The role of numerical simulation for geosynthetic-reinforced soil structures
– from laboratory tests to full scale structures -

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Question: What is ‘Geosynthetic-reinforcement’? Where does ‘Geosynthetic-reinforcement’ come from?

1. Full scale model tests
   • ‘Soil Bridge’, ‘Overhanging criff’ (strong and rigid structure & weaker reinforcement), ‘Pre-stressed’ geosynthetic-reinforced soil structure,
     ‘Formative arts of geosynthetic-reinforced earth

2. Mechanical properties of compacted soil and geosynthetics
   • Similarity between compacted soil and OC clay

3. Numerical modeling of compacted soil and geosynthetics
   • Mechanical interaction between compacted soil and geosynthetics
     = geosynthetic-reinforcement effect

4. FE simulations of ‘Soil bridge’, ‘Overhanging criff’ & ‘Pre-stressed soil

5. Further targets
   • More realistic modeling of compacted soil
     Inconventional plasticity, suction effect
   • Application in the engineering practice
Experiments

'Model tests in labo. (preparatory model tests)' To 'Full scale model test'

'Experiment' To 'Analysis'

Theory

Analysis

\[ \varepsilon \]
‘Soil bridge’ was realized by removing steel H piles in number order, which supported the geosynthetic-reinforced soil structure.
**Geosynthetics**

aramid and polyethylene woven fabric coated by vinyl chloride resin

**Compacted soil**

sandy soil named ‘Omma sand’

Unsaturated, compacted sand

<table>
<thead>
<tr>
<th>specific gravity of soil particle ( \rho_s ) (t/m³)</th>
<th>2.71</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand fraction 75 mm–2mm (%)</td>
<td>89.3</td>
</tr>
<tr>
<td>gravel fraction 2mm–75mm (%)</td>
<td>0.2</td>
</tr>
<tr>
<td>clay fraction less than 0.075 mm (%)</td>
<td>10.4</td>
</tr>
<tr>
<td>uniformity coefficient ( U_c )</td>
<td>1.60</td>
</tr>
<tr>
<td>coefficient of curvature ( U_c' )</td>
<td>1.23</td>
</tr>
<tr>
<td>maximum grain size (mm)</td>
<td>4.75</td>
</tr>
</tbody>
</table>

**Materials**

Geosynthetics

(ADEM G-6)

\[ \text{load} \text{ (kN/m)} \]

\[ \text{strain} \text{ (%)} \]

\[ \text{vertical strain rate} \text{ 50%/min} \]

\[ 67.3 \text{ kN/m} \]

**Experiment result of ‘Soil bridge’ 1992**

<table>
<thead>
<tr>
<th>step</th>
<th>removed H pile</th>
<th>settlement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.160</td>
</tr>
<tr>
<td>3</td>
<td>1 – 3</td>
<td>0.319</td>
</tr>
<tr>
<td>4</td>
<td>1 – 5</td>
<td>0.438</td>
</tr>
<tr>
<td>5</td>
<td>1 – 6</td>
<td>0.590</td>
</tr>
<tr>
<td>6</td>
<td>1 – 7</td>
<td>0.770</td>
</tr>
<tr>
<td>7</td>
<td>1 – 8</td>
<td>0.880</td>
</tr>
<tr>
<td>8</td>
<td>1 – 9</td>
<td>1.200</td>
</tr>
<tr>
<td>9</td>
<td>1 – 10</td>
<td>1.200</td>
</tr>
</tbody>
</table>

It happened to cut the geosynthetics, when #7 steel H pile was removed.
Remove the supporting fill then realize the ‘overhanging cliff’

Overhanging cliff 1993

Construction of ‘overhanging cliff’

Start of the construction

Installation of the displacement markers

The final appearance of the overhanging cliff of reinforced earth in the end of the experiment
**Materials**

