DISCRETE ELEMENT SIMULATION OF WIRE-MESH RETAINING SYSTEMS: AN INSIGHT INTO THE MECHANICAL BEHAVIOUR

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Abstract This work presents a numerical study of the interaction between a granular soil and a wire-mesh retaining system with reference to an anchored flexible wire mesh system. The discrete element method is used to describe both the wire mesh and the soil. Each wire is represented by remote interactions having tensile properties. The soil behind the mesh is described by spheres with rotational resistance in order to mimic the mechanical properties of different real granular soils. The test consists in a punching plate that pushes the mesh and the soil behind like in a real mesh-anchor plate connection. The contribution of the mesh has been investigated at different displacement values of the plate. At low strain the contribution of the soil loading capacity is combined with the confinement given by the mesh that increases the initial peak of resistance. For further displacement the mesh starts to play a major role. Different soil types, mesh types and plate dimensions have been considered in a parametric analysis. The results of these tests can help to identify the best performance of the system for a given combination of plate size, mesh type and soil type.

1 INTRODUCTION

The application of wire-mesh for soil slope stabilization has experienced a significant growth in the last decades combining their high resistance capacity, its versatility and easiness of installation and the low environmental and visual impact [1,2]. However, the knowledge of the mechanical behaviour of the entire system and of its crucial parts (e.g. connection between mesh and anchor plate) are still limited. This is due to the lack of field performance data about their mechanical behaviour. Advanced numerical methods can help to enhance the understanding of mesh systems permitting the analysis of specific aspects which are non-trivial to measure experimentally. The discrete element method (DEM) has proved to be very efficient in simulating rockfall barriers [3,4] permitting investigations under large deformation conditions and to handle local ruptures. Recently, the same approach has been extended to wire-mesh retaining systems [5,6]. In the present study, the mechanical interaction between an anchored wire mesh and a granular soil is analysed with a micromechanical discrete approach. A modified punch test condition, similar to the one presented in [7], is used to focus on the local punching process that takes place at the mesh-anchor plate connection and the soil. The data thus obtained can be used to characterize the relationship between the anchor post-tensioning force and the plate settlement as well as to have an insight into the interaction mechanism between the mesh and the retained soil. Finally, the macroscopic soil characteristic, the mesh type and the anchor plate dimension are modified in order to provide a better understanding of their role in the mechanical response of the mesh-plate connection.
2 NUMERICAL MODEL

2.1 Numerical model of the wire mesh

The wire mesh used in this work is a standard hexagonal 8x10 double-twisted wire mesh. The periodic hexagonal cell is geometrically characterized by a mesh opening size of 12cm and the height of the single wire and the length of the double-twisted wire are both equal to 4cm. In the numerical model the mesh is represented by a regular grid of spherical particles which are connected by long-range remote interactions [8,9]. The particles handle the contact with external bodies, while the remote interactions define the mechanical behaviour of the mesh. These remote interactions can support only tensile forces, while bending resistance of the wire is not considered. Two different stress-strain curves are used for two different wire elements that characterize this type of mesh, namely single and double-twisted wire. This curves are derived from the experimental data presented in [9]. The validation of the mesh model has been done in previous works and is not presented in this work for the sake of brevity. The interested reader can refer to [9,10].

2.2 Test setup

The test configuration consists in a frictionless box (2.92x3x1.5m³) filled with ≈206k spherical particles above which a ≈200k mesh panel (2.92x3m²) is placed. The granular soil is constituted by ≈200k spherical grains having a mean diameter \(D_{50}=0.04\text{m}\) and prepared by gravitational deposition. The original Cundall and Strack law [11] is used to describe the contact force between the particles with the introduction of an additional rolling resistance (as defined in [12]) to obtain realistic values of the macroscopic soil friction angle. The loading element is a rigid square anchor plate (side \(B=0.32\text{m}\)) placed in the centre of the panel and shifted downward in z-direction against the mesh and the soil volume with a fixed velocity equal to 0.02m/s. The test is considered concluded at the first failure of a wire in the area around the plate. Plate’s rotations are not allowed as well as its translation along \(x\)-axis and \(y\)-axis. Symmetric boundary conditions are imposed at the edges of mesh panel (i.e. displacements orthogonal to the considered side are blocked). For the sake of clarity a sketch of the test setup and of the boundary conditions are reported in Figure 1(a) and Figure 1(b) respectively. During the test, the stress and strain on the wires as well as the force acting on the plate and its displacement are measured. The final output is a set of force-displacement curves (force sustained by the system, force sustained by the mesh). The numerical parameters used in the reference test are reported in Table 1.

![Diagram](image)
Figure 1: (a) Geometry of the modified punch test configuration and (b) scheme boundary conditions of the mesh.

