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Initial Research on Mechanical Response of Unbound Granular Material under Static Load with Various Moisture Content

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Abstract. In road engineering, the role of solid foundation is performed by base and sub-base layers which are often made of unbound materials. Cohesive and non-cohesive soils as well as unbound materials used in lower road pavement construction layers show a significant sensitivity to alterations of moisture content. Susceptibility to changing moisture conditions can be observed in variations of mechanical properties of cohesive or non-cohesive medium which describe material's behaviour under applied load. Observation of parameters such as internal friction angle (ϕ), cohesion (c) and modulus of elasticity (E) allows noticing clear connection between mechanical parameters of granular material and variable moisture content. In this article, authors presented the results of initial laboratory tests consisting of trial loadings of a non-cohesive granular medium with different graining and moisture content and a numerical analysis of the problem. Research program was divided into three parts: material testing, trial loadings of non-cohesive soils - medium sand and dolomite executed on a special laboratory test stand and a back calculation analysis using finite element method (FEM). Firstly, materials were identified by obtaining grain composition, optimum moisture content and dry density in Proctor apparatus and values of internal friction angles and cohesion. Trial loadings were performed in a small scale in test cylinder using static load transferred to a steel plate with a diameter of 10 cm. Diameter of the loading plate was chosen in accordance to model similarity principles. Attained vertical displacements were used to execute the back calculation analysis of granular layers for which parameters of Coulomb-Mohr model were obtained using finite element method (FEM). The results shown in this article are the part of a wider research program in which main aim is to evaluate the influence of variable moisture content of materials used in road pavement structures on their fatigue life and costs of maintenance in full life cycle of pavement structure (LCA – Life-cycle Assessment).

1. Introduction

Strong and solid subsoil is one of principal conditions to build sustainable and stabile engineering construction. It seems that high parameters of subsoil are notably important when building linear road or rail infrastructure, because of relatively thin road or rail pavement structure in comparison to cubature object, bridge or other engineering structures. Quality of subsoil is characterized by numerous parameters of which modulus of elasticity (E) is mostly equated to bearing capacity. Values of elastic modulus of subsoil are variable throughout the year according to intensity of precipitation, alterations of temperature or changes in moisture content [1]. Especially noticeable is the influence of variable moisture content on mechanical parameters of cohesive and non-cohesive soils under loading

[2]. High moisture content in subsoil causes a decrease of mechanical and strength parameters such as internal friction angle (φ) or cohesion (c) as well as leads to a quicker deterioration of a pavement structure represented by internal damages and damages visible on the surface layer. In road pavement structures, the role of foundation is also held by sub-base and base layers, which are in general made of unbound granular materials. Influence of excess water on these layers is as significant as on subsoil and causes accelerated deterioration of pavement manifested, i.e. by rutting or permanent deformations [3].

In this paper authors present findings of initial laboratory tests and numerical analyses of obtained results. Laboratory tests were executed in the Laboratory of Civil Engineering Faculty on Silesian University of Technology (SUT) and consisted of two groups: investigation of granular materials (sand and dolomite) and main tests - small-scale trial loadings of materials in different moisture conditions. Investigation of materials based on a sieve analysis, tests in Proctor apparatus and shear tests in a direct shear apparatus. Small-scale trial loadings were carried out on a special test stand with steel cylinder, VSS hydraulic plate equipment, vertical displacement sensor and counterweight. Further numerical analyses were carried out using ZACE Z_Soil 2014 software [4]. Numerical model of tested medium was built using Coulomb-Mohr (C-M) model and was preceded by studies and numerous iterations to obtain the best dimensions of mesh, impact of boundary conditions in the small-scale test and conditions of models similarity. Results obtained in Z_Soil software were used in the back-calculation process of mechanical parameters of granular materials to find the best match between laboratory and numerical deformation - applied load curves and to check if the chosen grain distribution is appropriate for small-scale tests.

2. Laboratory research methodology

Initial laboratory tests, which consisted of investigation of the material and small-scale trial loadings executed in Laboratory of Civil Engineering Faculty on SUT. The first part focused on obtaining key parameters of analysed granular materials - grain composition presented in the grading curve, optimum moisture content and dry density from Proctor test and cohesion and internal friction angle in different moisture conditions from the shear test in direct shear apparatus. The second part of the laboratory initial research consisted of trial loadings executed in small-scale with observation of vertical displacements under static load generated by VSS hydraulic equipment and loading plate.

