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Physical and numerical modeling of an unpaved road structure liable to void forming. The effect of a biaxial geosynthetic reinforcement.

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ABSTRACT

Earth structures are commonly designed using numerical calculation programs. This kind of modeling relies on predefined mathematical equations and boundary conditions for approximating deformations, strains and interactions. In most cases, numerical modeling is sufficient for drawing long-term conclusions on earth structure behavior, but there are special situations which require physical modeling in order to verify the results of virtual modeling. For example, a cavern forming in a road embankment requires a physical model, because simulating the arch effect in the earth structure represents an important challenge for most of the finite element based calculation programs. The comparison between the scale model settlements and the deformations from the modeling program can show how suited the applied mathematical model is, and if the results are close, then the numerical calculation is reliable in displaying the behavior of the granular structure, which is impossible to measure on the scale model.

Keywords: biaxial geogrid, finite element modeling, scale model testing

1. INTRODUCTION

Cavern forming in road embankments is relatively common, due to a multitude of favorable factors, like hydrological factors leading to formation of sinkholes, or different construction activities, such as pipeline leaking, or poor compaction of the base layer which causes differentiated settlements. The following pictures were taken on the DJ108A road located in Sălaj county, Romania. Figure 1.a. shows a pipeline intervention conducted in the summer of 2012, while Figure 1.b. shows roughly the same location six months later, in autumn 2012. Clearly the road safety was affected by the resulting deformations. Eventually, the road structure was subjected to costly interventions, that implied scraping and auxiliary compaction.

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Figure 1.a. Regular pipeline interventions on DJ108A

Figure 1.b. Differentiated settlements resulted from poor compaction works

Although biaxial geogrids are designed for a combined effect of dissipating the pressure cone due to traffic loads through surface friction, the question of using geosynthetic reinforcement in the present case in order to stabilize the road structure and decrease settlement is open to debate.

2. SCALE MODELING

Trying to replicate the presented case, our study consisted of building two structures at natural scale (1:1) in the laboratory using a box, according to the detail given in Figure 2**.** The road bed was made of 40 cm thick cohesive earth/clay where a void was created. Over the earth, a layer of 40 cm crushed stone was laid and compacted. For the second model, we had the same structure, only that, between the two material layers, a layer of biaxial geogrid with 40 mm apertures was inserted. [Moldovan D., Nagy A., Farcas V., Muntean L., Coţ, R. 2014]

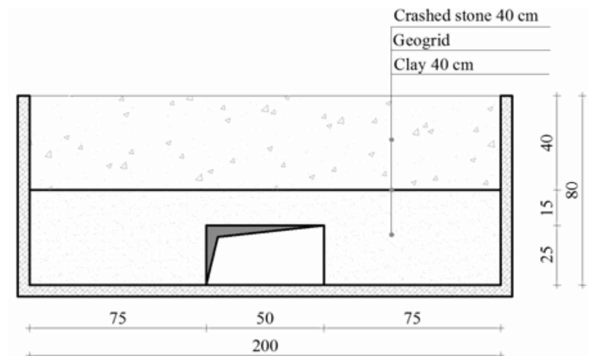

Figure 2. The configuration of the scale model subjected to laboratory testing

A void of 50 cm wide and 25 cm high was created at the bottom-center of the span on both series of models.

Load stage	Equivalent concentrated force	Equivalent pressure in tone-force/square meter	Pressure transmitted to the surface of the testing plate
[kPa]	[kN]	[tf]/m^2	[tf]
50	3.55	5.100	0.362
100	7.10	10.200	0.724
150	10.65	15.300	1.086
200	14.20	20.400	1.448
250	17.76	25.500	1.811
300	21.31	30.600	2.173
350	24.86	35.700	2.535
400	28.41	40.800	2.897
450	31.96	45.900	3.259
500	35.51	51.000	3.621
550	39.06	56.100	3.983
600	42.61	61.200	4.345
650	46.16	66.300	4.707
700	49.71	71.400	5.069
750	53.27	76.500	5.432

Table 1. Load stages and their equivalent concentrated force and pressure transmitted on the surface of the Lucas plate

The void was formed by using an inverted drawer, having the specified dimensions, which was retracted after ending the compaction works for both of the earth layers used in the experimental stage. The final configuration of the test model was influenced by similar studies on geosynthetic reinforced earth models combined with void forming, found in the works of Agaiby S., Jones J. F. P., Asakereh A., Ghazavin M., and Tafreshi S.N. Moghaddas, quoted in the reference part of the study. For a preliminary calculation we used a design pattern from a study conducted by Giroud J.P., Bonaparte R., Beech J.F., and Gross B.A., also quoted in the references.

