LATERAL SWELLING FAILURE OF UNREINFORCED CRUSHED STONE COLUMNS AND REDUCTION OF THIS PHENOMENON BY GEOGRID REINFORCEMENT. NUMERICAL ANALYSIS PERFORMED WITH FINITE ELEMENT METHOD (FEM)

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Abstract. In many countries around the world, including Romania, there are highly compressible soils that include a wide range of geological materials such as: saturated silts, unconsolidated deposits, soft clay soils, loose or medium-density sands, etc. Due to their very high compressibility, these types of soils have significant settlements under the loads transmitted by the foundations, settlements that are incompatible with the integrity and normal operation of the buildings.

Crushed stone columns have been used to improve such foundation soils. In highly compressible soils this improvement technique may be limited by the absence of sufficient lateral confining pressure to limit the phenomenon of lateral swelling failure of the crushed stone column. For this reason, the crushed stone columns must be reinforced / confined to ensure the minimum necessary lateral pressure.

To study the behavior of conventional crushed stone columns and those reinforced / confined with geogrids, 2D numerical analyses were performed in the plane stress state using the Mohr-Coulomb model and a FEM program.

Keywords: #highly compressible soils, #crushed stone column, #lateral swelling failure, #geogrids, #numerical #analysis, #FEM.

1 Introduction

Granular material columns have been used to improve highly compressible foundation soils. Columns are vertical cylindrical elements made from granular materials, also known as granular piles, and are usually composed of compacted materials such as sand, ballast, or crushed stone, which are introduced into highly compressible soils using various installation techniques [1 ÷ 11]. By introducing rigid granular material columns into the low-consistency material mass, the following objectives are aimed to be achieved [5]:

- Improvement of the physical and mechanical properties of the soils in terms of compressibility and shear strength.
- Increase in the linear deformation modulus of the improved ground. In the case of loose sands, the increase in the linear deformation modulus also occurs through their densification during the introduction of the granular material column.
- Improvement of the water drainage rate and consequently the acceleration of the consolidation process in the case of embankments placed on soft clays;
- Reinforcement of the soil and improvement of the stability conditions against sliding.

In highly compressible soils, this improvement technique can be limited by the absence of sufficient lateral confinement pressure to prevent the phenomenon of lateral swelling failure of the granular material column.

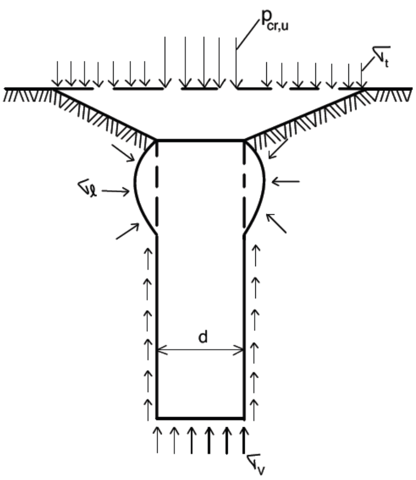


Fig. 1. The mechanism of lateral swelling failure of the granular material column. [5]

Lateral swelling failure of the granular material column occurs at a certain pressure value, which is called the critical lateral swelling pressure. The calculation expression for this pressure is as follows [5]:

$$p_{cr,u} = \frac{1+sin\varphi_c}{1-\sin\varphi_c} \cdot \sigma_l = k_p \cdot \sigma_l \quad (1)$$

Or [5]

$$p_{cr,u} = \gamma \cdot d \cdot N_\gamma + q \cdot N_q \tag{2}$$

where:

- σ_l it is the ultimate lateral stress corresponding to the surrounding soil of the column under conditions of plastic equilibrium. The calculation expression for this stress is as follows:

$$\sigma_l \cong 6 \cdot c_u \tag{3}$$

- σ_t the pressure absorbed by the surrounding soil of the granular material column.
- σ_V the pressure at the tip of the granular material column.
- $p_{cr,u}$ the critical pressure corresponding to the lateral swelling of the granular material column;
- φ_c the internal friction angle of the material from which the column is constructed;
- γ the natural bulk density of the soil;
- N_γ și N_q bearing capacity factors that depend on φ_c and q. The calculation expressions for this bearing capacity factors are as follows:

$$N_\gamma = k_p^{5/2} - k_p^{\frac{1}{2}}\,;\;\; N_q = k_p^2 \tag{4}$$

- q the surcharge at ground level;
- c_u the undrained cohesion of the foundation soil obtained through direct shear tests or triaxial compression tests.