**Geosynthetics**
aramid and polyethylene woven fabric coated by vinyl chloride resin

**Compacted soil**
sandy soil named ‘Omma sand’
Unsaturated, compacted sand

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity of soil particle, ( \gamma_s ) (t/m³)</td>
<td>2.69</td>
</tr>
<tr>
<td>Grain size distribution</td>
<td></td>
</tr>
<tr>
<td>Gravel fraction</td>
<td>2mm—75mm (%)</td>
</tr>
<tr>
<td>Sand fraction</td>
<td>75mm—2mm (%)</td>
</tr>
<tr>
<td>Silt fraction</td>
<td>0.01—0.001 mm (%)</td>
</tr>
<tr>
<td>Clay fraction</td>
<td>less than 0.01 mm (%)</td>
</tr>
<tr>
<td>Uniformity coefficient, ( U_c )</td>
<td>23.4</td>
</tr>
<tr>
<td>Coefficient of curvature, ( U_c' )</td>
<td>12.3</td>
</tr>
<tr>
<td>Maximum grain size, (mm)</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Experiment result**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Water content, ( w ) (%)</th>
<th>Dry density, ( \rho_d ) (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.2</td>
<td>1.41</td>
</tr>
<tr>
<td>2</td>
<td>26.2</td>
<td>1.41</td>
</tr>
<tr>
<td>3</td>
<td>26.9</td>
<td>1.45</td>
</tr>
<tr>
<td>4</td>
<td>24.1</td>
<td>1.45</td>
</tr>
<tr>
<td>5</td>
<td>26.4</td>
<td>1.48</td>
</tr>
<tr>
<td>6</td>
<td>25.7</td>
<td>1.41</td>
</tr>
<tr>
<td>7</td>
<td>25.3</td>
<td>1.39</td>
</tr>
<tr>
<td>8</td>
<td>26.3</td>
<td>1.39</td>
</tr>
<tr>
<td>9</td>
<td>26.2</td>
<td>1.37</td>
</tr>
<tr>
<td>10</td>
<td>16.9</td>
<td>1.37</td>
</tr>
</tbody>
</table>

The experiment began with gradually removing the base embankment supporting the overhanging portion.

When all supporting portions were removed, little deformation amazingly occurred.
Another ‘Overhanging cliff’ 1994

We asked it a geosynthetic manufacture to offer the geosynthetics much weaker than their usual products. Then, in the summer of 1994, another ‘overhanging cliff’ was carried with much weaker geosynthetics at the same site in 1993.

Cutting the geosynthetics along the 60 deg. and 70 deg. lines from the top layer

Remove the supporting fill then realize the ‘overhanging cliff’
The experiment began with removing the fill supporting the overhanging cliff. The remaining part of the fill was brought to failure by mechanically cutting the embedded geosynthetics along the 60 deg. and 70 deg. lines from the top layer. The ‘nose’ dropped down accompanied by an unexpected breakage of the geosynthetics that was made intentionally weak.

Pre-stressed geosynthetic-reinforced soil structure 1996

Cantilever (span: max 2.0m)

Type A: pre-stressed in the interval of 1.0m

Type B: pre-stressed in the interval of 0.5m
pre-stressing

Initial support of pre-stressed soil cantilever

<table>
<thead>
<tr>
<th>Layer</th>
<th>Water Content w (%)</th>
<th>Dry Density ρ_d (t/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embankment A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.9</td>
<td>1.385</td>
</tr>
<tr>
<td>2</td>
<td>15.0</td>
<td>1.340</td>
</tr>
<tr>
<td>Embankment B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.0</td>
<td>1.350</td>
</tr>
<tr>
<td>2</td>
<td>15.1</td>
<td>1.340</td>
</tr>
</tbody>
</table>

Experiment result

Type A (when span: 1.5m) Buckling occurred

Type B (when span: 1.5m) Well maintaining the shape of cantilever
Combination: ‘Formative arts of reinforced earth’ 1996

Tightening by pre-stress
Cutting embedded geosynthetics
Overhanging cliff
Simple beam & Cantilever

Support (fill)
Steel H pile
Styrene form A
Geosynthetics A
Geosynthetics B
Geosynthetics C

