Assessment of deformations of a reinforced soil structure

Evaluation des déformations subies par l'ouvrage en terre armée

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ABSTRACT: Deformations of a 13 m wall of reinforced soil were measured during the wall construction at three levels along the wall height by the use of sliding deformeters with tubes 12 m to 18 m long. These deformations are compared to calculated values obtained by incorporating a special constitutive relationship for soil into the computer program FLAC. Nonlinear behavior of the soil and the reinforcement were taken into account in the numerical analysis.

RESUME: Déformations subies par un mur en terre armé, 13 m d'hauteur, ont été mesurées pendant la construction du mur à trois niveaux le long d'hauteur du mur en utilisant les déformètres glissants à tubes 12 à 18 m de longueur. Ces déformations sont comparées aux valeurs calculées en introduisant une relation spéciale constitutive pour sol dans le logiciel FLAC. Le comportement non-linéaire de la terre et l'armature a été pris en compte lors de l'analyse numérique.

1 INTRODUCTION

Four walls of reinforced soil were constructed along the Zagreb-Rijeka highway in Croatia. The Maccaferri Terramesh System was used as reinforcement. The design requirements for the reinforced soil stiffness and deformations were set forth on the basis of the numerical analysis carried out by the computer program FLAC.

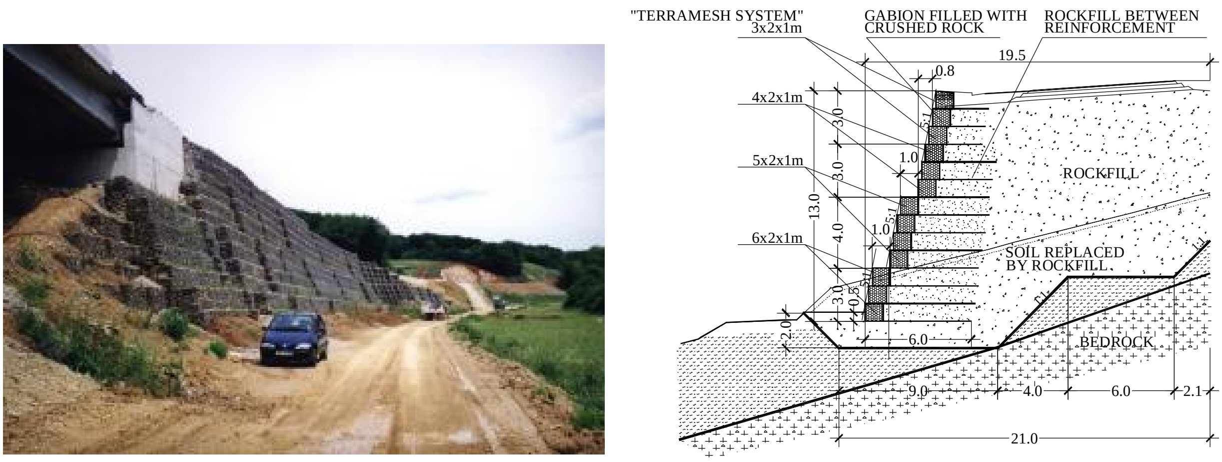


Figure 1. Wall of reinforced soil.

Measurements of the stiffness and deformations of the reinforced soil were taken during the construction of the walls (Stanić et al. 2001). Tubes for sliding deformeters (Kovári and Amstad 1982) were fixed to the reinforcement wire mesh at several levels behind the retaining structures. The measured deformations by sliding deformeters were compared to those calculated by using a nonlinear elasto-plastic constitutive model with kinematic hardening (Szavits-Nossan and Kovačević 1994, Kovačević 1999). The maximum shear modulus G_0 was determined by using the Spectral Analysis of Surface Waves (SASW) during the wall construction. The wire mesh characteristics were determined from test results published by Lo (1990).