If the lateral confinement pressure of the granular material column is insufficient, lateral deformation and lateral swelling failure easily occur in highly compressible soft soils.

To reduce the effects of the lateral swelling failure phenomenon and to increase the bearing capacity of granular material columns, geosynthetics can be used by installing them in vertical or horizontal layers. The use of geosynthetics not only effectively solves the problem of the granular material column, which is prone to lateral swelling failure, but also retains the advantages of reduced environmental impact, convenient construction, and low costs [1÷11].

Thus, geosynthetic-encased granular material columns (GESC or VESC) have begun to be increasingly used in recent decades for the improvement of highly compressible soils [1÷11].

This article presents a theoretical study of the lateral swelling failure phenomenon of a crushed stone column both in the case where it is unconfined with geogrid and in the case where it is confined with geogrid.

This theoretical study is actually a numerical analysis of the lateral swelling failure phenomenon of the crushed stone column conducted using a FEM calculation program.

2 Brief Overview of the FEM Program

The modeling of the lateral swelling failure phenomenon was done using the GEO5 program, which is a suite of software that offers solutions for most geotechnical engineering problems. The program includes modules for the calculation of slope stability, direct or indirect foundations, retaining walls, sheet pile enclosures or buried walls, excavation analysis, tunnel analysis, settlement calculation, and finite element analysis [12].

For the modeling of the lateral swelling failure phenomenon, the finite element analysis (FEM) module was used. This module, based on the finite element method, can model and analyze a wide range of geotechnical problems, including foundation settlement, sheet pile or buried walls, slope stability, and excavation analysis. FEM offers multiple material models for soils and a variety of structural elements such as walls, anchors, geotextiles, geogrids, etc. FEM provides the possibility to work with a variety of conventional and cutting-edge material models, such as: linear elastic model, modified linear elastic model, Mohr-Coulomb model, modified Mohr-Coulomb model with hardening/softening characteristics definition, Drucker-Prager model, Cam Clay model, and hypoplastic model for clays. Each material model can be used for both drained and undrained conditions [12].

Additionally, in FEM, the interface zone between structural elements and the foundation soil can be defined using the „contact elements" function, which allows for choosing a linear or nonlinear stress-displacement relationship between the foundation soil and the structure [12].

The Mohr-Coulomb model was chosen for the numerical analysis conducted in this article. Since traditional soil mechanics and partly rock mechanics are based on this model, the Mohr-Coulomb model represents one of the most frequently applied material models in engineering practice. In GEO5 – FEM, the corresponding yield surface is defined using three limit functions, which are displayed in the principal stress space as an irregular hexagon [12].

3 Numerical Modeling of the Lateral Swelling Failure Phenomenon of the Granular Material Column. Calculation Methods.

The analysis of the lateral swelling failure phenomenon was conducted for a single crushed stone column in two cases: the case of the unconfined column and the case of the column confined with geogrid. The crushed stone column has a diameter of 0.40 m, a length of 6.50 m, is introduced into a highly compressible yellow-brown silt layer with low consistency, and is supported on a layer of stiff, medium-compressibility reddish silty clay. The geotechnical characteristics of the foundation soil and the material from which the column is composed are presented in Table 1.

In order to perform the numerical modeling, a foundation soil area with a width of 10.00 m and a depth of 13.00 m was considered. The crushed stone column was positioned in the middle of the calculation domain.

Table 1. Geotechnical characteristics of the foundation soil and the material from which the column is composed.

Material Name	γ [kN/m^3]	γ_{sat} [kN/m^3]	υ	E [MPa]	φ_{ef} [˚]	c_{ef} [kPa]
Yellow-brown clayey silt	18,50	19,50	0,35	4,0	15,0	5,0
Reddish silty clay	19,50	20,50	0,35	10,0	23,0	19,0
Crushed stone from the column body	23,0	24,0	0,27	40,0	36,0	-

The calculation domain was discretized using triangular finite elements with a side length of 0.50 m. The finite element mesh was refined in the crushed stone column body and the immediately adjacent area using triangular finite elements with a side length of 0.15 m. The calculation was performed under the assumption of plane stress and strain conditions. The boundary conditions were as follows:

- on the horizontal plane located 13.0 m below the natural ground level, horizontal and vertical displacements were blocked;
- on the vertical planes located on either side of the calculation domain, horizontal displacements were blocked.

