The soil-geogrid interaction process was analyzed by the Particle Image Velocimetry furthermore spatial discretization scheme in finite element method to understand about the dilatancy mechanism and shear strain distribution during unloading-reloading process. In this test the geogrid was pushed back and forth at three stages of pullout test: before peak, at peak and at residual part to simulate the seismic activities. Results showed that the shear strain concentrated in front of transverse ribs and upper apart of pullout box. The dilative behavior appears in front of transverse ribs and contractive behavior exits at behind of these bars. The alternative soil dilatancy-contraction distribution in between the two transverse ribs can be seen throughout the length of geogrid.

Keywords: Pullout test, Unloading-reloading, dilatancy

1. INTRODUCTION

Stress distribution along reinforcement contains two components, frictional resistance and passive resistance as shown by Bergado et al. The frictional resistance depends on the surface area between geogrid and soil, the friction angle between geogrid and soil, and effective normal stress at the interface. The passive resistance is considered similar to bearing capacity mechanism. The failure mechanism is based upon the Terzaghi-Buisman bearing capacity equation for a strip footing as described by Jones (1996). Peterson and Anderson (1980) provided a bearing capacity failure mechanism shown in Figure 1. Passive resistance depends on area of transverse elements, effective vertical stress and friction angle of soil. Experiment has shown the existence of confining effect which is independent of tensile force of geogrid. The confining effect is a factor of reinforcing effects related to soil dilatancy. Yasufuku and Ochiai reported an existence of confining effect in a sliding box shear test.

In this study, a special pullout test was designed to carry out the pullout test with different geogrid types. The square and circle geogrid types were tested. To understand and stimulate geogrid working mechanism under seismic activities, unloading-reloading was applied during the pullout test by pushing the geogrid back and forth. The interaction between geogrid and soil especially at the transverse ribs was analyzed by the Particle Image Velocimetry (PIV) method to understand about the interaction mechanism during unloading-reloading process expressed later by Unloading-Reloading process.

Figure 1. Failure plane for bearing resistance after Peterson and Anderson (1980)

F_p: Pullout resistant, d: Diameter, P_p: Passive resistance, c: Cohesion
2. PULLOUT TEST

2.1 Test apparatus

Figure 2 shows the schematic diagram of pullout test apparatus with dimensions of 300 mm (width) x 202 mm (height) x 400 mm (length).

![Pullout test apparatus diagram]

Two dummy specimens were put inside the box to reduce the frictional area between geogrid and soil making the contact length of 240 mm. The test apparatus was mainly made of steel except the longitudinal sidewalls which were made of hard transparent plastic plates. Color sands were attached at the observation square at the box side with an area of 134 mm (width) x 80 mm (height), where distance from left side of the box to the square was 30 mm, to observe the deformation at the interface between geogrid and sand by a digital video camera. Dry Toyoura sand was poured through a sieve to make the soil homogeneous and the density \( D_{50} \) (mm): 0.19; \( U_r \) : 1.56; \( e_{\max} \) : 0.973; \( e_{\min} \) : 0.609; \( e \) : 0.682; \( D_r \): 80%; \( \phi \) (°): 42

Two types of geogrid made of polycarbonate, a square geogrid (SG), a circle geogrid (CG) and a polycarbonate plate (P) are shown in Figure 3 and Table 1.

![Polycarbonate types]

Table 1. Properties of model geogrid

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit</th>
<th>SG</th>
<th>CG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IT</td>
<td>mm</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>IL</td>
<td>mm</td>
<td>32.5</td>
<td>10</td>
</tr>
<tr>
<td>WL</td>
<td>mm</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>WT</td>
<td>mm</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>(kN/m)</td>
<td>20.2</td>
<td>14.8</td>
</tr>
<tr>
<td>Stiffness</td>
<td>(kN/m)</td>
<td>499</td>
<td>391</td>
</tr>
</tbody>
</table>

IT: Interval of transverse ribs; IL: Interval of longitudinal ribs; WL: Width of longitudinal ribs; WT: Width of transverse ribs; PC: Polycarbonate