1. Remove the support embankment for overhanging cliff ⊙ ‘Overhanging cliff’
2. Remove Steel H piles and melt (remove) styrene form A ⊙ ‘Soil bridge’
3. Melt (remove) styrene form B ⊙ ‘Soil cantilever’
4. Cut geosynthetics C
5. Cut geosynthetics D ⊙ lead the failure of ‘Soil cantilever’
6. Cut geosynthetics E ⊙ lead the failure of ‘Overhanging cliff’
<table>
<thead>
<tr>
<th>Layer</th>
<th>Water Content (w, %)</th>
<th>Dry Density (ρ_d, g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.7</td>
<td>1.29</td>
</tr>
<tr>
<td>2</td>
<td>14.7</td>
<td>1.29</td>
</tr>
<tr>
<td>3</td>
<td>13.7</td>
<td>1.29</td>
</tr>
<tr>
<td>4</td>
<td>17.2</td>
<td>1.30</td>
</tr>
<tr>
<td>5</td>
<td>13.0</td>
<td>1.29</td>
</tr>
<tr>
<td>6</td>
<td>12.4</td>
<td>1.30</td>
</tr>
<tr>
<td>7</td>
<td>15.1</td>
<td>1.30</td>
</tr>
<tr>
<td>8</td>
<td>15.4</td>
<td>1.31</td>
</tr>
<tr>
<td>9</td>
<td>14.8</td>
<td>1.31</td>
</tr>
<tr>
<td>10</td>
<td>17.5</td>
<td>1.37</td>
</tr>
</tbody>
</table>

The ‘nose’ dropped, approx. 0.32m

Settlement approx. 0.11m

When the 6th geosynthetic was cut in the order from the top
Reinforcement mechanism by geosynthetics

Field Test

- mechanical interaction (compacted soils vs. geosynthetics)
- shear characteristics of soils (dilatancy)

Lab. Model Test + F.E. Simulation

confining dilative deformation of compacted soils by geosynthetics
**Elasto-plastic model (Sekiguchi and Ohta’s model) for compacted soils**

**Compacted soil**

1. Dilative deformation
2. Strain-hardening to Strain-softening

---

**SO model**

Yield function of SO model

\[ f = \frac{\lambda - \kappa}{1 + \epsilon_y} \ln \left( \frac{P'}{P_0'} \right) + D \eta^* + \epsilon_y - \epsilon_y^* = 0 \]

\[ \eta^* = \frac{h}{3\left( S_{ij} \right)} \left( \left( S_{ij} - S_{ij}^* \right) \left( P'/P_0' \right) \right) \]

\[ \beta = \frac{D}{P_0'} \left( \frac{3G}{2\eta} \left( \eta_0 - \eta_{y*} \right) + \beta' \kappa \delta_0 \right) \]

\[ \beta' = M - \frac{3}{2\eta} \eta_0 \left( \eta_0 - \eta_{y*} \right), \quad \eta_0 = \frac{S_0'}{P_0'}, \quad \eta_{y*} = \frac{S_{y*}}{P_0'} \]

---

**Yield function of SO model**

- Incorporate to F.E. program, DACSAR
Evaluation of mechanical characteristics of soils

Unsaturated compacted soil VS Unsaturated disturbed & loosened soil

Soils used in experiment

- Disturbed loose sample
- Compressibility
- Shear
- Adjust water content
- $K_{0}$ consolidation

Unsaturated compacted soil
- Like saturated over-consolidation (OC) clay

Unsaturated disturbed & loosened soil
- Like saturated normally-consolidation (NC) clay
Soil sampling and laboratory tests

Labo. tests
compaction tests
$\$BT
Ko-consolidation
shear under constant volume

<table>
<thead>
<tr>
<th>specimen</th>
<th>test equipment</th>
<th>consolidation pressure (kPa)</th>
<th>initial water content (%)</th>
<th>number of test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yuhidera (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disturbed</td>
<td>Conventional</td>
<td>39.2, 78.4</td>
<td>20, 23, 25, 27, 30</td>
<td>20</td>
</tr>
<tr>
<td>Undisturbed</td>
<td>Conventional</td>
<td>156.8, 313.6</td>
<td>18.5, 21.1</td>
<td>30</td>
</tr>
<tr>
<td>Taiyogaoka (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disturbed</td>
<td>Conventional</td>
<td>39.2, 78.4</td>
<td>5, 7, 12, 15, 18, 21, 25</td>
<td>34</td>
</tr>
<tr>
<td>Mikasa's</td>
<td></td>
<td>39.2, 78.4</td>
<td>7, 25</td>
<td>4</td>
</tr>
<tr>
<td>Undisturbed</td>
<td>Conventional</td>
<td>156.8, 313.6</td>
<td>6.4, 17.8</td>
<td>30</td>
</tr>
</tbody>
</table>

Compacted soils: mechanical properties

Similar to OC clays

Key:
How much is OCR?

