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## INFLUENCE OF STRESS RATIO IN SHEAR SURFACE ON SHEAR STRENGTH OF DEPOSITED MATERIAL

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### ABSTRACT

The "Ribnica" landfill of the "Vrtlište" surface mine bordered the river Ribnica until during 2017, a landslide was started and the river Ribnica was interrupted, and a water reservoir was formed. After the completion of the tunnel that diverted the river Ribnica, its previously interrupted riverbed in the downstream part is planned for continuation of the disposal of masses from the surface mine "Vrtlište" by making an earth dam. The dam has the role of retaining large waters in case of exceeding the maximum tunnel flow, as well as in cases of monitoring and construction work in the tunnel.

The requirement to use landfill material for the construction of the dam poses a significant risk due to the lack of data on its shear strength. This paper presents the results of research on the shear strength of materials in the conditions of dam construction, under optimal moisture conditions and maximum compaction and analyzes the obtained results, which should define the behavior of the tested materials in the conditions of dam construction. The conducted research represents the first phase of the research, which will be followed by research into the shear strength of completely saturated materials, which will determine the behavior of deposited materials in the dam body and the final slopes.

Key words: *shear strength, landfill, dam, Ribnica*

### INTRODUCTION

Problems that are very present in detailed analyzes of the stability of slopes built of unbound fill materials, are related to the lack of input data in the appropriate volume and quality.

Deposited masses at the external landfill "Ribnica" consist of an uneven mixture of rocks and soils of different lithological composition, and it is very difficult to define representative geomechanical parameters for these materials, especially given the changes related to water content, looseness, compaction, stress change in the plane of failure and the rheological properties of individual rocks. [1]

Laboratory geomechanical tests that are standardized for rock and soil tests are designed for undisturbed samples of natural soil and rocks, while landfills are materials whose structure and water content change, so the behavior of these materials should be viewed differently.

Available data on geomechanical laboratory tests conducted in the phase of geological exploration of mineral resources are not of particular importance for estimating geomechanical parameters of deposited

materials, due to changes caused by blasting, loading, transport, dumping, compaction, changes in water content, exposure to atmospherics, and changes of stress in potential failure planes and rheological characteristics of the material.

A special problem is the content of the sample, which is a mixture of rocks and soil, which creates significant limitations for standard laboratory tests that are design either for soil or rocks. [1]

The representativeness of the sample of deposited masses represents significant issue during selection for testing, having in mind the uneven lithological composition, granulometric composition, water content, compaction, etc., so when choosing samples for testing special attention should be paid on possible influencing factors on shear strength. [2]

In order to determine the real values of geomechanical parameters of deposited materials that are changeable depending on the previously mentioned influencing factors, and which are necessary to take into account when analyzing the stability of the landfill and determining the allowable heights and inclination of slopes. Therefore, it is necessary to conduct laboratory tests that will take into account the various possible cases, especially in terms of water content and compaction of the material that is disposed of or it is intended to build a dam. [3,4]

Having in mind the above, it is planned to conduct shear strength tests in several phases. In the first phase of the tests, tests of the deposited material with a focus on bulk density, moisture and particle size distribution were performed. In the second phase, for materials of granulometric composition with pieces smaller than 63 mm, which is planned to be used for the construction of the dam, the optimal moisture and maximum dry bulk density are defined by the Proctor method. Then, in the third phase, the shear strength of the material is tested at optimal water content and maximum compaction, which should represent the shear strength that can be expected in the phase of construction and further functional existence of the dam.

After that, it is planned to perform control tests of shear strength for different water content and compaction of the material that may appear during the operation of the dam.

## INFLUENTIAL FACTORS ON SHEAR STRENGTH

Defining the shear strength of soil or rock materials represent the most reliable way to obtain material resistant parameters, which allows the definition of an adequate geotechnical model for performing calculations of stability, load-bearing capacity, etc.[5]

Shear resistance of the soil is based on:

1. structural resistance of displacement in the soil due to mutual entrapment of particles
2. friction resistance during the movement of individual particles along the contact surfaces
3. cohesion between particle surfaces

One of the experiments that define the resistance parameters, cohesion in the angle of internal friction (angle of shear resistance) is the direct shear test with controlled increment of shear deformation. When performing this type of test, the normal stress on the shear plane is constant during the test, and the complete test is performed for different values of the normal stress acting perpendicular to the sliding plane. [6]

Influencing factors on the obtained values are factors related to the apparatus itself and the method of performing the experiment, such as:

- the moisture of the material changes during the test,
- the state of stress in the sample we are testing,
- rate of shear load application or size of deformation,
- deformation of the material due to the impression of the filter plates and
- influence of lateral clamping.