3. OUTLINE OF THE PULLOUT TEST
The summary of data analysis is as follows. This is the method to evaluate the interaction between geogrid and backfill soil. The pullout resistance between soil and geogrid can be calculated by the following equation.

$$\tau_p = \frac{P_p}{2B_gL_G}$$

- $\tau_p$ : Pullout resistance (kPa)
- $P_p$ : Pullout force (kN)
- $B_g$ : Width of the geogrid (m)
- $L_G$ : Length of the geogrid (m)

The peak values of the pullout resistance are plotted against each overburden air pressure then the following relationship between pullout resistance and overburden air pressure is achieved.

$$\tau_{p,\text{max}} = c_p + \sigma_v \tan \phi_p$$

- $\tau_{p,\text{max}}$ : Pullout resistance at peak (kPa)
- $c_p$ : Apparent cohesion (kPa)
- $\phi_p$ : Pullout friction angle ($^\circ$)

4. RESULTS AND DISCUSSION

4.1 Pullout resistance

The overburden air pressures used for the tests were $\sigma_v = 5$, 20, and 35 kPa. To achieve zero pullout resistance in unloading, the geogrid was pushed back slightly at the jack. The UR steps were implemented at 3 stages: before the peak value, at the peak value and at the residual part. The whole process is presented through successive steps: O-A-B-C-D-E-F-G-H (as shown in Fig. 4 for example). UR process before the peak value is O-A-B-C. The process at the peak value is C-D-E and one more time at the residual part is F-G-H.

Before the peak values, the UR did not affect the pullout resistance however it reduced the pullout resistance at the peak and residual parts. The amount of decrease differed with geogrid types. Reduction in pullout resistance before and after UR process, e.g. $\tau_p$ at C and $\tau_r$ at E in Fig 4, was computed in the form of $(\tau_p - \tau_r)/\tau_p$ ($\%$). In these tests, the decreases at peak value of CG, SG and plate were 5%, 10% and 5% respectively.

When implemented at the residual part, pullout resistance of CG and plate showed a very little change while SG’s had a much bigger reduction. Figure 5 presents pullout strength of respective geogrid at peak value before and after the UR process under $\sigma_v = 5$, 20 and 35 kPa. The reduction of pullout resistance can be seen value decreases of $c_p$ and $\phi_p$ of each geogrid type.

The differences of reduction are due to the stiffness and geometry of geogrids. The stiff geogrid reached to the peak pullout resistance at the small pullout displacement while soft geogrid needed large pullout displacement and deformation of geogrid to mobilize the peak pullout resistance (Izawa et al.). In this test series, CG has a smaller stiffness as compare with the SG. However, there might be another factor affecting the pullout resistance. The factor would be due to soil’s dilatancy as mentioned by several authors, e.g. Bergado et al., Yasufuku and Ochiai. Soil dilatancy or confining effect is the effect of restriction of soil around the geogrid by the geogrid during the shearing. The confining effect increases the confining stress around geogrid. Restriction of soil is affected by the interval between transverse ribs, stiffness of transverse.
and longitudinal ribs and stiffness at nodes. As the frictional resistance was similar during the UR process, the reduction in the pullout resistance can be explained by the reduction in bearing interaction mechanism which occurred at the nodes and the transverse ribs. Resistance effect of the ribs at the right angle to the pullout direction is transferred more effectively to the longitudinal ribs and supported in the case of geogrid with stiff nodes. In this study, the CG has harder nodes than the SG which has rectangular nodes. Therefore, CG mobilizes more bearing resistance than the SG does. To further investigate the effects of bearing mechanism and dilatancy, the PIV method and spatial discretization scheme in finite element method analysis were used.