The completed wall of reinforced soil described in this paper is shown in Figure 1, as well as the geometry of the wall. The wall height is 13 m and it is composed of four blocks, three of which are 3 m high and one is 4 m high. The length of reinforcement is decreasing from 6 m in the lowest block to 3 m in the top block. The wall inclination is 5:1 and the foundation depth is 0,5 m.

2 MEASUREMENTS ON THE REINFORCED SOIL STRUCTURE

Three tubes for sliding deformeters were installed at three levels during the wall construction, as shown in Figure 2. The tube D1 is 18 m long, the tube D2 is 16 m long and the tube D3 is 12 m long. The table in Figure 2 shows the sequence of gabion construction, level 1 being at the bottom of the wall and level 13 at its top. The designations in the three columns of this table correspond to the three deformeter measurements as they were taken during the wall construction. For example, the designation “0”+8m corresponds to measurements taken by the sliding deformeter D1 after 12 levels of gabions were completed, i.e. 8 m of gabions were constructed above this deformeter.

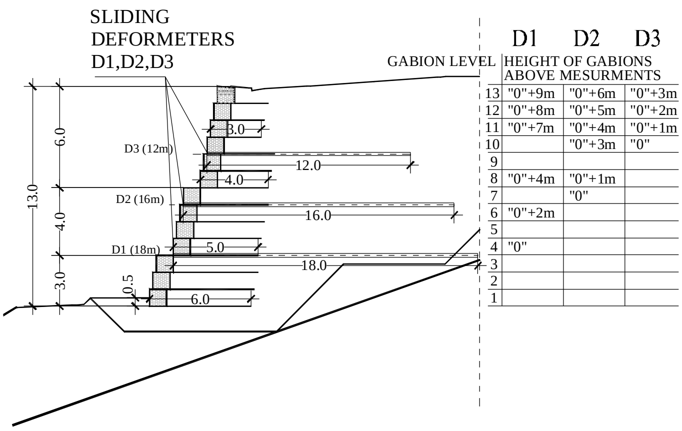


Figure 2. Locations of sliding deformeters.

The results of the sliding deformeter measurements are shown in Figures 3 to 5 for deformeters D1, D2 and D3 respectively. Axial strains and deformeter elongations are given with respect to the length of the corresponding sliding deformeter. In each case the length of the deformeter tube was sufficient to cover the whole region of the wall where displacements occurred. The measurements were taken for each meter of the tube length, so that relative strains are calculated from the elongation of 1 m of the tube length. The total wall displacement is calculated by integrating axial strains.

3 NUMERICAL ANALYSIS

The simulation of the wall construction was carried out by the use of the finite element program FLAC. The geometry of the model, the layout of different materials and material properties are shown in Figure 6. The gabions are denoted by M1, the reinforced soil by M2, the rockfill by M3, the foundation soil by M4 and the bedrock by M5.

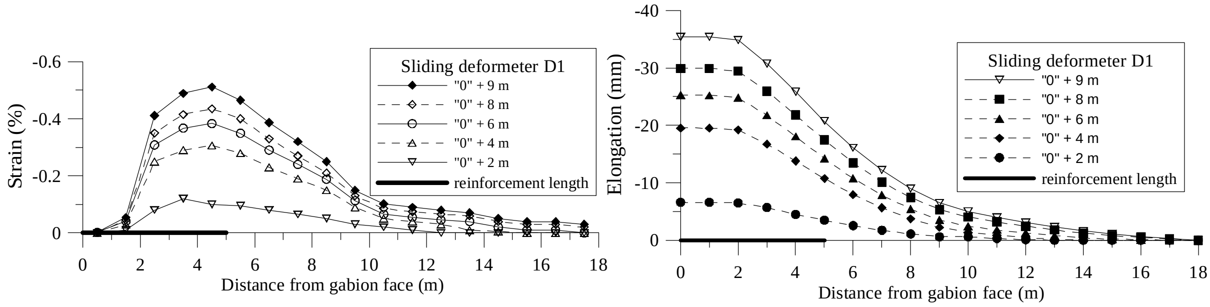


Figure 3. Measurements taken by sliding deformeter D1.