By performing the test correctly and setting the same conditions for each sample, the influence of these factors is reduced to constant values, so that the main influencing factors on the shear strength of the material remain the characteristics of the material itself (grain size and shape, structure of the material tested, etc.). [7,8]

## SAMPLE PREPARATION AND TEST METHODS

After the analysis of the situation in the field, the samples were taken from several locations of the “Ribnica” landfill, their mixing and division into samples was performed. Materials that passed through a 63 mm sieve were used for the tests, because the larger will not be used in the construction of dam layers. Due to the grain size, shear strength tests are performed in cells measuring 230 x 230 mm and 200 mm high. The cell consists of two parts that are connected with screws during preparation, and when shearing, unscrewing them enables shearing at the contact of the lower and upper part of the cell. After the granulometric analysis of the material was performed and the optimal water content and maximal dry bulk density determined, the sample was prepared in a cell by compaction at optimal water content in three layers with 65 strokes using a weight of 2.5 kg, in order to obtain maximum compaction of the material. During this compaction, the material is crushed, and the same material cannot be used for re-testing. [9]

The prepared sample in the cell is placed in a shear device (Figure 1) made for this specified cell size. The device is placed on a press through which a vertical load will be applied. Vertical force is controlled on the press. The horizontal shear stress is applied by means of a hydraulic press which is placed horizontally on the shear device so that it pushes the lower part of the cell which lies on 3 cm diameter rollers. The rollers allow the lower part of the cell to move without significant friction. The upper part of the cell is fixed in order to keep the vertical stress constant during the test. The lower part of the cell is shear by controlled shear deformation, and the shear force is read on a dynamometer with a measurement accuracy of 1 N. The horizontal displacement is monitored on a gauge with a measuring range of 70 mm and a possibility of reading of 0.01 mm. The vertical displacement is measured with a gauge with a measuring range of 25 mm and the possibility of measuring 0.001 mm. Readings are made on each millimeter of displacement for the first 30 mm (zone in which the maximum shear stress develops), and then every 5 mm until reaching 70 mm (according to the increment of deformations approximately the zone of residual stress).



Figure 1. Cell for shear test 230 x 230 x 200 millimeters

The tests are performed for 5 different vertical stresses and each time on a different sample. The deformation of the sample is concentrated in a narrow area around the horizontal plane of the joint of the cell parts. Neither the stress state nor the deformation of the specimen are homogeneous, which is

standard when performing such a shear test (direct shear test), but during shear a sliding surface develops as in some failure processes in materials on hillsides and slopes. [10,11]

## RESULTS OF PERFORMED TESTS

The tests that preceded the shear strength tests the optimal water content of the material and the maximum dry bulk density were determined. During construction of the dam, it is planned to make layers 30 cm thick at optimal water content, in order to achieve the required maximum compaction of the material. The shear strength of such compacted material is the subject of research in this paper, so compaction and water content tests will not be considered.

Results of the measurement for each vertical load are presented as the relation between the achieved shear stress and the corresponding displacement between the lower and upper part of the cell.

Shear ( $\tau$ ) and normal stress ( $\sigma$ ) in the plane at the contact of two parts of the cell are:

$$\tau = T/A \text{ and } \sigma = N/A$$

Where A is the area of the sample in the plane of contact of the two parts of the cell (cm<sup>2</sup>) and N is the applied force (kN). [12,13]

When performing the test, the normal stress on the sliding plane  $\sigma$  is constant throughout the test, and the shear stress  $\tau$  changes from zero to the maximum value corresponding to the peak value of the shear strength under the given conditions. During the test, the shear stress increment  $\tau$  changes in the device, due to the controlled development of deformation until the maximum value is reached, after which the shear stress value  $\tau$  remains constant or decreases, depending on the applied normal stress on the failure plane.

During the study of the resistance parameters of embankment materials, which will be used as input data for calculations, the shear stress limits are of special interest:

- peak strength as the highest value of shear stress
- residual strength as stress corresponding to large deformations.

Both values, as well as the whole curve, are determined by the magnitude of the normal stress in the same plane, and the shear rate, as influencing factors. Since the experiments were performed with controlled shear deformation, the rate of deformation development was the same in all samples, so that the normal stress on the fracture plane remained as the main influencing factor on the shear strength. As the normal stress changes, so does the development of shear stresses. It is expected that as the value of the normal load increases, so does the value of the shear stress required to bring the material to failure, which means that the shear strength also increases. Since the resistance parameters are the parameters the cohesion and the friction angle of material (in coarse-grained materials it is the angle of shear resistance), the ratio of these parameters and their values which are mobilized in the failure plane are very important for defining the geotechnical model for calculation.