Loading stages were applied according to the regulations in force in Romania, specified in STAS 2914/4-89 for road and railway works. Testing consisted in placing a 300 mm diameter plate on the top center of the span, and applying consecutive load stages, starting from 50 kPa (with a 50 kPa step) until the structure fails. Load stages were only increased when the surface settlement was considered stabilized (when settlement does not increase by more than 0.1 mm for 30 minutes under the applied load stage).

Figure 3. Lucas plate testing on the laboratory model

Behaviour differences between the reinforced and unreinforced structures became clear under the 350 kPa stage. Under this load, the geogrid provided sufficient confinement for the superior layer, in order to stabilize the deformations in a time interval of just 20 minutes, as against the other structure, of which consolidation under the same stage lasted 45 minutes. The tendency emphasized on the following phases of loading, respectively at 400 kPa we recorded a consolidation time of 45 minutes on the reinforced structure, compared to 65 minutes on the unreinforced one, whereas the surface deformations were noticeably larger in the case of the unreinforced structure. The 450 kPa load stage caused the falling of medium sized earth lumps from the gap ceiling on the unreinforced complex, projecting the nearby failure, while the gap on the reinforced structure suffered only slight geometrical modifications, because the grid acted by friction on the foundation layers. During this experiment, we also monitored the interior deformations of the void, and concluded that in the case of the unreinforced structure, the surface deformation coincides with the vertical deformation of the gap ceiling, while on the reinforced structure the settlement was significantly larger on the surface, due to the rearrangement of particles in the grill meshing, which seems to “filter” deformations. Under the 550 kPa stage the unreinforced structure collapses around the gap, the failure is sudden and unexpected. The maximum surface settlement on the unreinforced laboratory model was 2.76 cm (measured before the structure collapsed). The reinforced structure loses balance at 700 kPa, but unlike the previous model, the latter fails in 10 minutes, with constant deformations of cavity, until its ceiling touches down on the bottom of the testing box.

Comparing these results with those for the unreinforced structure we found that the presence of the geogrid grants an important increase in bearing capacity. Also the maximum settlement measured on the reinforced scale model was 5.20 cm. This highlights the difference between the failure types of the two structures. While the unreinforced structure collapses suddenly, with a fairly small surface settlement, the reinforced structure fails slowly and gradually, making it less hazardous for traffic.

Figure 4.a. Failure surface on the unreinforced scale model

Figure 4.b. Failure surface on the reinforced scale model

The failure surface is more extended in the case of the reinforced structure, as seen in Figure 4 a. and b.

3. VIRTUAL MODELING

A suited method for creating a virtual model for the present experiment must allow interaction between the earth layers and reinforcement material. Finite element modeling determines the stress domain corresponding to the applied load stage, and geometry of the given structure. Using a predefined failure criterion, the software indicates if flowing occurs in any given point of the model. Also it can model failure through conditions dependent or independent of hydrostatic pressure (inside the soil pores), which is an important aspect, considering the fact that the simulated structure consisted of both cohesive (initial layer of clay) and non cohesive (base layer of crushed stone) soil types.

