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The impact of clips between the reinforced layers on the performance of rockfall protection embankment

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SUMMARY: Rockfall protection embankments (RPEs) represent valuable mitigation measures against rockfalls, however their behaviour during the impact is not yet fully investigated. In this study, several numerical models of RPEs reinforced with double twist wire mesh have been developed using Abaqus/Explicit FEM code. Specific focus is given to the impact of clips installed between adjacent reinforced layers. The study presents and discusses the macroscopic behaviour of these structures with and without clips.

Keywords: Rockfall, rockfall protection embankment, numerical methods, double twist wire mesh.

Introduction

Rockfall phenomena are significant hazards that affects mountain areas and, due to the climate change effects, they are increasing in frequency. Rockfall protection embankments (RPEs) represent valuable mitigation measures, widely adopted especially in case of events involving multiple impacting blocks or very high kinetic energies (Peila et al., 2007, Vigna et al., 2023). Currently, RPEs structural response when impacted has not been comprehensively investigated and real-scale impact tests were limited, primarily due to challenges in reproducibility and cost constraints.

The present study focuses on the influence of the clips between layers on the behavior of the RPE reinforced made with double twist wire mesh. Numerical models, developed in Abaqus/Explicit FEM code, accurately replicate the wrap-up layered geometry of the reinforcement, as well as the clips (Figure 1) installed in the wrap-up area, which are punctual connection elements recommended from the producers when this kind of reinforce is employed. However, the clips influence on the RPE behavior during the impact has not been yet investigated. The tests conducted by Peila et al. (2007), which have not incorporated clip elements, have been back analyzed to calibrate the numerical mechanical parameters of the soil. Subsequently, with the same test conditions a comparison is performed considering both cases with and without clip elements.

Methodology

The numerical models are developed using Abaqus/Explicit FEM. The reinforcing elements used in the model is the double twist wire mesh “Green Terramesh Light”, produced by Maccaferri, type 8x10 (EN 10223-3) and wire diameter of 2.20/3.2 mm. The mesh has, in accordance with ETA n. 16/0758 (version 06 of 30.08.2023), a tensile resistance of $F_{max} = 40 \pm 5\ kN/m$ and an ultimate strain $\varepsilon_{max} = 10\%$ as reported by the technical datasheet. The mesh producer recommends a clip spacings of 0.20 m, with an ultimate strength of $T_{max} = 2\ kN$ each one (EAD 200086-00-0602).

The compacted soil is modeled with three-dimensional elements (C3D8R) and the material constitutive law is linear elasto-plastic with modified Drucker–Prager yield criterion.

The impactor is spherical and modeled as perfectly rigid body.
The double twist wire mesh is modelled as shell element (S4RS) and the constitutive law is elasto-plastic associated with the "Ductile Damage" law. This choice allows to manage the large deformations to which the wire mesh is subjected in the impact zone. Moreover, when a mesh element reaches ε_{max} it is removed from the analysis in order to simulate a wire mesh local failure. The clips among the reinforced layers are modelled using Abaqus fasteners elements whit the failure criterion depending on T_{max}.
RPE foundation interaction is modelled with a base layer having the same mechanical property of the compacted soil and meshed with solid elements (CIN3D8) (Vigna et al., 2023).
Due to the three-dimensional geometry of the problem and the computational effort, the symmetry of the problem is considered and half of RPE and impactor are modelled.
Figure 1 shows the cross section of the RPE, the wrap-up geometry and the clips spacing (a). The impact is perpendicular to the upstream side bank with a velocity of 32 m/s located between the layer n°4-5 with an overall kinetic energy of about 4180 kJ (Peila et al., 2007).
After the calibration of the soil mechanical parameters, the results obtained with and without the clips are compared.

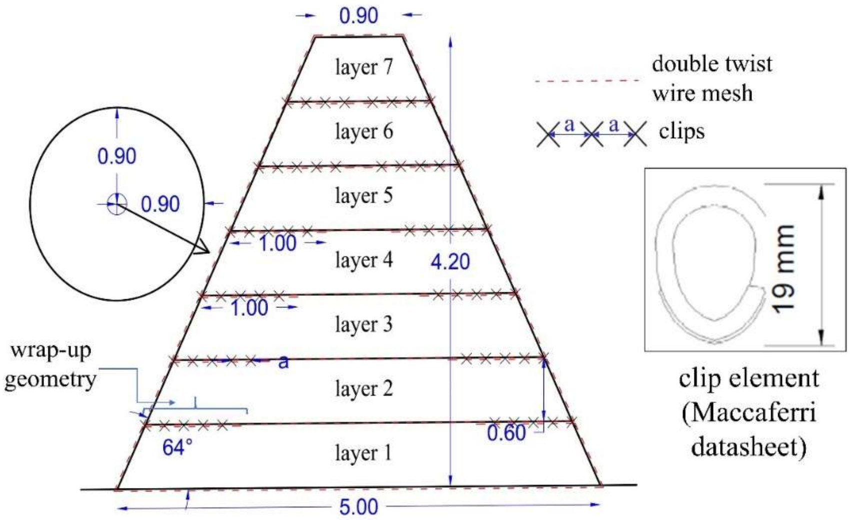

Figure 1: Cross section of the RPE tested by Peila et al., (2007) in which is shown the clips location used in the comparison models.