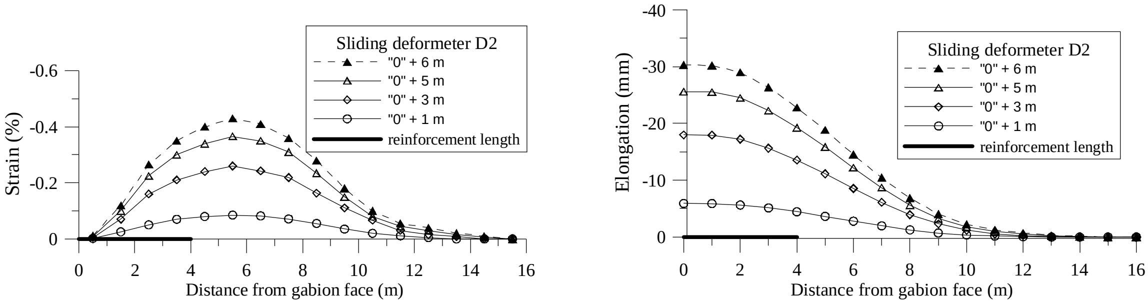


Figure 4. Measurements taken by sliding deformeter D2.

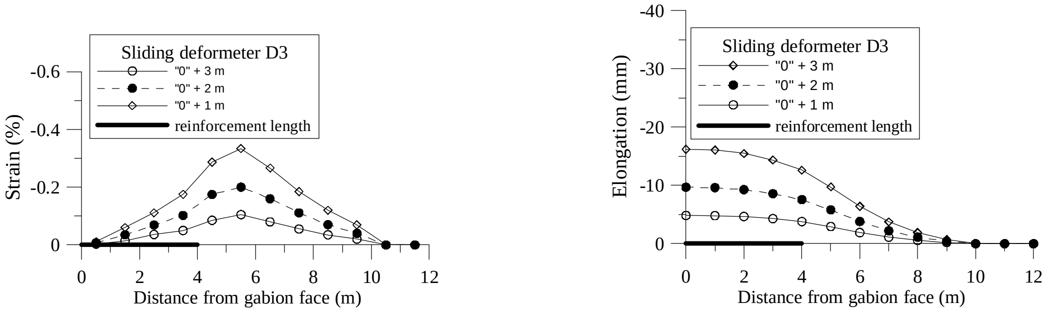
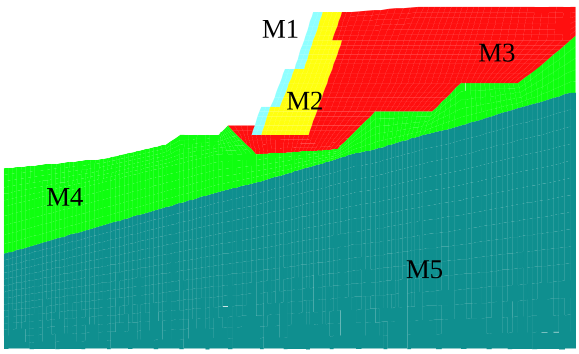


Figure 5. Measurements taken by sliding deformeter D3.



Material	ν	G_0 kPa	γ kN/m^3	c' kPa	φ' °
M1	0,25	60 000	19	-	-
M2	0,25	40 000	19	0	40
M3	0,25	40 000	19	0	40
M4	0,25	20 000	20	0	40
M5	0,25	7×10^6	26	-	-

Figure 6. Numerical model and material properties.

The average stiffness of 40 000 kPa was taken for the whole reinforced soil because the measurements have shown that the increase of stiffness with depth was within 5 %. There was also no significant difference between the stiffness of the reinforced soil and the rockfill behind it, so the same value was used for both materials. Materials M1 and M5 were modeled as linear elastic. A special constitutive equation developed by Szavits-Nossan and Kovačević (1994) was used for materials M2, M3 and M4.