Materials selected for main tests were non-cohesive materials - sand and dolomite. Both aggregates were sieved to obtain their grain composition and to draw the grading curve. Dolomite’s grading, dry density and optimum moisture content were tested by the supplier of the aggregate and declared in laboratory report. Specimen of sand before the sieve analysis was rinsed to obtain silt fraction (#<0,063 mm) which was further rejected. Initiatory mass of sand specimen was equal to 1501.1 g and after rinsing and drying to a constant mass it decreased to 1489.5 g. To perform the test, a set of 15 sieves was used: #80 mm, #63 mm, #31,5 mm, #20 mm, #16 mm, #12,8 mm, #8 mm, #5,6 mm, #4 mm, #2 mm, #1 mm, #0,5 mm, #0,25 mm, #0,125 mm and #0,063 mm. After the material was sieved, uniformity coefficient (Cu) and coefficient of gradation (Cc) were calculated and the grading curve was drawn.

Proctor apparatus is used for attaining dry density and optimum moisture content of tested medium. Proctor test for sand was carried out in accordance to procedures contained in Polish standards. Specimen of sand used to obtain dry density and optimum moisture content weighed 3000.0 g. These parameters were identified using Polish method I using a small cylinder (1 dm^3 volume) and a light compaction rammer with weight of 2.5 kg. Examined material was put inside the small cylinder in three layers with equal thickness. Each layer was compacted by 25 impacts of light compaction rammer. Test was performed in different moisture conditions of sand - 0.0%, 1.5%, 3.1%, 4.6%, 6.1%, 8.1% and 10.1%.

Tests performed in the direct shear apparatus allow determining shearing strength of cohesive and non-cohesive soils and aggregates as well as values of cohesion (c) and internal friction angle (φ). In case of using only the square shear box with side dimension of 10 cm, it was not possible to investigate c and φ parameters of dolomite with granulation 0/31.5 mm because of too large maximal dimension of single aggregates [5]. Measurements for sand were divided into four groups with variable moisture content equal to 1.0%, 5.0%, 7.5% and 10.0%. Every series of measurements was divided in two phases: consolidation step which lasted 3 minutes and main shearing test in which shearing was executed with a velocity of 1 mm per minute with values of nominal stress equal to 55 kPa, 110 kPa, 165 kPa, 220 kPa and 275 kPa. Every series ended as the horizontal displacement of each specimen reached 20% of specimen's width. Shearing apparatus test stand is showed in figure 1.

Trial loadings are performed to simulate a realistic engineering problem in smaller scale keeping the boundary conditions and stress paths in the medium. As a result, there is a possibility to obtain the relationship between deformation and applied load using the back-calculation analysis [6]. In order to perform small-scale tests on sand and dolomite aggregates, a special laboratory test stand was constructed. Test stand was composed of steel test cylinder (76.8 cm height, external diameter 54.2 cm, internal diameter 51.6 cm, 1.3 cm thick bottom), steel loading plate (diameter 10 cm, thickness 2.8 cm), VSS hydraulic equipment, counterweight, wooden plate (external diameter 51.0 cm, internal circle excision with diameter 10.5 cm) and concrete blocks (figure 1). Dimensions of elements of test stand and dimensions of specimens were matched together considering model similarity conditions and scale effect between initial and destined test stand.

Figure 1. Direct shearing apparatus test stand (left) and small-scale trial loading test stand (right)