4.2 Analysis of the bearing mechanism and dilatancy

Dynamic behaviors of geogrid and sand interaction subjected to UR processes were analyzed through PIV method and spatial discretization scheme in finite element method. The observed window on transparent wall which showed interaction between transverse elements and sand was captured by a video. The observed window (134 mm x 80 mm) was subdivided into a nodal point mesh and analyzed by PIV method. The domain of a straight-edged quadrilateral element was defined by the locations of its four nodal points as described by Hughes. The numbers of nodes and element are 150 and 126 respectively. During pullout test, increments in horizontal and vertical displacements of each nodal point were determined. From displacements of nodal points, volumetric strain and deviatoric strain were calculated under the assumption of plane strain condition.

Figure 6 a&b show deviatoric strain or shear-strain and volumetric-strain distribution of CG pullout test subjected to UR process under overburden pressure of 35 kPa. It can be seen from steps OÆA and AÆB. The concentration was higher in the upper side than the lower side of the geogrid. However, at these stages the shear strain was still relatively small. From reloading BÆC, shear strain distribution concentrated almost symmetrically in front of transverse ribs. It indicates that due to the bearing mechanism, soil around the front of transverse bars was pushed in to form slip planes which are shown in black color. This agrees well with the bearing capacity theory proposed by Anderson. At unloading step, CÆD shear strain concentration was less than that of step BÆC because when geogrid was pushed in opposite direction the bearing mechanism also appeared at the opposite side of transverse bars. These bars pushed the soil backward which caused shear strain concentration to reduce. The following steps from D to H, same procedure was applied and the behavior of geogrid and soil interaction was similar to previous steps.

The dilatancy (phenomenon) is related to development of passive failure surfaces, which are generated against the nodes and ribs. Figure 6b shows volumetric strain distribution during the pullout test in all steps. The dilative behavior appears in front of transverse ribs and contractive behavior exits at behind of these bars. As mentioned above, due to the bearing mechanism soil around the front of geogrid’s bars was pushed in large displacements while soil behind the bars had less effect of passive resistance therefore showed small displacements. In a relative distribution between these two zones, the soil in front of the bars was compressed while the soil behind the bars was extended. Similar to shear strain distribution, volumetric strain distribution was also different at each step, for example, the dilatancy of reloading BÆC was higher than that of unloading CÆD. The alternative soil dilatancy-contraction distribution in between the two transverse ribs can be seen throughout the length of geogrid. Soil dilatancy-contraction was more at the upper side than the lower side probably side due to the boundary condition of the test apparatus. The upper part was the flexible stress boundary by the air bag therefore the deformation was not restricted. But the lower part of the box had a rigid boundary that restricted the deformation of soil.

5. CONCLUSIONS

Study on the pullout resistance with unloading-reloading processes was made on the model geogrids. Special attention was directed in geogrids to see the dilatancy mechanism and stress strain distribution during UR processes.

The followings were obtained in this study

1. The unloading-reloading reduces pullout resistance at the peak and residual part however it shows very little effect before the peak.

2. Transverse ribs push soil in front of them to form slip planes due to bearing mechanism. The soil in front of transverse ribs shows dilative behavior while soil behind transverse ribs shows contractive behavior.
Figure 6. Shear-strain and volumetric strain of soil geogrid interaction during pullout tests under unloading-reloading process from steps O~H; CG; 35 kPa; (a) Shear-strain distributions; (b) Volumetric-strain distributions; — Original position; [ ]: Real position
REFERENCES


除荷－再載荷過程を伴う引抜き試験におけるジオグリッド周辺のせん断ひずみ分布

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除荷－再載荷過程におけるジオグリッド周辺のせん断ひずみ分布と体積変化特性を求めるため、PIV（Particle Image Velocimetry）法による模型地盤内の粒子移動の計測と有限要素法で使われる手法を用いたひずみ計算を行い、模型ジオグリッドと周辺の土の相互作用を調べた。実験では、ピークの前、ピーク時、およびピーク後の残留状態において、地震時の挙動を模擬してジオグリッドを前後に動かして載荷－除荷を行った。その結果、ひずみは特に横方向部材の上側前部に集中していた。体積膨張特性が横方向部材前部に見られ、逆に後部では収縮傾向が見られた。また、ジオグリッドの長手方向で、横方向部材ごとにこのような膨張－収縮の傾向が認められた。