3.1 Soil model

A nonlinear elasto-plastic constitutive model with kinematic hardening (Szavits-Nossan and Kovačević 1994, Kovačević 1999) was implemented in the program FLAC and used in the numerical analysis. This model can well describe the behavior of stiff cohesive and cohesionless soils in the whole range from small strains to failure.

The model used in this paper is composed of three simple linear elastic - ideally plastic 3D submodels connected in parallel, so that every submodel has the same strain history. All submodels have the same Mohr-Coulomb failure criterion and zero dilatancy.

The described constitutive model uses the relationship between the normalized shear modulus (G/G_0) and the normalized shear strain (g/g_r), where g_r is the elastic strain at failure. This relationship was obtained from triaxial test results on two types of sands (Matešić 2002), where measurements were made on the sample by means of linear displacement transducers, so that the behavior in the whole range of strains from very small to large strains was obtained. The maximum shear modulus G_0 was determined on the basis of a large number of SASW tests performed on reinforced soil structures. The triaxial test curves and the relationships used for the numerical model are shown in Figure 7.

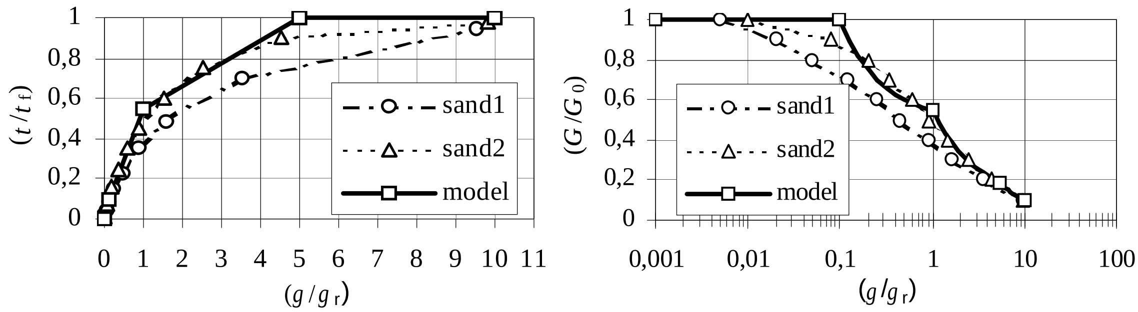


Figure 7. Normalized shear stress (t/t_f) and normalized shear modulus (G/G_0) vs. normalized shear strain (g/g_r) from triaxial tests (Matešić 2002), and relationships used for the numerical model.

3.2 Reinforcement model

The Terramesh system was used for gabions and to reinforce the backfill of the wall. This reinforcement consists of a double twisted hexagonal mesh with zinc coated and PVC coated steel wire 2,7 mm in diameter. The wire complies with BS EN 10223-3:1998. Its tensile strength is between 350 N/mm^2 and 550 N/mm^2, and its minimum axial strain at failure is 10 %.

For the given mesh geometry, number of wires per unit mesh width and wire diameter, the wire tensile strength of 450 N/mm^2 gives the theoretical mesh tensile strength of 46,54 kN per meter of mesh width. The mesh tensile strength tests performed in the air according to ASTM A-975 and BS EN 10223, give the average value of 50 kN per meter of mesh width, with a strain of 10 %.

Direct shear test results from literature (Lo 1990) were used to assess the properties of the reinforcement wire mesh. In these tests the strength and stiffness of the reinforcement were determined by placing it in sand with the dry density of 1,68 g/cm^3 and the angle of internal friction of 34,2°. The tests were performed with the vertical stresses of 35 kN/m^2, 75 kN/m^2, 150 kN/m^2 and 200 kN/m^2.