In present tests, both sand and dolomite with different moisture contents were used. Trial loading of sand was executed in three moisture conditions - 4.2%, 6.5% and 8.8%, and dolomite in two moisture conditions - 1.1% and 6.9%. Three trial loadings were executed on sand aggregate, each test on sand with a different moisture content and two trial loadings were performed on a two-layered structure consisting of sand in the moist state (8.8%) and dolomite with different moisture conditions. Tested sand was placed inside the cylinder in two layers of total thickness equal to 31.2 cm, dolomite was placed on sand in one layer of thickness equal to 8.3 cm. Each layer of both sand and dolomite was compacted by 35 impacts of heavy rammer (20 kg), 55 impacts of heavy compaction rammer used in Proctor test (4.5 kg) and 5 level-off impacts with heavy rammer (20 kg). On prepared one-layered (sand) or two-layered (sand and dolomite) surfaces wooden plate was placed and in the inner circle excision the steel loading plate was put. On the surface of wooden plate concrete ballast blocks were set to imitate the backfill and to prevent an uplift of the material under applied load generated by VSS hydraulic equipment and counterweight. When sand was tested, the weight of backfill was equal to 79 kg (total mass of 7.5 cm layer of concrete rubble and 8.3 cm of dolomite 0/31.5) and when two-layered structure was tested weight of backfill was equal to 35 kg (total mass of 7.5 cm of concrete rubble). Vertical displacements were measured by dial gauge with measurement range 0.0 - 25.0 mm and 0.01 mm precision. Load was applied as for improved subgrade in Polish standards in 0.0 - 200.0 kPa range with 12.5 kPa step. Values of vertical displacements at unloading process were recorded in 50.0 kPa steps. All tests had the same load-unload sequence consisting of 4 applications of load and 4 unloading processes.

3. Results of laboratory investigation

Results from the sieve analysis, which was the first part of investigation of parameters of chosen aggregates are presented in figure 2 and 3. From the progress of grading curve for sand, tested material was classified as medium sand (MSa) with uniformity coefficient equal to 2.93 (uniform soil) and coefficient of gradation equal to 1.04 (well-graded soil). Dolomite was not sieved in laboratory and the supplier of aggregate declared coefficient of gradation, uniformity coefficient and grading curve. Dolomite with grading of 0/31,5 mm was classified as well-graded with uniformity coefficient equal to 29.17 and coefficient of gradation equal to 4.34.

The same as in case of sieve analysis, Proctor test was executed only with medium sand and the supplier declared optimum moisture content and dry density for dolomite. Optimum moisture content w_{opt} obtained for sand was equal to 7.7% with dry density ρ_{ds} equal to 1.979 g/cm^3. Dolomite aggregate had identical value of w_{opt} equal to 7.7%, but dry density was equal to 2.120 g/cm^3.

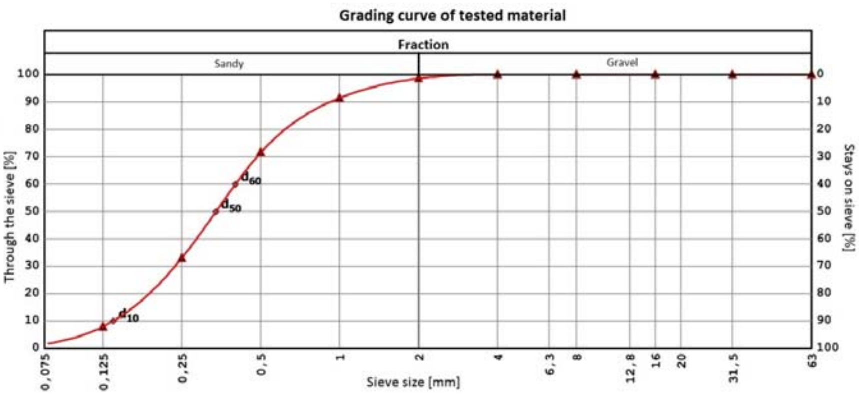


Figure 2. Grading curve of tested medium sand (MSa)

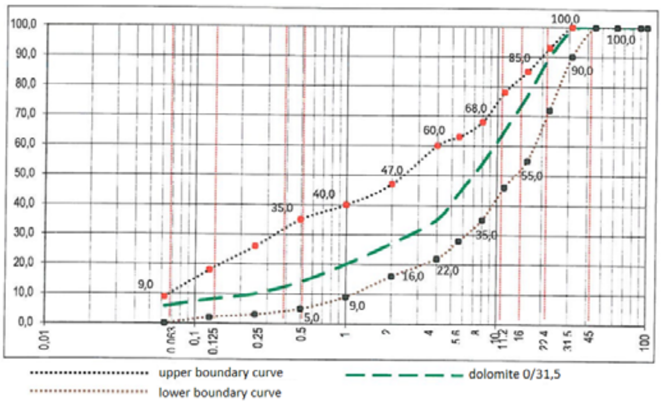


Figure 3. Grading curve of tested dolomite

The third test executed in direct shear apparatus allowed obtaining values of cohesion (c) and internal friction angle (φ) of tested sand in different moisture conditions. Results of direct shear test are showed in table 1. The values of cohesion and internal friction angle are connected with variable moisture content. Values of cohesion increase with an increase of moisture content (minimal value for moisture 1.0% and maximal value for moisture 10.0%). It can be explained by the growth of values of mutual interaction forces between respective grains of the aggregate in “moist” than in “dry” material [7]. Values of internal friction angle show inverse proportion - values of this parameter decrease with raising values of cohesion and moisture content.