Shear characteristics

A sample (1994)
B sample (1996)
Disturbed & loosened sample: mechanical properties

Similar to NC clays

Compressibility

Shear characteristics

‘Strength’ of soils

Critical State

Strength increase

Yuhidera sample (1994)
Taiyogaoka sample (1996)
Evaluation of material properties: compacted soils

undisturbed sample of compacted soil

water content

\[
\left( \frac{S_u}{\sigma_{vo}} \right)_{oc} = OCR \Lambda \left( \frac{S_u}{\sigma_{vo}} \right)_{oc},
\]

\[
\Lambda = 1 - \frac{C_v}{C_s}
\]

\[\phi' = 27.5 \text{ (deg)} \quad K_0 = 0.447\]

Specification of $\phi'$ and other input parameters

\[
\left( \frac{\tau_{vo}}{\sigma_{vo}} \right)_{oc} = \frac{1 + 2K_0}{3\sqrt{3}} M \exp(-\Lambda) \quad \text{(Ohta et al., 1985)}
\]

\[
\left( \frac{S_u}{\sigma_{vo}} \right)_{oc} = OCR \Lambda \left( \frac{S_u}{\sigma_{vo}} \right)_{oc}
\]

with

\[
\Lambda = \frac{M}{1.75} \quad \text{(Karube, 1975)}
\]

\[
K_0 = 1 - \sin \phi' \quad \text{(Jaky, 1944)}
\]

\[\frac{S_u}{\sigma_{vo}} = 0.234\]
Performance of constitutive models

SO96C1 (w = 12%)

SO96C2 (w = 12%)

SO96C3 (w = 12%)

FE simulation of ‘Soil bridge’ 1992

Side view of soil structure (mm)

Supporting portion (H steel)

Step in experiment and results

<table>
<thead>
<tr>
<th>Step</th>
<th>No. of steel pile to be removed</th>
<th>Maximum deformation</th>
<th>Maximum deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No.1</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>No.1, No.2</td>
<td>0.160</td>
<td>0.160</td>
</tr>
<tr>
<td>3</td>
<td>No.1, No.3</td>
<td>0.319</td>
<td>0.319</td>
</tr>
<tr>
<td>4</td>
<td>No.1, No.5</td>
<td>0.438</td>
<td>0.438</td>
</tr>
<tr>
<td>5</td>
<td>No.1, No.6</td>
<td>0.590</td>
<td>0.590</td>
</tr>
<tr>
<td>6</td>
<td>No.1, No.7</td>
<td>0.770</td>
<td>0.770</td>
</tr>
<tr>
<td>7</td>
<td>No.1, No.8</td>
<td>0.880</td>
<td>0.880</td>
</tr>
<tr>
<td>8</td>
<td>No.1, No.9</td>
<td>1.200</td>
<td>1.200</td>
</tr>
<tr>
<td>9</td>
<td>No.1, No.10</td>
<td>1.200</td>
<td>1.200</td>
</tr>
</tbody>
</table>
FE model of ‘Soil bridge’ 1992

Input parameters

<table>
<thead>
<tr>
<th>Layer</th>
<th>G-6</th>
<th>G-3</th>
<th>G-5</th>
<th>G-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st layer</td>
<td>1.46</td>
<td>1.40</td>
<td>1.52</td>
<td>1.40</td>
</tr>
<tr>
<td>2nd layer</td>
<td>1.32</td>
<td>1.37</td>
<td>1.48</td>
<td>1.37</td>
</tr>
<tr>
<td>3rd layer</td>
<td>1.28</td>
<td>1.26</td>
<td>1.38</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Material properties: Geosynthetics

Axial strain rate: 50%/min

Polyethylene polymer grid

Aramid fiber

Linearly elastic material
FE simulation of ‘overhanging cliff’ 1993 & 1994

Cut the embedded geosynthetics along the lines (1994)