The external pressure applied to the crushed stone column is equal to 140 kPa, and the pressure applied to the surrounding soil is equal to 40 kPa. These pressure values were determined through back-calculation starting from a value of 250 kPa for the pressure taken by the column, and 150 kPa for the pressure taken by the surrounding soil. This back-calculation was performed by decreasing the pressure values until the system of equations had a convergent solution.

We considered confining the crushed stone column with a biaxial geogrid Tensar SS40. For simulating the geogrid in the calculation model, the „contact elements" function of the FEM program was used. In fact, we considered the geogrid as an interface zone between the column body and the foundation soil, choosing a linear stress-displacement relationship for this interface zone.

The additional parameters of the material in the interface zone are the elastic stiffnesses in the normal and tangential directions K_n and K_s, respectively, which can be imagined as spring stiffnesses. A reliable choice of the values for these parameters is not an easy task and usually depends on the problem being analyzed. The calculation relationships for these elastic stiffnesses are as follows [12]:

$$K_n = \frac{E}{t};\ K_s = \frac{G}{t} \tag{5}$$

where: t – assumed (estimated) thickness of the contact (interface) layer
G – shear modulus
E – Young's modulus of elasticity

For the calculation of elastic stiffnesses in the normal and tangential directions K_n and K_s, respectively, we used the technical specifications provided by the manufacturer of the biaxial geogrid Tensar SS40 which are presented in Table 2. For the numerical analysis in this article, we considered that the two elastic stiffnesses are equal and have a value, resulting from the calculation using the calculation relationships (4), equal to: $K_n = K_s = 35{,}0$ kN/m^3.

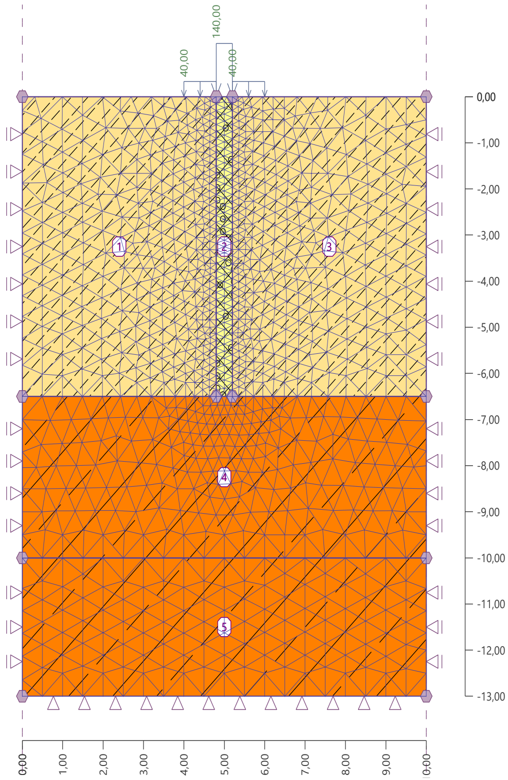


Fig. 2. Discretization of the Calculation Domain and the Crushed Stone Column, Boundary Conditions, and External Pressure Applied to the Column and Surrounding Soil

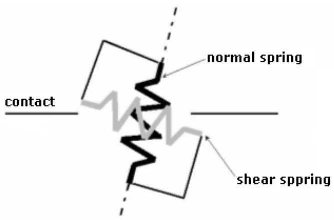
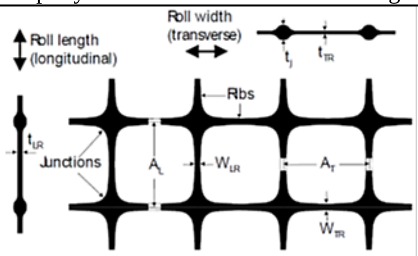


Fig. 3. Contact Element Scheme with Visualization of Elastic Stiffnesses [12]

In order to compare the results, the numerical analysis was conducted for both the unconfined column and the column confined with geogrid, using the same geotechnical characteristics of the foundation soil, the same boundary conditions, the same discretization settings, the same loads, the same loading application steps, and the same numerical analysis settings.