Table 1. Results of shear test in direct shear apparatus obtained for sand

	Moisture content [%]	Cohesion [kPa]	Internal friction angle [°]
1	1.0	0.5	32.0
2	5.0	2.4	31.5
3	7.5	3.3	30.7
4	10.0	4.4	29.9

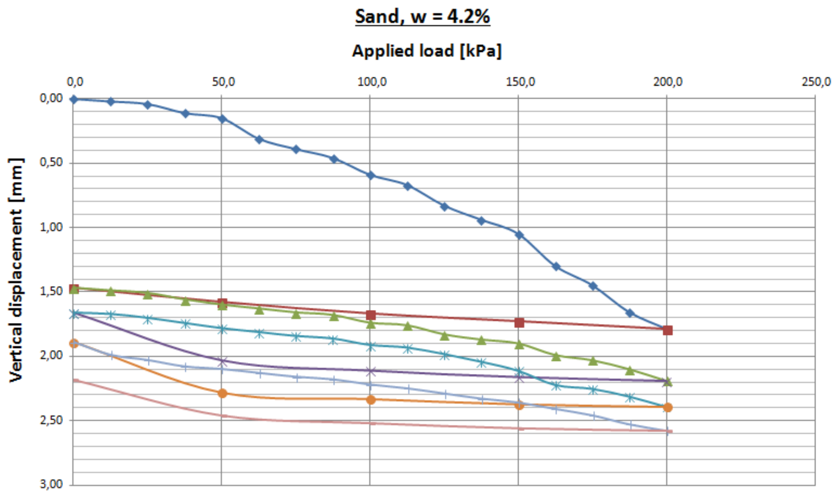


Figure 4. Applied load - vertical displacement curve for sand with moisture content of 4.2%

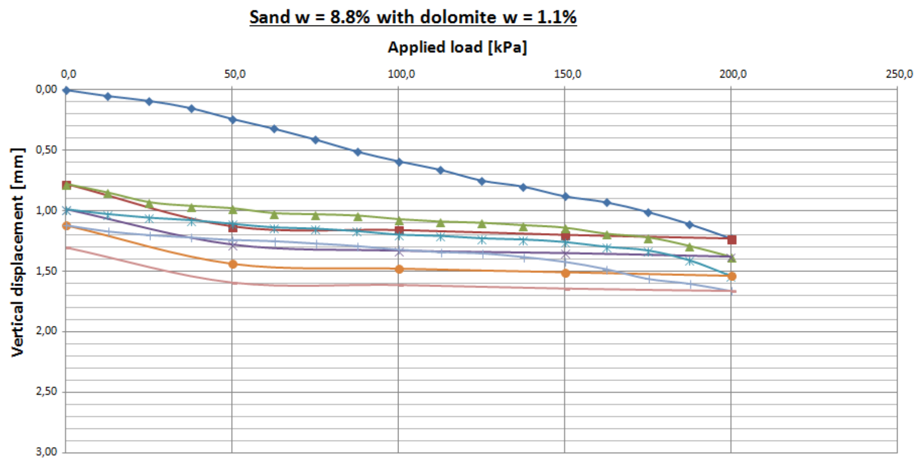


Figure 5. Applied load - vertical displacement curve for sand with moisture content of 8.8% and dolomite with moisture content of 1.1%

The final result of trial loadings of sand and two-layered structure built from moist sand and dolomite an applied load - vertical displacement curves were drawn. Examples of obtained curves are showed in figures 4 and 5.

4. Finite element method (FEM) - recognition tests

In mechanistic approach of pavement structure, designing the relationship between response of pavement structure (i.e. strain, stress or deflection) and the physical parameters is described through a numerical model [8]. Presented results of numerical analyses of small-scale laboratory tests were obtained using ZACE Z_Soil 2014 software in which the finite element method (FEM) is incorporated. Before starting the main phase of back-calculation process, it was necessary to study the impact of boundary conditions and impact of mesh size on the final results for proposed model.

