FE Analysis implemented with particle discretization for reinforced-stabilized soil with geogrid

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ABSTRACT: Geogrid reinforcement technique can improve the brittle behavior of stabilized soil. This paper discusses new Finite Element (FE) analysis method to simulate mechanical behavior of reinforced-stabilized soil by geogrid. The biggest feature of the proposed analysis method is the ease of expressing discontinues deformation as separation of two adjacent Voronoi blocks owing to the particle discretization that uses non-overlapping characteristic functions. In this paper, outline of geogrid reinforcement of stabilized soil and basic concept of new FE method are explained. Numerical simulation results for laboratory model test are shown.

1 INTRODUCTION

In the construction of marine structure, utilization of dredged soft soil is an important issue to reduce environmental impact due to construction work. A popular utilizing method is to mix dredged soil with stabilizing material such as cement. However, the stabilized soil is generally brittle material.

Authors and members in project team in Port and Airport Research Institute (Japan) have developed a geogrid reinforcing method of stabilized soil for marine structure. Its feasibility was studied by performing 1/24-scale model shaking table tests (Miyata et al., 2006). In this test, high seismic performance was observed. Geogrid reinforcement technique can improve the brittle behavior of stabilized soil.

Numerical simulation method for reinforced-stabilized soil should consider discontinuous behaviour. Finite Element (FE) method is one of the most popular simulation methods. However, special technique is needed to simulate discontinuous behaviors. The FEM-β proposed by Hori et al. (2005) is a powerful solution to deal with such behavior. The biggest feature of this FE method is the ease of expressing discontinues deformation as separation of two adjacent Voronoi blocks owing to the particle discretization that uses non-overlapping characteristic functions. Authors developed new FE method based on this FEM-β. In this paper, outline of geogrid reinforcement of stabilized soil and basic concept of new FE method are explained. Numerical simulation results for laboratory model test are shown.

2 GEOGRID REINFORCEMENT FOR CEMENT STABILIZED SOIL

2.1 *Concept and application*

The invented method; SG-Wall method is combing technology of cement stabilization (S) of dredged soil and geogrid (G) reinforcement for quay wall (Wall). Typical cross section of the SG-wall is shown in Figure 1. The wall consists of cement stabilized soil, geogrid and sheet pile facing. Geogrid is used to reduce the tensile strain of stabilized soil and to prevent the propagation of cracks in the stabilized soil. Facing of the SG-wall is sheet pile. It is connected to geogrid directly. Sheet pile has high axial, shear and bending rigidity. The sheet pile is installed into base ground to fix the toe of facing. This facing system will make a rule in increase of stability.

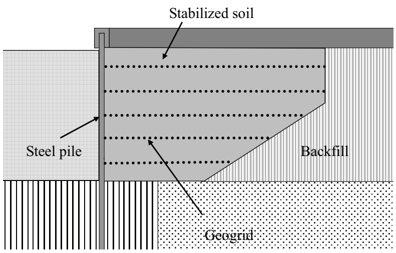


Figure 1 Geogrid reinforced quay wall with stabilized soft soil

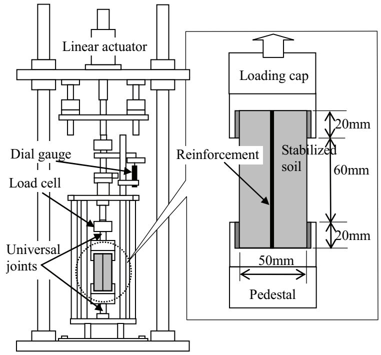


Figure 2 Outline of laboratory model test

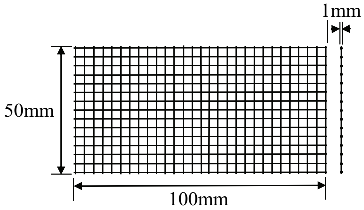


Figure 3 Geogrid used in laboratory test

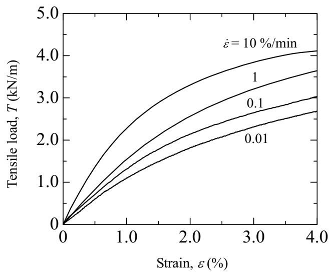


Figure 4 Tensile strength properties of geogrid

2.2 *Strength properties of reinforced-stabilized soil*

To investigate strength properties of reinforced-stabilized soil, laboratory test was conducted. The laboratory test setup is shown in Figure 2. The shape of the specimen resembled that of a square pillar (50mm×50mm×100 mm). Geogrid was placed at center of stabilized soil vertically. After curing of sample, the sample was fixed to the loading cap with gypsum. The loading was performed by making the cap move at fixed speed. A series of isotropic consolidation and triaxial tensile loading were performed by referencing the JGS-0523. Consolidation time was determined by the 3t method. The model tests ware performed for non-reinforced and reinforced-stabilized soil. In a series of test, under the 5 kinds of consolidation condition, strength properties were investigated.