Failure criteria define the linear – elastic behavior limit of materials. The natural humidity of the clay used in the scale model was 40%, determined in laboratory conditions. Cohesion and internal friction angle values were considered under drained conditions, and were determined in laboratory shear tests. The crushed stone base layer would have been more accurately defined by the Mohr – Coulomb failure criterion, but it was stored outdoors, in rainy weather, and as a consequence, it accumulated a high amount of water. As the primary objective of the study was to correlate scale and numerical modeling results, von Mises criterion was chosen for this layer too. The von Mises perfectly plastic models approach is based on the assumption that plastic deformation begins when the potential energy required for changing the shape of the finite elements (noted with W_d) reaches a critical value specific to each type of material introduced in the numerical model.

$$W_d = \frac{1+\upsilon}{6E}\left[(\sigma_1-\sigma_2)^2+(\sigma_2+\sigma_3)^2+(\sigma_3+\sigma_1)^2\right] \quad (1)$$

where E is the linear deformation modulus, υ is the Poisson ratio, respectively σ_1, σ_2 and σ_3 are the normal stresses on the main directions. A graphical representation of the von Mises failure criterion can be seen in Figure 5.

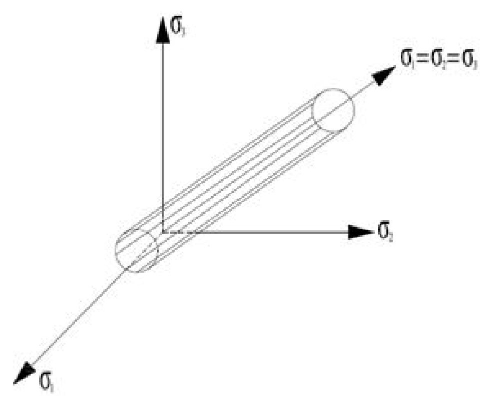

Figure 5. Graphical representation of the von Mises failure criterion [Chiorean C. 2010]

The two foundation layers were introduced with their geological characteristics, while the geogrid was introduced as a linear element, defined by its physical and mechanical properties. A cooperation coefficient was also introduced, for simulating the confinement effect.

The two layers were defined as (after being tested in the laboratory):

Layer 1 – clay

module of elasticity: E=4200 kN/m^2

specific weight: γ=18 kN/m^3

cohesion (drained): c_d=79.92 kN/m^2

cohesion (undrained): c_u= 45.81 kN/m^2

internal friction angle (drained): $φ_d$=9.01°

Layer 2 – crushed stone

linear deformation modulus: E=130000 kN/m^2

specific weight: γ=20 kN/m^3

cohesion: c=0 kN/m^2

internal friction angle: φ=35°

Layer of geosynthetical reinforcement – biaxial geogrid with 40 mm apertures

linear deformation modulus: E=185000 kN/m^2

density: ρ= 1kN/m^3

traction resistance: T=30 kN/m [Tensar UK Catalogue]

Load stages on the scale model were applied statically. On the virtual model, a number of seven joints were selected (on a surface roughly the size of the 300 mm Lucas plate), applying concentrated forces onto the joints, equivalent to the failure value obtained from the laboratory tests. This way, on the unreinforced model a value of 6 kN was chosen (with a total value of 7x6 kN = 42 kN, slightly superior to the failure value of 39 kN), while on the reinforced model the 7 kN value was found appropriate, as seen in Figure 6. Then an iteration value was introduced, in order to apply the force gradually. Tables 2 and 3 show the number of iterations performed on the reinforced and unreinforced models, also displaying the corresponding settlement values. The boundary condition on the FEM model was set as fixed, as no interaction was determined between the box walls and the earth layers on the scale model.

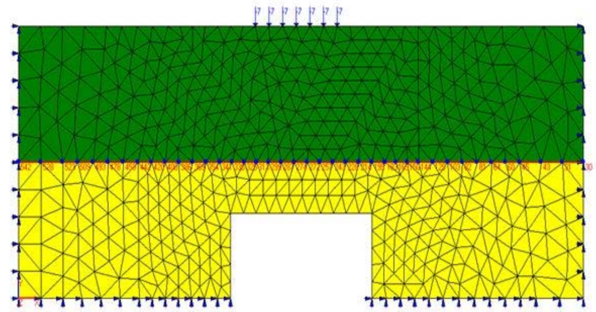

Figure 6. Boundary conditions and load application on the joints of the FEM model

The amount of iterations set by the user requires attention. Usually, the number of iterations ranges from 200-1000, but total displacement resulting from the program should be followed at every step. If after two different iteration values, the difference between the two surface settlement values (total maximum displacement) is greater than 20%, the number of optimal iterations is exceeded, and the program gives altered values. [Chiorean C. 2009]