4.1. Effect of mesh density

General rule of numerical analyses is that main calculation should have been preceded by introductory tests aimed to recognize the correctness of prepared numerical model [9]. Firstly, an influence of mesh density on values of vertical displacements was investigated. To verify the effect of mesh density on values of vertical displacements, eight models were prepared using axisymmetric mode in Z_Soil 2014. In each model, test cylinder filled with sand aggregate was prepared by using Coulomb-Mohr (C-M) model of soil. The density of mesh in the vertical section along the plate having the same C-M parameters (E, c, ϕ) and loading conditions (static load, backfill load) diversified models. Mesh sizes and model parameters used in models C1 - C8 are showed in table 2 and examples of models are showed in figure 6.

Table 2. Mesh sizes and model parameters of models C1 - C8

	Mesh size [cm x cm]	Modulus of elasticity [MPa]	Cohesion [kPa]	Internal friction angle [°]
C1	1.00 x 0.83	22.0	3.0	30.0
C2	1.00 x 1.25	22.0	3.0	30.0
C3	1.95 x 1.25	22.0	3.0	30.0
C4	2.60 x 1.25[a]	22.0	3.0	30.0
C5	2.60 x 1.25	22.0	3.0	30.0
C6	2.84 x 1.25	22.0	3.0	30.0
C7	1.95 x 2.50	22.0	3.0	30.0
C8	2.60 x 2.50	22.0	3.0	30.0

[a] mesh was denser on width of 15 cm when in other models on width of 10 cm

4.2. Effect of diameter of loading plate

The second recognition test was studying the influence of diameter of loading plate on boundary conditions. In the analysis, four models were taken into account - model C4.P0 without loading plate and loaded only with backfill and models C4.P10 - C4.P30 with loading plates with different diameters - 10 cm, 20 cm and 30 cm loaded by static load and backfill (figure 7). Validation of each model was obtained by calculating maximum horizontal stresses in the edge part of model, where the influence of applied load had to be unnoticeable.