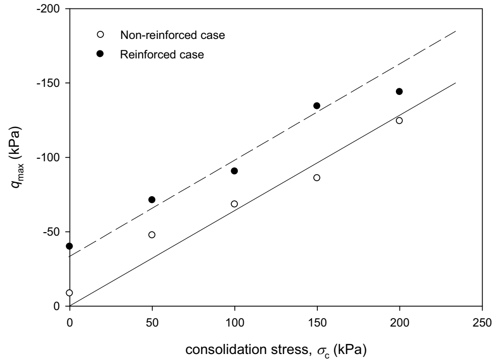
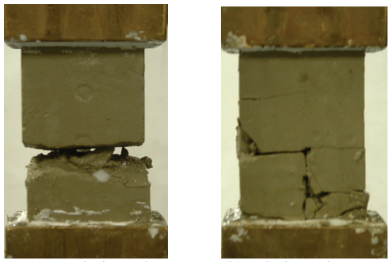


Figure 5 Peak deviator stress, q_{max} – consolidation stress, σ_c


(a) non-reinforced case (b) reinforced case
Figure 6 Observed failure modes of test samples

The stabilized soil was prepare by mixing cement with Kibushi clay (w_L=92%, PI=59, D_{50}=0.0025mm) under the condition of high water content (w=135%). Cement content, which is the weight ration of cement to dried soil, a_w, was 17.3%. In a series of test, reduced-scale model of geogrid was used as shown in Figure 3. Tensile force per unit width - strain relations are shown in Figure 4. Curing of the sample was conducted in the mold. All of the test specimens were cured for 7 days in a humid room under atmospheric pressure at a temperature of 20±3 ^{o}C.

The relations between peak deviator stress, q_{max} and consolidation stress, σ_c are shown in Figure 5. In which, q_{max} is peak value of observed deviator stress q, $q=\sigma_a-\sigma_r$, $\sigma_c=\sigma_r$, σ_a is axial stress, σ_r is lateral pressure, respectively. In this figure, strength properties of reinforced and non-reinforced cases are compared. The q_{max}-σ_c relations can be estimated by linear functions regardless of reinforcing condition. Reinforcing effect can be estimated as appearance cohesion term.

Figure 6 shows the failure mode of test samples. Strong discontinuous behaviour was observed regardless reinforcing condition. When we consider reinforcing effect of stabilized soil, this discontinuous behaviour should be considered.

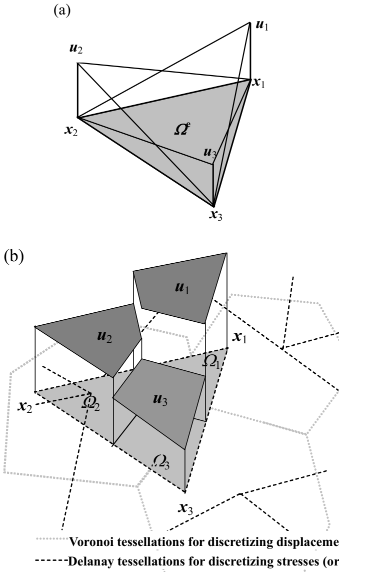


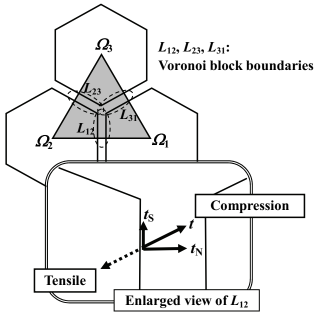
Figure 7 Comparison of discretization for (a) FEM and (b) FEM-β

3 NUMERICAL MODEL WITH PARTICLE DISCRETIZATION

3.1 *Outline*

To predict performance of the reinforced-stabilized soil structure, numerical model is needed. Stabilized soil has brittle mechanical properties as shown in the previous section. The model should be one that can consider discontinuity behaviour of solid material. The FEM-β proposed by Hori et al. (2005) is a powerful solution to deal with such behavior. The authors extended this FEM-β for simulation of reinforced-stabilized soil. In this section, at first, outline of FEM-β is introduced. Secondly, the content of our developing is explained.

The biggest difference between FEM-β and ordinary FEM lies in how the displacement field is discretized. As shown in Figure 7, in an ordinary FEM, the displacement field is discretized by the shape functions that overlap each other. In FEM-β, the displacement field is discretized by the characteristic functions that do not overlap each other. More specifically, the displacement field is discretized by Voronoi tessellation and the stress (or strain) field is discretized by Delaunay tessellation. The failure is judged with the traction calculated on Voronoi block boundaries. If the traction exceeds the failure condition, it will be considered that the concerned Voronoi block boundary failed. The failure is expressed by setting the stiffness matrix component $\boldsymbol{k}_{\mathbf{L}}$ to zero, corresponding to the Voronoi block boundary that is judged to be broken.