Iteration value F	Iteration force value [kN]	Number of iterations performed	Settlement value [cm]
0.1	0.6	2	0.02
0.2	1.2	23	0.049
0.3	1.8	57	0.126
0.4	2.4	103	0.271
0.5	3	139	0.485
0.6	3.6	217	0.85
0.7	4.2	371	1.636
0.8	4.8	500	3.1

Table 3. Performed iterations and corresponding settlement values for the unreinforced FEM model

Iteration value F	Iteration force value [kN]	Number of iterations performed	Settlement value [cm]
0.1	0.7	2	0.02
0.2	1.4	4	0.045
0.3	2.1	39	0.09
0.4	2.8	73	0.221
0.5	3.5	93	0.397
0.6	4.2	153	0.689
0.7	4.9	239	1.299
0.8	5.6	367	2.562
0.9	6.3	500	5.17

Table 4. Performed iterations and corresponding settlement values for the reinforced FEM model

FEM model displays internal stress on the meshed elements. The average value on the elements of the reinforced model is between 90-110 kPa. Values on the unreinforced model are sensibly higher averaging in between 130-210 kPa, as shown in Figures 7.a. and b. Comparing the resulted graphics we can conclude that in the case of the reinforced model the vertical stress values on the elements above the void is considerably lower due to the presence of the geosynthetical reinforcement, and only a small amount of pressure is transmitted to the side of the void.

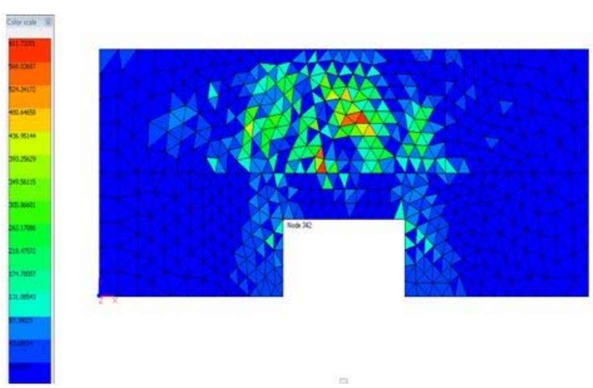

Figure 7.a. Vertical stress distribution on the elements of the unreinforced FEM model

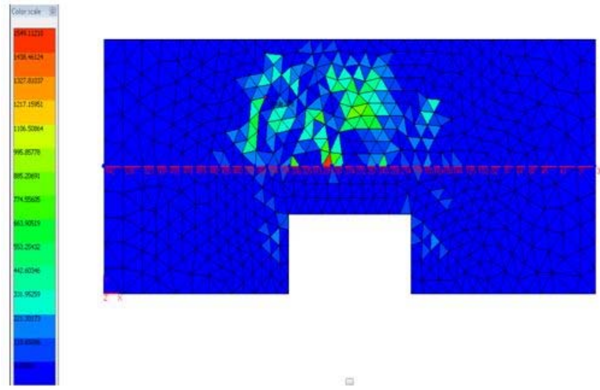

Figure 7.b. Vertical stress distribution on the elements of the reinforced FEM model

4. COMPARRISON BETWEEN THE RESULTS OBTAINED BY SCALE MODELING AND VIRTUAL MODELING

The results of virtual modeling were largely confirmed by the measurements obtained from the 1:1 scale model testing. On the numerical model without geosynthetical reinforcement failure occurred at a force equivalent of 34 kN. This value corresponds to the 500 kPa load stage. The scale model collapsed at a uniformly applied pressure (under the loading plate) of 550 kPa. The maximum settlement of the computer generated model was 3.10 cm (at 500 kPa), while at the same pressure on the laboratory model a 2.76 cm value was measured, resulting a 12% difference. Figure 8.a. displays a chart based on the settlement – equivalent applied force function for both the FEM (highlighted in blue) and scale model (highlighted in red). The behavior of the two models is remarkably similar.

In the following step of the study a rectangular meshed (biaxial) geogrid was used for the road structure reinforcement. The nonlinear analysis performed on this configuration showed that failure occurs at 650 kPa load stage, meanwhile the laboratory model collapsed at 700 kPa. Comparing these results with those for the unreinforced structure we found that the presence of the geogrid grants an important increase of bearing capacity.