The results of the numerical analyses are presented in Fig. 4÷9 in the form of iso-surface diagrams for the analyzed variable quantities in both cases.

Table 2. Tensar SS40 geogrid product specifications [13]

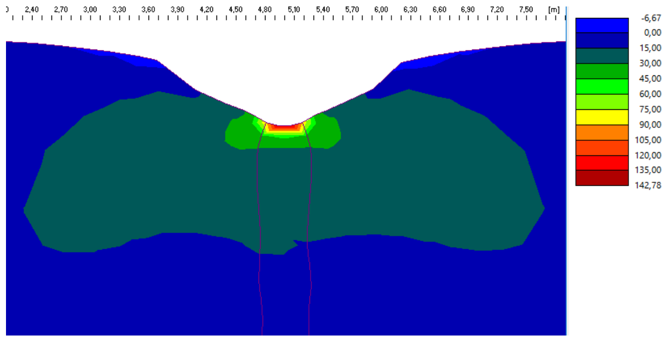


Property	Units	Geogrid Tensar SS40
Typical unit weight	kN/m^2	0.54
Typical Dimensions		
A_L	mm	33.0
A_T	mm	33.0
W_{LR}	mm	2.4
W_{TR}	mm	3.2
t_J	mm	5.8
t_{LR}	mm	2.7
t_{TR}	mm	2.1
Quality control strength longitudinal		
Minimum T_{ult}	kN/m	40.0
Typical strength at 2% strain	kN/m	14.0
Typical strength at 5% strain	kN/m	28.0
Approx strain at T_{ult}	%	11.0
Junction efficiency	%	100-10%
Quality control strength longitudinal		
Minimum T_{ult}	kN/m	40.0
Typical strength at 2% strain	kN/m	14.0
Typical strength at 5% strain	kN/m	28.0
Approx strain at T_{ult}	%	10.0
Junction efficiency	%	100-10%

4 Conclusions

In this article, the phenomenon of lateral swelling failure of a crushed stone column was theoretically analyzed, both in the case where it is unconfined with geogrid and in the case where it is confined with geogrid. The crushed stone columns had a length of

6.50m, a diameter of 0.40m, and were introduced into the same type of foundation soil. The crushed stone column was confined with the biaxial geogrid TENSAR SS40.



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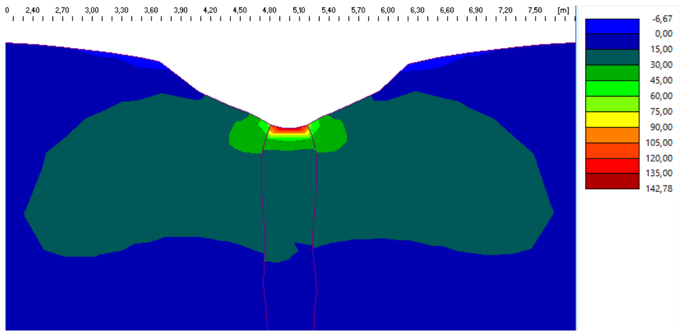

b

Fig. 4. Stress diagram σ_x [kPa]: a – unconfined crushed stone column; b – crushed stone column confined with geogrid

The geogrid confining the crushed stone column was simulated / modeled using the „contact elements" function and the technical characteristics of the geogrid provided by its manufacturer.

We can draw the following conclusions:

1. The difference between the behavior of an unconfined crushed stone column and that of a geogrid-confined column consists mainly in the differences in volume and the modification of the stress state in the column body and the surrounding soil.
2. Due to the increased lateral constraint provided by the geogrid, the lateral swelling of the confined column is reduced compared to that of the unconfined column. This aspect is also observed after analyzing the diagrams in Fig. 4-9.
3. Also, after analyzing the diagrams in Fig. 4-9, it can be observed that in the case of the geogrid-confined column, the evolution of deformation and stress quantities is concentrated in the column body, unlike the unconfined column where the evolution of these quantities develops both in the column body and in the surrounding soil.