Soil mechanical parameters calibration

The soil mechanical parameters are calibrated by back analyzing the tests made by Peila et al. (2007). The tests have shown a behavior mainly involving the impacted layer and characterized by an upstream maximum depth of the crater (U_u) and a rigid downstream sliding (U_d) (more details are reported in Peila et al., 2007). The experimental values are $U_u \approx 1\ m$ and $U_d \approx 0.60\ m$ and are used as comparison values in the calibration process.
The soil calibrated parameters are shown in Table 1, in which ρ is the density, E is the Young modulus, υ is the Poisson ratio, φ is the friction angle, k is the flow stress ratio, ψ is the dilatancy and c is the cohesion. More details about the soil constitutive law are reported in Vigna et al., (2023). The back-analysis results are shown in Figure 3 and Figure 4 with reference to the curves with $a = NC$.

Table 1: Soil mechanical parameters back-analysed.

$\rho\ [kg/m^3]$	$E\ [MPa]$	$\upsilon\ [-]$	$\varphi\ [°]$	$k\ [-]$	$\psi\ [°]$	$c\ [kPa]$
2100	90	0.3	34	0.78	0	85

Results

The model results are presented in the following. The test is simulated with clips spaced apart of $a = 0.20\ m$ and $a = 0.30\ m$. Figure 2 shows a comparison of the final configuration of the RPE after the impact, respectively, without clips and with clips equally spaced of $a = 0.20\ m$.

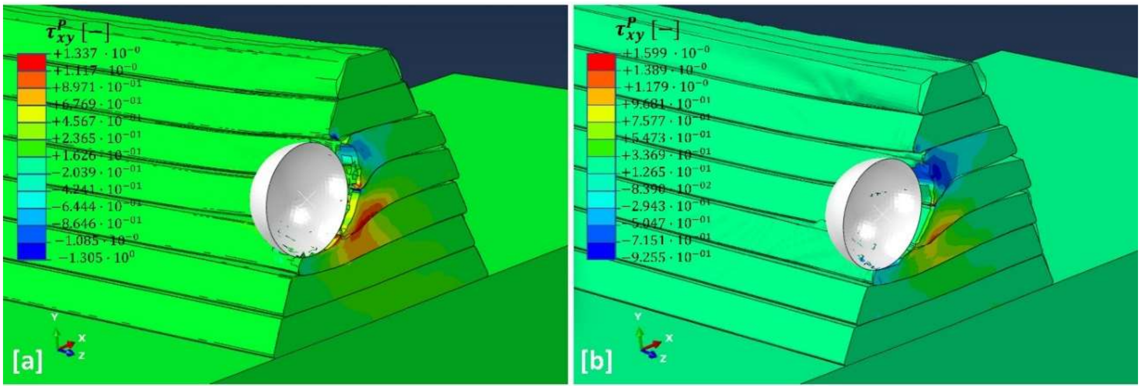

Figure 2: Final configuration of the RPE models in which it is shown the plastic shear strains (τ_{xy}^{P}): [a] without clips ($a = 0$), [b] with clips spaced of 20 cm ($a = 0.20\ m$).

Figure 3 and Figure 4 show the displacements curves of the most deformed layer along the RPE extrusion (layer names are referred to Figure 1). According to these models, the effect of clips appears to reduce the final maximum deformations of the RPE by a few centimetres: $U_u = 1.04\ m$ and $U_d = 0.48\ m$ without clips, $U_u \approx 1\ m$ and $U_d \approx 0.4\ m$ in both cases with clips. However, the presence of clips results in a more uniform deformation of the structure, engaging multiple layers in the resistance mechanism (Figure 2b).
Table 2 reports the number of clips broken during the impact upstream and downstream (respectively N_u and N_d), the maximum deceleration on the sphere a_{max}, the impact energy redistribution (plastic energy E_p, friction energy E_f and elastic energy E_{el}), the normal force F_n applied to the foundation in addition to the self-weight, and the tangential force F_t due to the impact. It is important to underline that few clips broke in the simulated impact condition. The clips tend to result a stiffer response of the RPE, leading to a higher a_{max} and lower displacement field. Regarding the effects on the foundation layer, the presence of clips tends to reduce the amplification of the self-weight, to the detriment of the increase in the tangential force; those values should be taken in to account in the overall stability of RPE-slope system. Based on the outputs of the analysis, the energy distribution remains largely unaffected by the clips density values investigated, confirming Peila et al. (2007) results.

