is located in Tokyo, Japan. It has 28 cast-in-place concrete piles and a grid-form soil improvement for liquefiable soil between depths of 3m to 10m. Fig.9 shows a schematic view of the building and the foundation with a soil profile and a photo and details of the joint.

The foundation was needed to be designed for a seismic inertia force of 14.7MN. The proposed method was employed to protect pile heads for the large force. We installed 43 bumps in x-direction and 38 bumps in y-direction. The ultimate lateral resistances of the joints were calculated to be 20.5MN in x-direction and 18.1MN in y-direction by Eq. (8). As a result, the lateral load sharing ratio of the piles was reduced to 58%.

5 CONCLUDING REMARKS

We proposed the joint of adding the periodic dents and bumps to the head of grid-form soil improvement in consideration of simplicity of construction for transmitting lateral force from concrete foundations to the soil improvement, and confirmed the performance of the joint by the theoretical and experimental study.

1) The calculation formula which depends on the shape of dents and bumps and contact pressure is derived by limit equilibrium method and it was examined to confirm the validity of the calculation by the loading test.
2) The reduction of the shear strength occurred after the ultimate lateral load and the residual resistance force was more than the frictional resistance force.
3) The equivalent coefficients of friction was improved to 1.2 ~ 3.0 by the effect of the dent and bump, though the coefficients of friction of the flat joint was about 0.8.
4) The practical example and the effect of the joint were shown.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. T. Usami, Mr. H. Ousalem and Mr. N. Nakatsu of Takenaka Corporation for useful advice and suggestions.

REFERENCES

1) Hamada, J., Aso, N., Hanai, A. & Yamashita, K. (2012):Stress of piles and lateral load sharing ratio between piles and raft evaluated from seismic observation on piled raft foundation, J. Struct. Constr. Eng., Vol.77 No.680, 1537-1544 (in Japanese).
2) Hamada, J., Honda, T., Omoto, S., Ousalem, H. and Usami,T. (2014): Monotonic lateral loading tests on mechanical system transmitting lateral loads to grid-form deep mixing walls using connecting cotters, Proc. 49th Annual Conference of Japanese Geotechnical Society, 1419-1413, (in Japanese)