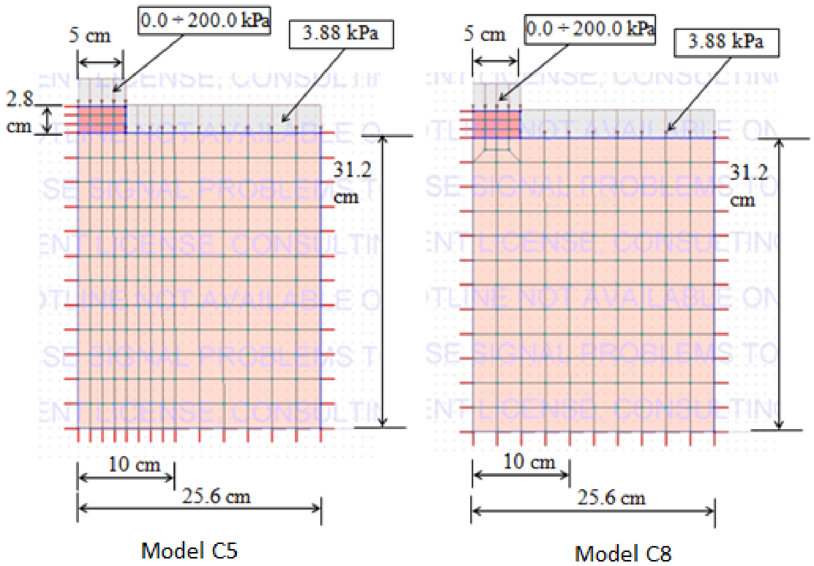


Figure 6. Examples of mesh density in model C5 and C8

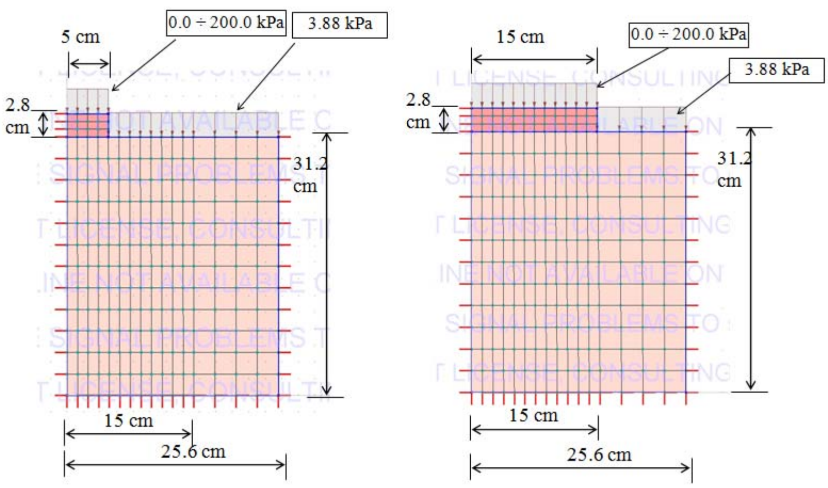


Figure 7. Examples of different diameter of loading plate analysis in model C4.P10 and C4.P30

5. Finite element method (FEM) - main analysis

Before the main analysis in Z_Soil software, conclusions from the identification step were drawn. Values of vertical displacements carried out in the same loading and material conditions in the same finite element allowed to verify the effect of mesh density. For models C1 - C5, values of maximum vertical displacement were stable near 1.60 mm as values for models C6 - C8 were notably lower (figure 8). For further analysis, mesh density from model C5 was selected, because obtaining precise vertical displacement values with thin mesh density allowed quicker calculations. In the plate diameter, values of horizontal stresses in the edge part of the model were obtained and the results are showed in figure 9 and table 3. The reference value of horizontal stresses is represented by values from model C4.P0 when static load was not applied. The lowest value of maximal horizontal stress was obtained in model C4.P10 with 10 cm diameter plate and it was almost 3 times and 5 times lower than in model C4.P2 and C4.P3, respectively. In further calculations, plate with diameter of 10 cm was used.

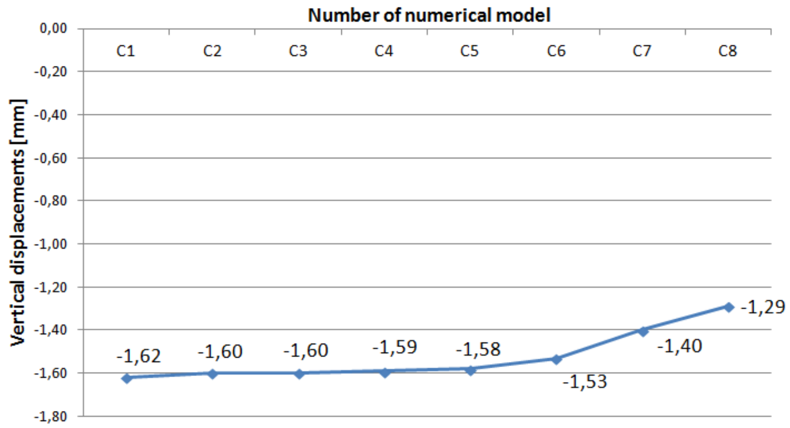
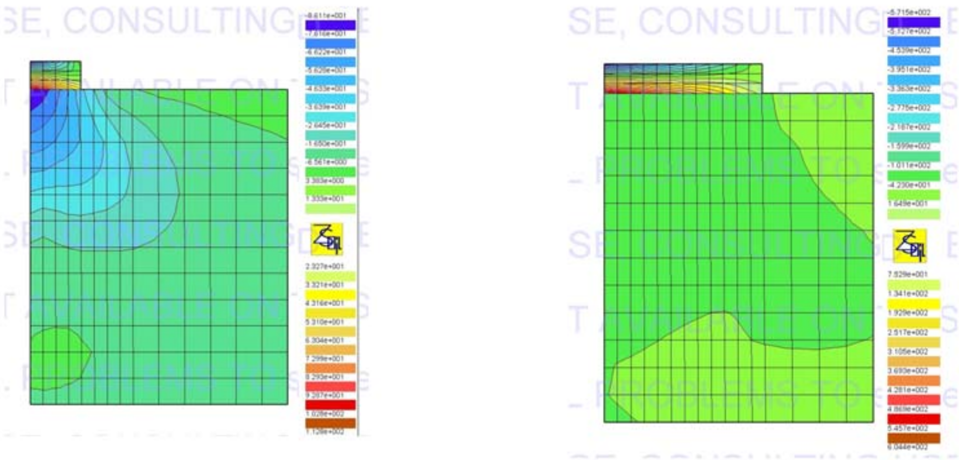