Table 2: Numerical model results.

a $[m]$	N_u $[-]$	N_d $[-]$	a_{max} $[m/s^2]$	E_p $[\%]$	E_f $[\%]$	E_{el} $[\%]$	F_n $[kN]$	F_t $[kN]$
NC	-	-	1412	86.6	8.9	4.5	3112	692
0.20	31	2	1679	88.8	5.6	5.6	2318	807
0.30	41	11	1595	88.8	5.7	5.5	2322	804

Conclusion

Numerical FEM models of a rockfall protection embankment reinforced with double twist wire mesh have been studied with special focus on the influence of clips between adjacent reinforced layers.
Based on the results, it appears that the presence of clips reduces the final deformation of the RPE (Figure 3 and Figure 4) improving, from a macroscopic point of view, the structural collaboration among the layers during the impact phase. Nevertheless, a deeper parametric

analysis is necessary to better understand the influence of clips on the dynamic response of the structure, as well as incorporate their structural contribution into current analytical design methods proposed by Marchelli & Deangeli (2022).

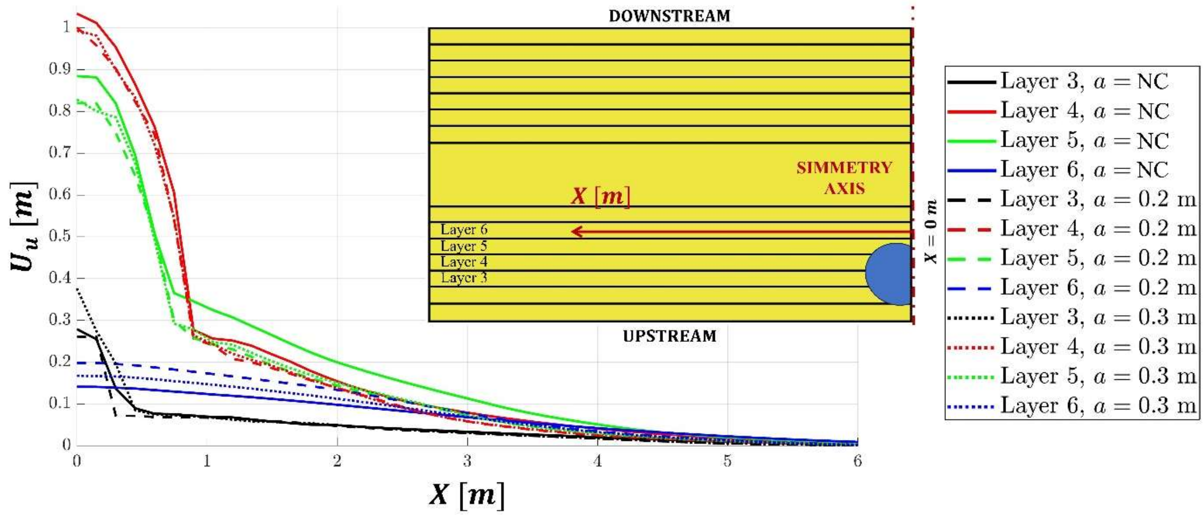

Figure 3: Downstream displacement at the impact n°2 tested by Peila et al., (2007) on different soil layers.

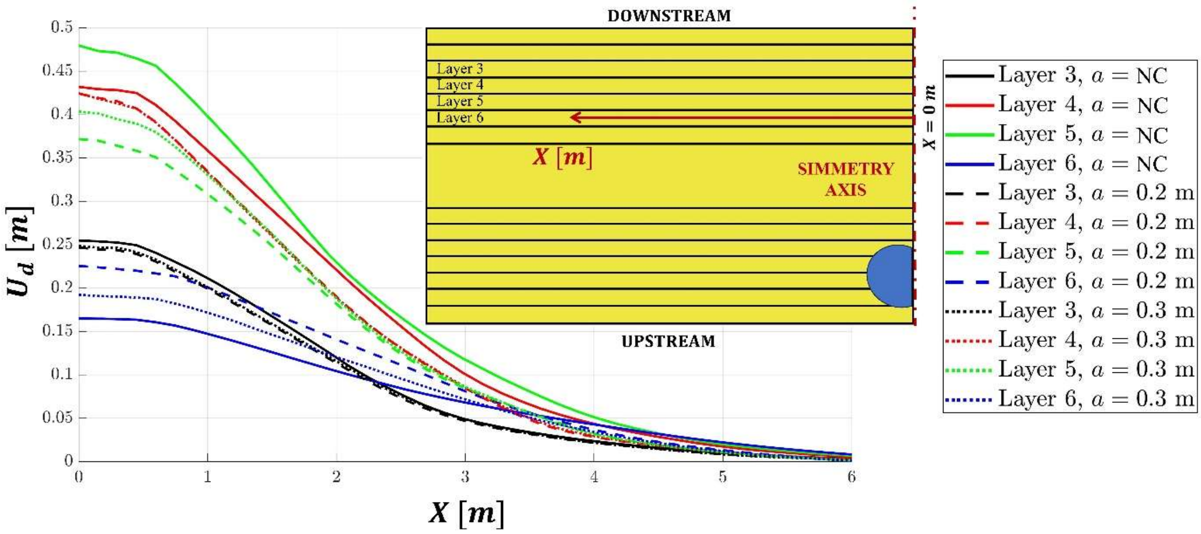

Figure 4: Upstream displacement at the impact n°2 tested by Peila et al., (2007) on different soil layers.

Acknowledge

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