0. Setting the failure condition at each Voronoi block L

   $\boldsymbol{f} = \boldsymbol{f_0}$, ***Eq.*****(4)**

1. Calculation of traction $\boldsymbol{t}$ at each Voronoi block L
2. Judgment of failure

   IF $\boldsymbol{f} < \mathbf{0}$

   L fails & $\boldsymbol{k}_{\mathrm{L}}=\mathbf{0}$

   go to 3.

   ELSE

   go to 1.

3. Updating the failure condition at each Voronoi block L

   $\boldsymbol{f} = \boldsymbol{f_d}$, ***Eq.*****(5)** & go to 1.

Figure 8 Numerical scheme of the proposed method

In this research, the author extended the FEM-β to simulate the reinforced stabilized soil. Algorism of the proposed model is shown in Figure 8. The feature of this modification is introduction of updating the failure condition during the loading step. When the traction on Voronoi block boundaries become t_0, the failure is expressed by setting the stiffness matrix component $\boldsymbol{k}_{\mathbf{L}}$ to zero. In this step, equation (1) is used as the failure condition. After that, failure condition is updated from equation (1) to (2).

$$f_0 = |t| - t_0 \tag{1}$$

$$f_d = |t| - (\alpha \cdot \langle p \rangle) \tag{2}$$

Here, α are parameters showing the confining stress dependency, p is the mean principle of stress; p_0 is the initial value of p; σ_{ij}, the average stress; δ_{ij}, Kronecker's delta; and < >, the ramp function expressed as $\langle x \rangle=(x+|x|)/2$.

This operation means that contact force at closed discontinuity plane is considered when confining stress is positive. The boundary condition assumed is shown in Figure 10. This problem was solved by giving the Dirichlet boundary conditions to the lower and upper parts under the plane strain condition however test condition was three dimensions. Parameters used are shown in Table 1.

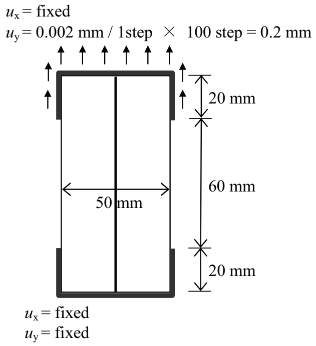


Figure 10. Outline of calculation

Table 1. Numerical parameters used in this simulation

Stabilized soil	E (kPa)	12.0x10^5
	ν	0.499
	t_0	38
	α	0.3
Geogrid	J (kN/m^2)	200
	T_{ult} (kN/m)	3.0

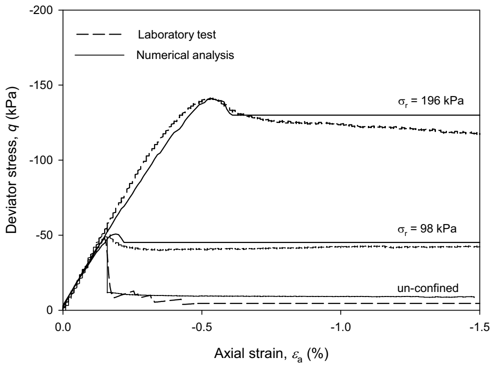


Figure 11 Simulation results for stabilized soil (without reinforcement)

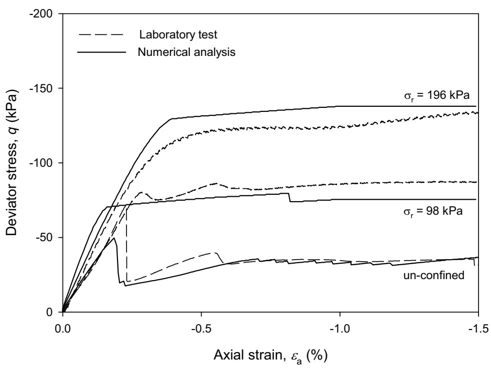
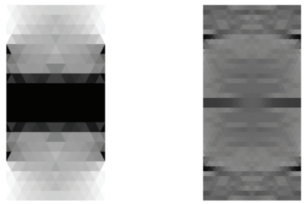


Figure 12 Simulation results for reinforced-stabilized soil



(a) non-reinforced case (b) reinforced case
Figure 13 Simulated discontinuous behavior of test sample

3.2 *Numerical analysis results for laboratory test*

Figure 11 shows numerical analysis result for stabilized soil (without reinforcement). The results for reinforced case are shown in Figure 12. The analysis reproduces the behavior of the stabilized soil or reinforced-stabilized soil observed in the laboratory test result. The strain hardening and softening behavior are well simulated by using the same parameters.

Figure 13 shows simulated failure mode for non-reinforced and reinforced cases. Comparing with those results with one shown in Figure 6, the propose method capture the actual discontinuous behavior observed at laboratory model tests

CONCLUSION

Main conclusions are as follows.

1) Geogrid reinforcement is effective for stabilized soil. By reinforcing, ductility can be improved.
2) Numerical model is proposed to simulate the mechanical behavior of reinforced stabilized soil. The validity was examined by conducting the simulation of laboratory model test.

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