These test results provided the basis for the determination of the relationships between the tensile force in the reinforcement and the tensile axial strain, as well as between the reinforcement stiffness and the tensile axial strain (Figure 8), that were used for the numerical modeling of the reinforced soil structure. The reinforcement stiffness was limited to 12 000 kN/m for axial strains less than 0,15 %, and the best fit curve from Figure 8b was used for calculating the stiffness for axial strains greater than 0,15 %, irrespective of the vertical stress.

The limit axial strain, which causes the reinforcement failure, depends on the vertical stress. This limit strain is equal to 2 % for vertical stresses greater than 150 kN/m^2. The reinforcement breaks down when the limit strain is greater than 2 %, and its stiffness is then equal to zero. For vertical stresses between 75 kN/m^2 and 150 kN/m^2, the limit axial strain is equal to 3 %, and for vertical stresses between 30 kN/m^2 and 75 kN/m^2, it is equal to 4,5 %.

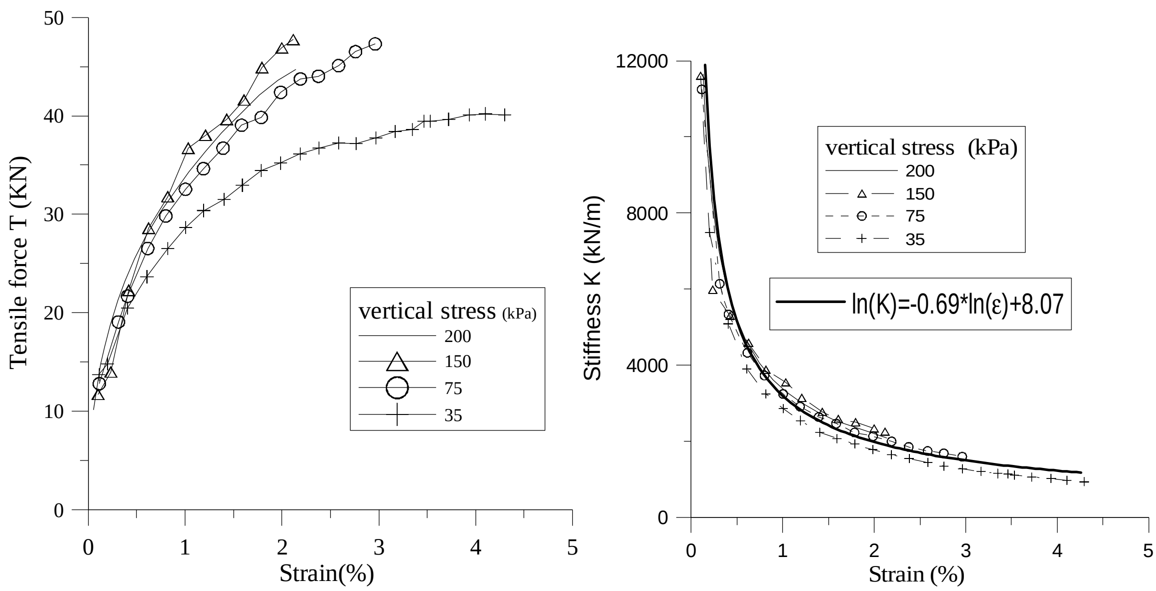


Figure 8. Reinforcement tensile force and stiffness vs. tensile axial strain (data interpreted from Lo 1990 up to the mesh failure).

4 COMPARISON OF MEASUREMENTS AND CALCULATIONS

The comparison of measured and calculated displacements at the level of sliding deformeters D1 and D2 is shown in Figure 9. The match between the corresponding curves is very good at the gabion face, which demonstrates that the described numerical method can be used for predicting the wall displacements. The computed values, however, do not match the measurements that well at a distance form the gabion face. It can be seen that the measured values are reduced at smaller distances from the gabion face than those from the numerical analysis.