4. The modeling / simulation of the confinement geogrid as an interface element between the column body and the foundation soil, using the „contact elements" function, was appropriate. Regarding this aspect, it must be mentioned that the study of using the „contact elements" function should be continued and deepened to define the elastic stiffnesses K_n and K_s as accurately and realistically as possible.
5. As a final conclusion: the GEO5 – FEM program can be successfully used in the analysis of such geotechnical engineering applications.

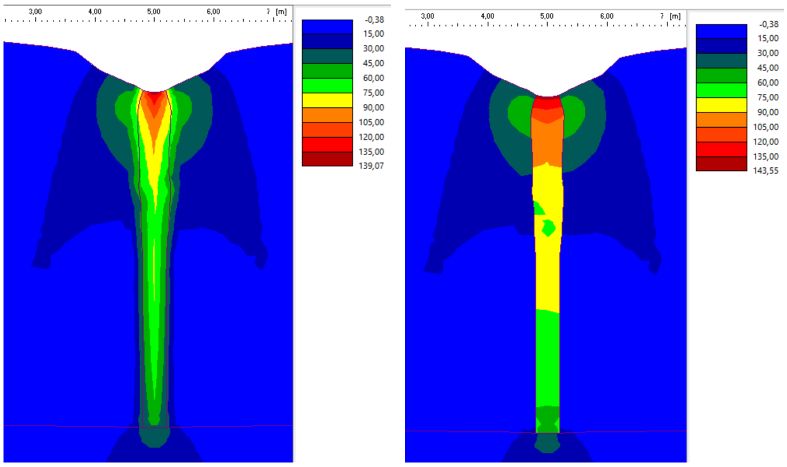

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Fig. 5. Stress diagram σ_z [kPa]: a – unconfined crushed stone column; b – crushed stone column confined with geogrid

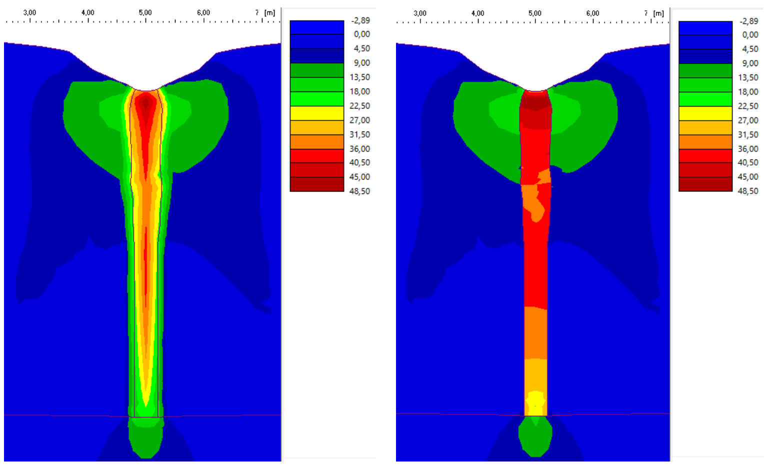

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Fig. 6. Equivalent Stress Deviator Diagram J [kPa]: a – unconfined crushed stone column; b – crushed stone column confined with geogrid

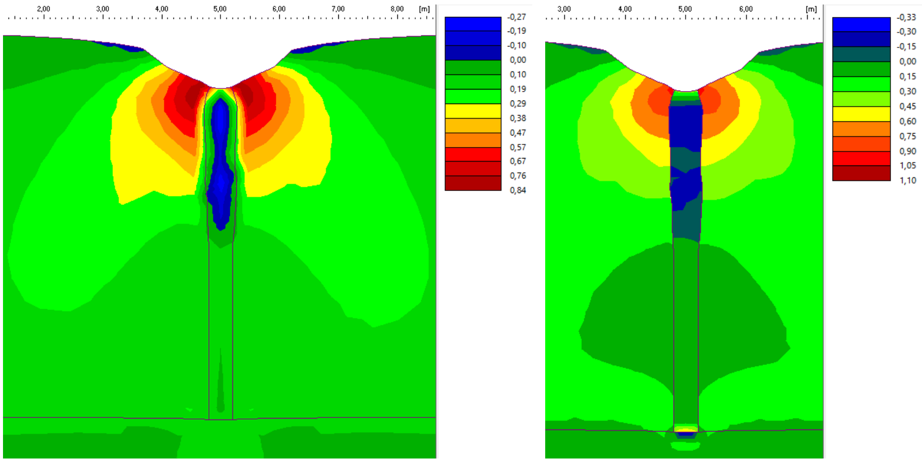

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Fig. 7. Volumetric Strain Diagram ε_v [%]: a – unconfined crushed stone column; b – crushed stone column confined with geogrid