Figure 8. Values of vertical displacements for model with different mesh density



Map of horizontal stresses - model C4.P10 Map of horizontal stresses - model C4.P30

Figure 9. Maps of horizontal stresses in model C4.P10 and C4.P30

Table 3. Results of shear test in direct shear apparatus obtained for sand

	Plate diameter [cm]	Horizontal stress value [kPa]	Percentage gap in acc. to C4.P0 [%]
C4.P0	-	-4.10	-
C4.P10	10.0	-10.40	153.7
C4.P20	20.0	-27.12	561.5
C4.P30	30.0	-47.27	1052.9

Numerical analyses were performed using model C5 for sand and developed model C5 with the same mesh density and loading plate, but with additional 8.3 cm layer of dolomite for two-layered sand - dolomite structure. As mentioned in paragraph 2, materials were tested in changeable moisture conditions, thus models were diversified in terms of model parameters - cohesion (c), internal friction angle (ϕ) and modulus of elasticity (E). Parameters of models were obtained by using the back-calculation method. Based on experimental curves of loading - vertical displacement relationship model curves were stated by numerous iterations. The process of iteration ended while both experimental and model curves had the best match described by coefficient of determination R^2, which enabled to state the parameters of Coulomb-Mohr model.

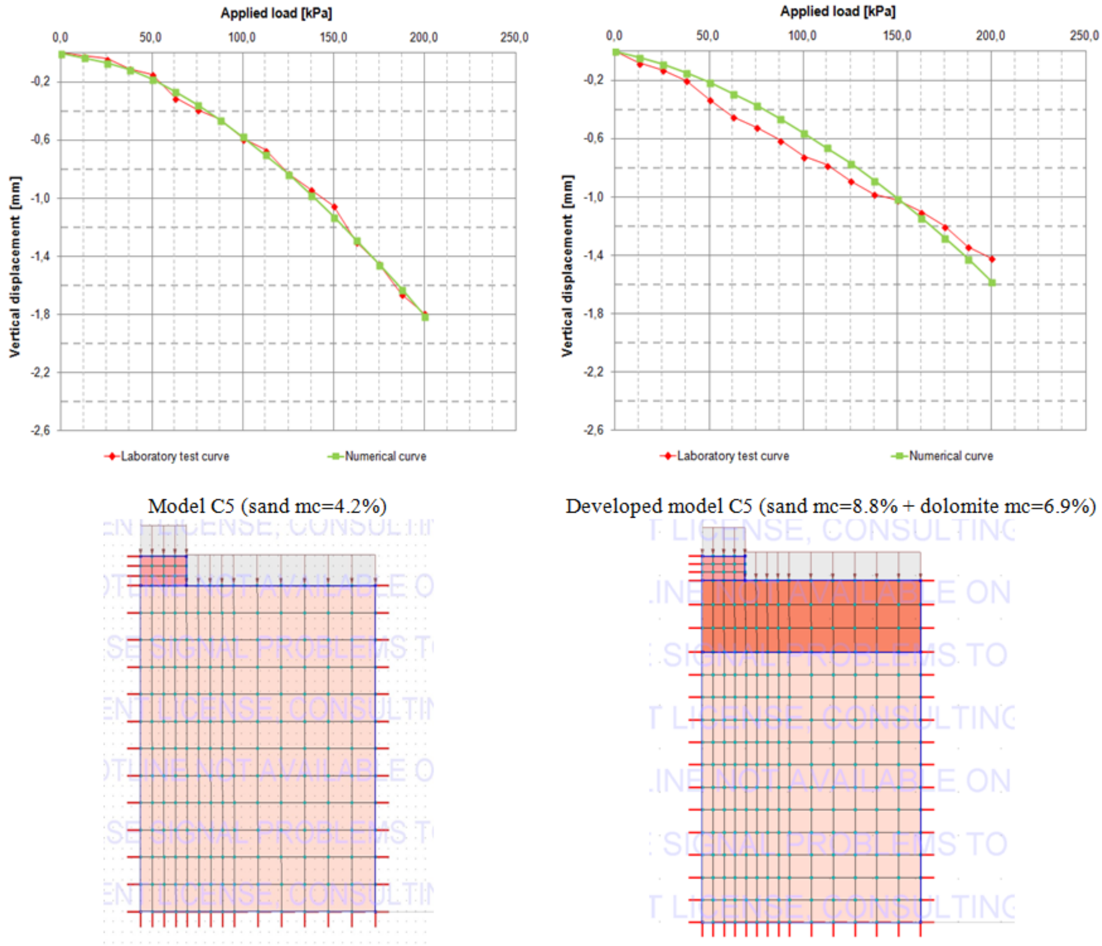


Figure 10. Examples of applied load - vertical displacement relationship for models with sand mc=4.2% and sand mc=8.8% with dolomite mc=6.9%