Table 1: Numerical parameters used in the DE model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus at the contact $E_m$ [MPa]</td>
<td>100</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu_m$ [-]</td>
<td>0.3</td>
</tr>
<tr>
<td>Contact friction angle $\phi_m$ [°]</td>
<td>35</td>
</tr>
<tr>
<td>Rotational stiffness coefficient $\beta_r$ [-]</td>
<td>0.02</td>
</tr>
<tr>
<td>Twisting stiffness coefficient $\beta_tw$ [-]</td>
<td>0.02</td>
</tr>
<tr>
<td>Rotational resistance coefficient $\eta_r$ [-]</td>
<td>0.02</td>
</tr>
<tr>
<td>Rotational resistance coefficient $\eta_tw$ [-]</td>
<td>0.02</td>
</tr>
<tr>
<td>Soil particles mean diameter $D_{so}$ [m]</td>
<td>0.04</td>
</tr>
<tr>
<td>Mesh nodal particles diameter $D_{mesh}$ [m]</td>
<td>0.0108</td>
</tr>
</tbody>
</table>

3 NUMERICAL RESULTS

The mechanical response of the mesh-soil punch test is provided in terms of force-displacements ($F - d_z$) curves. The displacement is defined as the displacement of the plate, while three different measurements for the force are used:

- the overall force sustained by the system;
- the force sustained by the wire mesh;
- the force sustained by the soil back-calculated as the difference between the previous two;

In this way the contribute of the different parts (i.e. wire mesh and soil) on the overall resistance and their possible mutual interaction can be evaluated. In Figure 2 these curves are reported together with the one obtained without the presence of the mesh. Finally, a curve given by the algebraic sum of the mesh mechanical response and the solely soil mechanical response is reported in the same figure for a direct comparison.

Observing the results of the mesh-soil punch test it is possible to argue that, the mechanical response of the system, for small displacement (i.e. $d_z \leq 0.1B$), is dominated only by the soil mechanical response. For small displacement, in fact, the mesh cannot provide a significant contribution to the system resistance because of its soft response against out-of-plane loads. Once a first failure mode is triggered (i.e. soil failure) an abrupt change in the $F - d_z$ curve is observed. From this moment a further increase of the plate displacement leads to a progressive increase of the mesh response in terms of sustained force. After the first force peak, therefore, the mechanical response of the system seems to be controlled by the wire mesh with a residual (almost constant) contribute of the soil.
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Figure 2: Mechanical response ($F - d_z$ curves) of: the system (solid line), its different parts (mesh (dashed line), soil (▲)), the soil in the absence of the mesh (●) and the algebraic sum of the latter and the mesh (▼). For the sake of clarity, a graphical explanation of the legend is also reported.

From the comparison of the soil response obtained with and without the mesh it is possible to observe that the presence of the mesh plays an important role. In the first phase of the test, without even sustaining a significant force, the mesh postpones the soil failure providing an increasing of its bearing capacity. In the second phase, the mesh continues to limit the soil deformations contrasting the lateral spreading of the soil. This kinematic constraint avoids the strong reduction of the sustained force after the peak phase. Instead, a reduction of the force is observable in the absence of the wire mesh accordingly with the classical theory of shallow foundations [13,14] (see Figure 2). However, the kinematic of the failure mechanism remains similar to the one of shallow foundations also in the presence of the mesh as shown in Figure 4. For a more precise evaluation of role played by the mutual interaction between the mesh and the soil, the $F - d_z$ curve of the system is compared, in Figure 3, with the one computed as the algebraic sum of the mesh mechanical response and of the soil (without the mesh). The filled area between the two curves provides a graphical quantification of the contribution given by mesh-soil interaction. This interaction increases the soil peak failure force (for $d_z<0.02$m) by a factor of 1.35 and the ultimate failure force of the system (characterized failure of the mesh) by a factor of 1.45. The mean difference, in terms of force, between the two curves in Figure 3 is approximatively equal to 26 kN ($\approx 33\%$ of the ultimate force) denoting the significant enhancement of system resistance given by the interaction between the mesh and the soil.
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Figure 3: Comparison between the mechanical response of the system and the algebraic sum of the mesh and soil taken separately. The filled area graphically quantifies the mesh-soil interaction.

Figure 4: Evolution of the soil displacement field in the soil and a snapshot of a piece of the system an instant prior to the mesh failure.

4 PARAMETRIC ANALYSIS

In order to better understand the mechanical behaviour of the mesh-soil punch test, the soil type as well as the mesh stiffness and the plate dimension are varied.