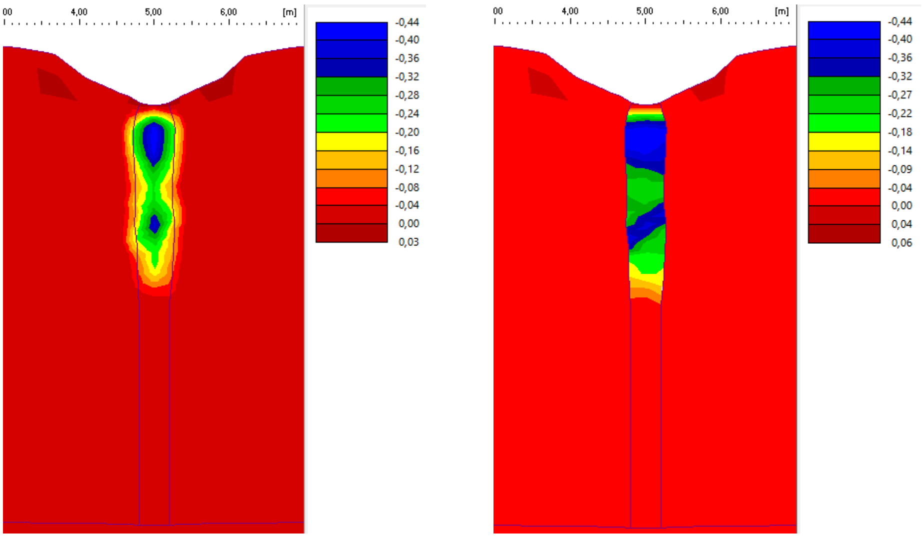

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Fig. 8. Plastic Volumetric Strain Diagram ε_{vpl} [%]: a – unconfined crushed stone column; b – crushed stone column confined with geogrid

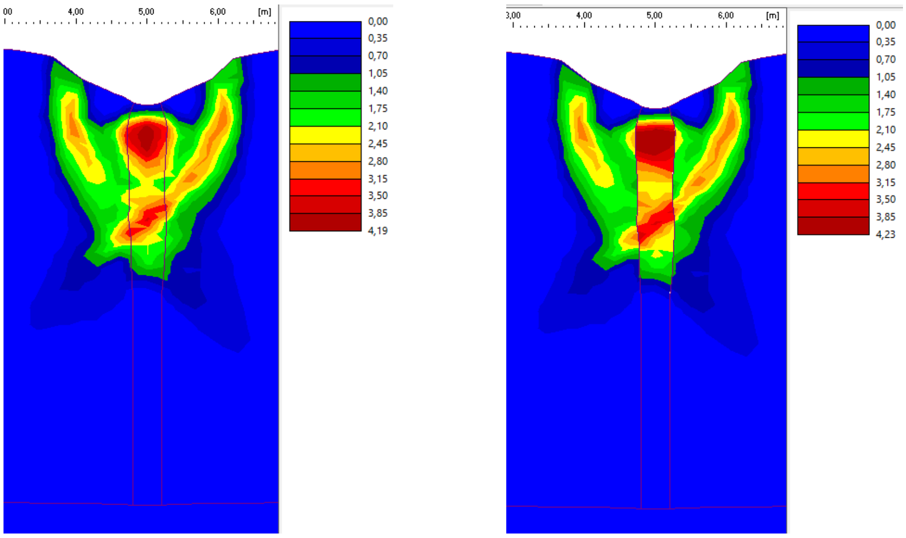

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Fig. 9. Equivalent Plastic Strain Deviator Diagram E_{dpl} [%]: a – unconfined crushed stone column; b – crushed stone column confined with geogrid

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