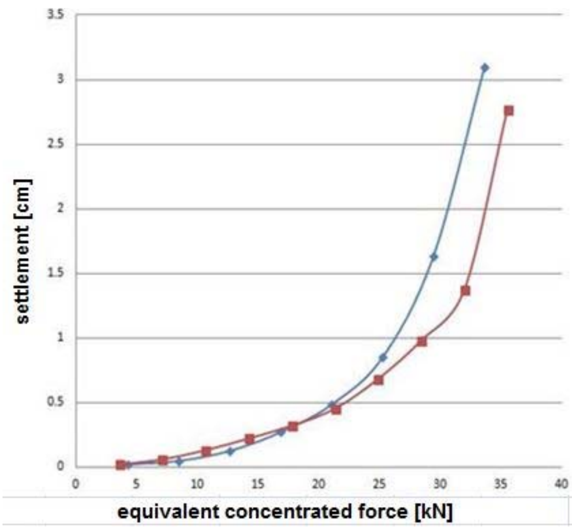

Figure 8.a. Applied force – surface settlement comparison chart between FEM (blue) and scale modelling (red) on the structure without geosynthetic reinforcement

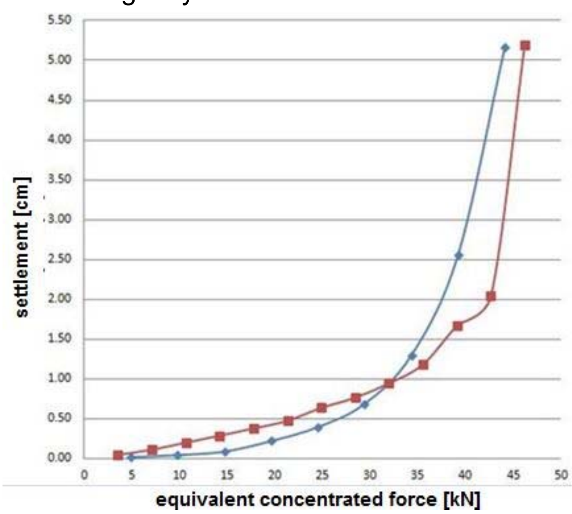

Figure 8.b. Applied force – surface settlement comparison chart between FEM (blue) and scale modelling (red) on the structure with geosynthetic reinforcement

Also, the difference between the maximum settlements of the virtual and real model was very small, 5.17 cm in the finite element method, respectively 5.20 cm on the scale model, with a difference of 1%. Comparing the scale model and the FEM model behavior wise, as displayed in Figure 8.b., shows, as in the first case, a highly similar curve. Reinforcing the road structure with biaxial geogrid grants an increase of 22% in load capacity. The presence of the geosynthetic reinforcement also allows higher settlement values to be reached, before the collapsing of the structure.

5. CONCLUSIONS

The resulting 1% difference between surface settlements in numerical and physical modeling, in the case of the reinforced structure proves that virtual modeling by the finite element method can get very close to the behavior of a 1:1 scale model. The 50 kPa difference between failure values, obtained in both cases, is due to the constant particle rearrangement in the soil structure, which results in additional bearing capacity. This aspect is impossible to take in consideration in the numerical modeling, as the finite element method only allows deformation of the subdivisions, and does not permit rotations or translations of the divided parts.

Other noteworthy conclusions of the study are:

- if the failure criterion is chosen respecting the initial condition and type of material used, the behavior of the numerical model comes very close to the behavior of the scale model;
- the unreinforced scale model fails suddenly, while reinforced models fail slowly making them less hazardous for traffic;
- biaxial geogrid increases the bearing capacity by 22% as against the results obtained on the unreinforced structure;
- while the surface settlement coincides with the gap deformation in the case of the unreinforced model, using geosynthetic reinforcement leads to a smaller deformation of the void, due to the arrangement of the earth particles from the superior layer;
- in the FEM model, stress distribution inside the structure is influenced by the presence of the reinforcement, as the values obtained on the elements adjacent to the void are considerably lower;

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