4.1 Soil type

The macroscopic properties of the numerical soil are changed using different values of the rolling resistance contact parameters. This allows to virtually account for the non-spherical shape of the grains obtaining materials with different macroscopic friction angles (peak and
residual) using spherical particles [15,16]. The macroscopic properties of the numerical soils have been derived from 3D triaxial test on a cubic periodic sample. The deviatoric stress-axial strain curves thus obtained are reported in Figure 5(a). The numerical rolling (twisting) and the back-calculated macroscopic parameters are summarized in Table 2.

Table 2: Characteristics of the numerical soils used in the parametric analysis.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus $E_{M,50}$ [MPa]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu_M$ [-]</td>
<td>0.27</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td>Peak friction angle $\phi_{M,p}$ [°]</td>
<td>29</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>Residual friction angle $\phi_{M,p}$ [°]</td>
<td>19</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Rotational stiffness coefficient $\beta_r$ [-]</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Twisting stiffness coefficient $\beta_{tw}$ [-]</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Rotational resistance coefficient $\eta_r$ [-]</td>
<td>0.00</td>
<td>0.02</td>
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<tr>
<td>Rotational resistance coefficient $\eta_{tw}$ [-]</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
</tr>
</tbody>
</table>

In Figure 5(b) the force-displacement curves obtained for the entire system and for the mesh only are reported. The force sustained by the system highly increases when increasing the strength resistance of the soil according to the classical geomechanical theories [13,14]. An interesting effect is instead the slight increase of the mesh capacity which is probably imputable to a better redistribution of stresses on the mesh itself.

4.2 Mesh type

The mesh type is modified varying the diameter of the steel wires. This allows to modify the strength and the stiffness of the mesh without affecting the deflection at failure of the mesh panel. Three different diameters for the single wires are used: 2.0mm, 2.7mm
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The diameter of the double-twisted wires is, obviously, twice the one of the single wire. In Figure 6(a) and Figure 6(b) the contribute of the mechanical response provided by the mesh and by the soil respectively, are reported. Finally, in Figure 6(c) the overall force-displacement curve is reported.

As expected, the ultimate force of the system increases using a larger wire diameter (see Figure 6(c)). However, it is interesting to note how this gain is provided not only by the increase of the mesh ultimate strength (see Figure 6(a)), but also in terms of mesh-soil interaction which reflects in an enhancement of the soil bearing capacity (see Figure 6(b)). This latter derives from the higher confinement that the mesh exerts on the soil contrasting the soil squeezing effect under the plate.

4.3 Plate dimension

Finally, the dimension $B$ of the square plate is varied in a range between 160mm and 480mm. In Figure 7(a) the force-displacement curves of the entire system and of the mesh are reported. For the sake of clarity only four values of $B$ are reported. As a general observation, the increase of the plate dimension leads to an increase of both the soil bearing capacity and the mesh sustainable force which entails a significant gain in terms of ultimate force of the system. The force value characteristic of the occurrence of these two mechanisms are represented in Figure 7(a) with a star ($\star$) and a diamond ($\bigdiamond$) marker respectively. However, these two contributions are differently influenced by a variation of the plate dimension. The two failure mechanisms involved in the problem are, thus, separately investigated. In Figure 7(b) the values related to eight different values of $B$ are reported. It can be observed that the ultimate force of the mesh ($\bigdiamond$) linearly scales with the plate dimension ($F_{m,u} \propto B$); this is in agreement with the assumption that the resistance of
an anchored mesh is a function of the number of the wires intercepted by the anchor plate. On the other hand, the contribute given by the soil resistance \( (\bullet) \) scales with the cube of \( B \) \( (F_{s,f} \propto B^3) \) being in perfect agreement with the classical theory of shallow foundations \([13,14]\).

![Figure 7: (a) Mechanical response of the system varying the anchor plate dimension and (b) fit of the maximum force value provided by the soil (\( F_{s,f} \)) and the mesh (\( F_{m,f} \)).](image)

### 5 CONCLUSION

In this work a 3D discrete element model was used to analyse the local punching behaviour which develops below the anchor plate of a secured drapery mesh system. The numerical simulations have shown that mechanical response of the system is characterized by two phases, however the failure mechanism remains similar to one typical of a shallow foundation. Firstly, for low displacement \( (d_z \leq 0.1B) \), its response is controlled by the soil bearing capacity. Secondly, for further plate’s displacements, the mesh contribute is progressively activated and acts as a confinement for the retained material. This confinement contrasts the lateral spreading of the soil and avoid the significant reduction of sustained force observed in the absence of the mesh showing that the mesh-soil interaction plays a significant role. It was shown this interaction increases when increasing the mechanical properties (i.e. stiffness and strength) of the mesh. Finally, it has been proved that the ultimate force of the mesh scales linearly with the plate dimension, while the contribute provided by the soil scales with its cube.

### REFERENCES


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