Example of match between the test and model curves for sand with moisture content equal to 4.2% and two-layered structure with sand with mc equal to 8.8% and dolomite with mc equal to 6.9% is shown in Figure 10. Obtained values of cohesion, internal friction angle and modulus of elasticity are displayed in Table 4. Parameters of medium sand layer (c, φ, E) stated with three different moisture conditions are acceptable as well as the match between experimental and model curves is satisfactory. Cohesion and internal friction angle values obtained in numerical analysis are connected with laboratory tests. For moisture content between 5.0 - 7.5 % values of cohesion vary between 2.4 - 3.3 kPa (2.4 - 3.4 in model) and values of internal friction angle vary between 30.7 - 31.5 degrees (30 - 31 degrees in model).

Crucial difference in model parameters for sand was obtained for moisture content under the value of optimum moisture content (mc equal to 4.2% - E^1 = 21.0 MPa, E^4 = 35.0 MPa) and above the value of optimum moisture content (mc equal to 8.8% - E^1 = 14.8 MPa, E^4 = 31.0 MPa). The value of modulus of elasticity decreased by 16.2 MPa (E^1) and 4.0 MPa (E^4). Because of lack of results from shearing tests for dolomite, influence of moisture on mechanical parameters of this aggregate was not studied. The results of first loading cycle where values of moduli of elasticity (E^1) were equal to 17.5 MPa and 13.8 MPa show that graining of aggregate was too coarse or the thickness of dolomite layer should be greater.

Table 4. Results of back-calculation analysis in Z-Soil for sand and sand-dolomite structure

	$E^{1\,a}$ [MPa]	$E^{4\,a}$ [MPa]	c [kPa]	φ [°]	ν [-]	γ [kN/m³]	R^2 [for E^1]	R^2 [for E^4]
MSa mc=4.2%	21.0	35.0	2.4 - 2.7	30 - 37	0.30	19.0	0.997	0.898
MSa mc=6.5%	18.5	31.0	2.9 - 3.7	31 - 36	0.30	19.0	0.991	0.911
MSa mc=8.8%	14.8	31.0	3.4 - 4.6	31 - 36	0.30	19.0	0.974	0.956
MSa mc=8.8% + dolomite mc=1.1%	17.5	120.0	2.5 - 3.5	32 - 36	0.30	19.0 24.0	0.966	0.957
MSa mc = 8.8% + dolomite mc = 6.9%	13.8	118.0	2.7 - 3.8	31 - 38	0.30	19.0 24.0	0.953	0.804

[a] E^1 value - values of modulus of elasticity from first loading cycle, E^4 - values of modulus of elasticity from fourth loading cycle

6. Conclusions

In this paper, authors show results of comprehensive laboratory and numerical studies on initial tests to obtain mechanical parameters of soils in different moisture conditions under static load. The main conclusions are:

- Obtained values of cohesion, internal friction angle and modulus of elasticity were modelled using finite element method and back-calculated to obtain analytical values of parameters.
- Numerical analyses could be performed for model C5 and developed model C5, because of precise results of vertical deflections, optimum mesh density shortening time of calculation and loading plate with a diameter of 10 cm to obtain minimal horizontal stress values at the edge part of model in accordance to boundary conditions.
- Different moisture content affected the value of modulus of elasticity, as well as parameters of C-M model. Value of E modulus decreased with an increase of moisture content in sand aggregate. The lowest values of cohesion were obtained for “dry” medium (mc=4.2%, c=2.4 kPa) and highest for “moist” medium (mc=8.8%, c=3.4 kPa).
- Trial loadings for the two-layered structure were focused on verifying of graining of dolomite. Graining of this material has to be finer than 0/31,5 mm in further small-scale tests.
- Wider scope of tests in small and large scale is needed to make more precise conclusions. Results of initial laboratory tests shown in this article are only the preface to main laboratory tests and attend to develop further research program.

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