5 CONCLUSION

The presented comparison of measured and computed deformations of a wall of reinforced soil shows that it is possible to improve the prediction of the behavior of reinforced soil structures by using nonlinear constitutive equations for soil and reinforcement. Sliding deformeters and SASW were used for measurements during the wall construction. Triaxial test results on sand were adjusted to the measured in situ small strain stiffness, and they were then used for the constitutive equation for soil. Published results of direct shear tests on wire meshes were used to model the behavior of reinforcement. The computed displacements of the wall correspond very well to measured values. Sliding deformeters used in this project have proven to be a reliable tool for monitoring the performance of retained structures of reinforced soil.

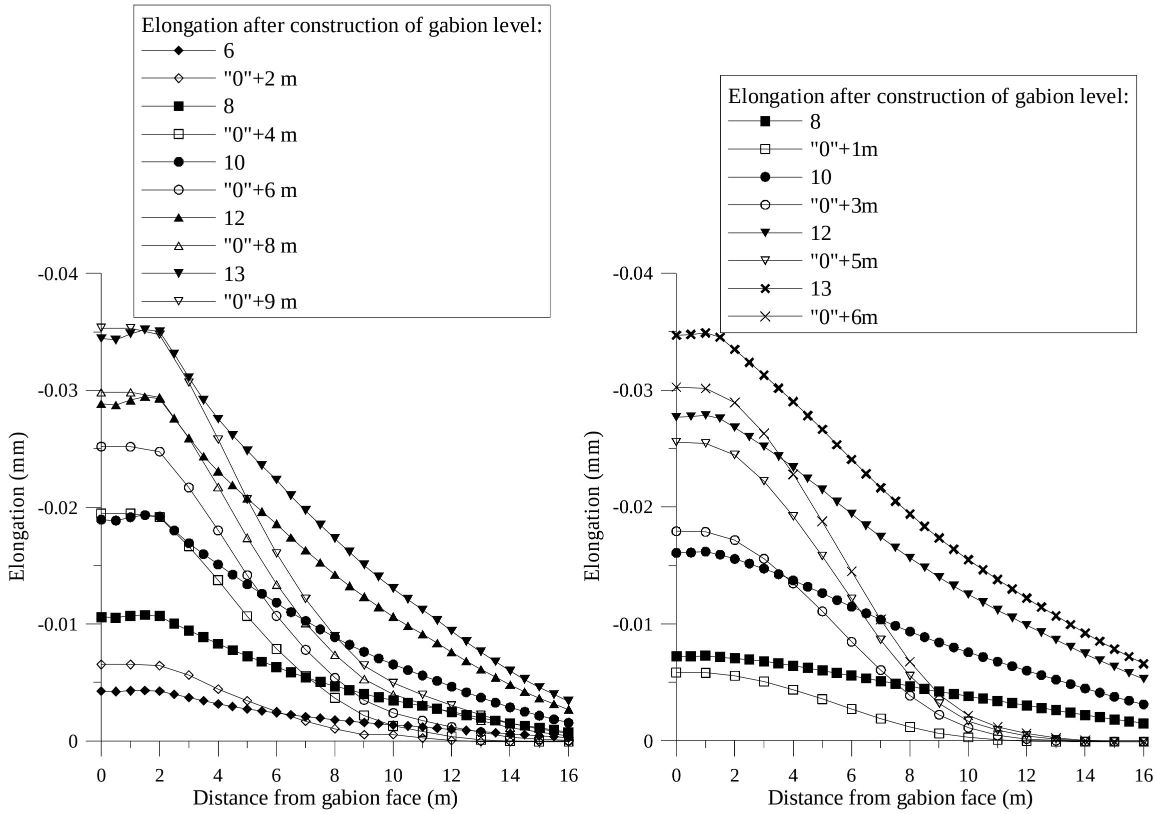


Figure 9. Comparison of computed (full symbols) and measured (void symbols) values at the level of sliding deformeter D1 (left) and D2 (right).

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