Overhanging cliff 1993 (geosynthetics F-10)
Very strong & stiff

Overhanging cliff 1994 (weaker geosynthetics F-3)
The ‘nose’ dropped down

Weaker geosynthetics

<table>
<thead>
<tr>
<th>Layer</th>
<th>0.47</th>
<th>1.73</th>
<th>0.85</th>
<th>598</th>
<th>78.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vertical displacement of markers installed in the 1994 embankment body

FE analysis of ‘Soil cantilever’

1. Introduce pre-stress to the steel bars installed at the interval of 0.5 m
   (1) Load the pre-stress to the element
   (2) Install the bar element
   (3) Applied extension force to the bar element

2. Remove the support (plastic foam) in number order so as to realize the ‘soil cantilever (2.0m span)’
**Input parameters for ‘Soil cantilever’**

<table>
<thead>
<tr>
<th>1st layer</th>
<th>2nd layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.30</td>
<td>1.35</td>
</tr>
<tr>
<td>14.0</td>
<td>15.1</td>
</tr>
</tbody>
</table>

**Effective normal stress, \( \sigma' \) (kPa)

- 3rd layer
- 4th layer

**Coefficient of earth pressure at rest:**

- 1st layer: 0.49
- 2nd layer: 0.49

**Critical state parameter:**

- 1st layer: 1.41
- 2nd layer: 1.41

**Preconsolidation vertical pressure:**

- 1st layer: 87.6 kPa
- 2nd layer: 180.7 kPa

**Effective overburden pressure:**

- 1st layer: 9.7 kPa
- 2nd layer: 3.0 kPa

**Simulation result**

- Model: ADEM F-8
- Axial strain rate: 1%/min

**Deformation when the span reaches 1.5m**

- Point A: measured = -0.16, F.E. result = -0.16
- Point B: measured = -0.12, F.E. result = -0.12

**Shear strain distribution when the span reaches 1.5m**

- Point A: measured = -0.08, F.E. result = -0.08
- Point B: measured = -0.04, F.E. result = -0.04

**Some difference between the monitored and the computed values, why?**
Reduction of pre-stress

Measured the pre-stress force working in the steel bar with time

\[ \frac{P_W}{P_I} = 0.42 \]

The pre-stressed force is reduced with time and only 42% remains at the end.

Simulation result #2 (considering reduction of pre-stress)

Well agreement between the monitored and the computed values
Combination soil structure 1996

Side view

Pre-stressed bar

No.2
No.3
No.4
No.5
No.6
No.7
No.8

Plane view

after removal of supporting portion (1)

after removal of supporting portion (2)

after cut geosynthetics

Much difference, yet

Subloading surface concept applied to SO model

\[ R = \frac{p'}{p} = \frac{p_{0}'}{p_{0}} \]

\[ f : \text{normal-yield function} \]
\[ f : \text{subloading function} \]

(Sekiguchi-Ohba model)

(Hashiguchi et al. 1989)

\[ f = MD \ln \frac{p'}{p_{0}} + D\eta - \varepsilon' = 0 \]
\[ \eta = \frac{\sqrt{\left(\frac{2}{3}\sigma_{c} + \frac{2}{3}\sigma_{0} - \frac{2}{3}\kappa_{0}\right)}}{\sqrt{p'}} \]

\[ F_{v} = MD \ln \frac{p'}{p_{v}} + D\eta - \varepsilon' \]
\[ = MD \ln \frac{p'}{p_{v}} + D\eta - \varepsilon' \]
\[ = MD \ln \frac{p'}{p_{v}} + D\eta' \left( (\varepsilon' + MD \ln R) = 0 \right) \]
Triaxial CU specimen

Smoother change from hardening to softening

Higher ability of expressing dilatancy characteristics

Considering suction effect in compacted soil

possible bands of pre-consolidation pressure of compacted soils
Estimate of preconsolidation stress considering suction

Compression curve

Compaction curve

Suction distribution

Void ratio contours
(Matyas et al. (1968))

Water retention curve model
(Kawai et al. (2000))

Leading to
A new soil structure and a new construction method

A new method to prevent slope slide
(soil structure with geosynthetics reinforcement confined by pre-stress)

TOWGA-WALL

50m high
slope 1:1
Thank you for your attention

Atsushi IIZUKA
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