The possible change of the ratio of these parameters in the failure plane depending on the applied stress, which can change in the field as well due to the increase in slope height, represent a key factor for performing adequate calculations of slope stability of deposited materials, and thus slopes of earth dams. Wrong choice of parameters, due to insufficient knowledge of the stresses that can develop in the projected slope, can lead to a failure in the slope by changing the geometric elements (for example by increasing the height).

Typically, a minimum of three experiments with different vertical loads are performed on the same sample to perform adequate tests. Considering that this is material from the landfill and that it will form the slopes of the dam, and in order to determine the existence of a nonlinear relationship between shear and normal stress, five different vertical loads were used for the subject tests. [14,15,16,17,18,19,20]

The optimum water content for the 10 prepared samples ranged from 12.5% to 13.3%, and the maximum dry bulk density was 1.684 to 1.698 Mg / m<sup>3</sup>.

For normal stresses ranging from 94.52 to 567.11 (kPa) the shear stress values ranged as in the diagram.

The stress-strain diagram for the performed shear tests shows significant changes depending on the applied normal stress (Figure 2). At lower values of normal stress, the peak value of the shear strength is about 0.1 kPa, while the residual value is 0.09, which represent a small difference between the peak and residual value. This difference is due to dilatation in the material, which is due to the rotation of the particles in the shear plane and their mutual friction. In this state of stress in the shear plane, the greatest influence is exerted by the friction between the particles and the structure of the material itself in the shear plane. The effect of cohesion, which could occur by particle crushing, is relatively small in this stress state.

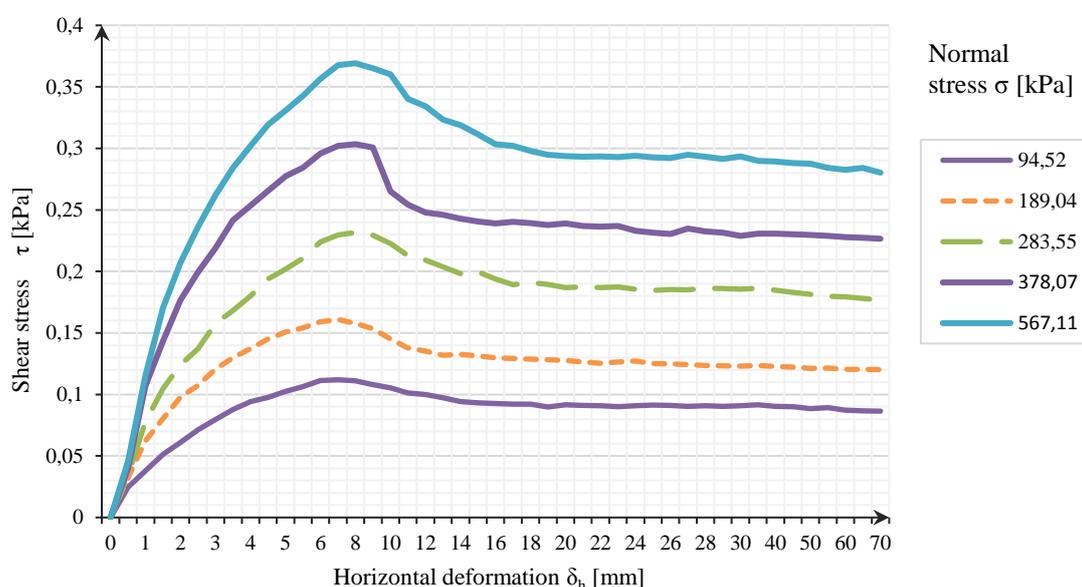


Figure 2. Shear stress and horizontal deformation for different values of normal stress

As the value of the normal stress increases to the shear plane, the value of the shear stress required to cause the material to failure increases, which is logical in conducting such tests.

As the value of the normal stress increases, the difference between the peak and residual values of the shear stresses required to cause the material to failure also increases. Since the material has a fairly uniform granulation, the same compaction and water content, large differences between the peak and residual value of shear stress are related to preventing dilatation in the material, that is preventing rotation and orientation of grains in the failure plane, thus increasing resistance parameters, especially cohesion, because for the development of a fracture in a plane it is necessary for a fracture to occur through pieces of material in which cohesion appears as a significant parameter.

However, how excessive is the mobilization of cohesion and friction angle (shear resistance angle) in a certain material and at a certain stress ratio can best be analyzed from the diagram of the ratio of shear and normal stress.

In order to better analyze the impact of cohesion and changes in parameters in the same material, a diagram of normal / shear stress was made, based on which groups of values of cohesion and shear resistance angle depending on the stress state in the fracture plane were determined (Figure 3). The obtained diagram shows the nonlinear ratio of shear and normal stress, which is important to define when choosing the input parameters for the calculations of slope stability of certain geometric relations. [5]

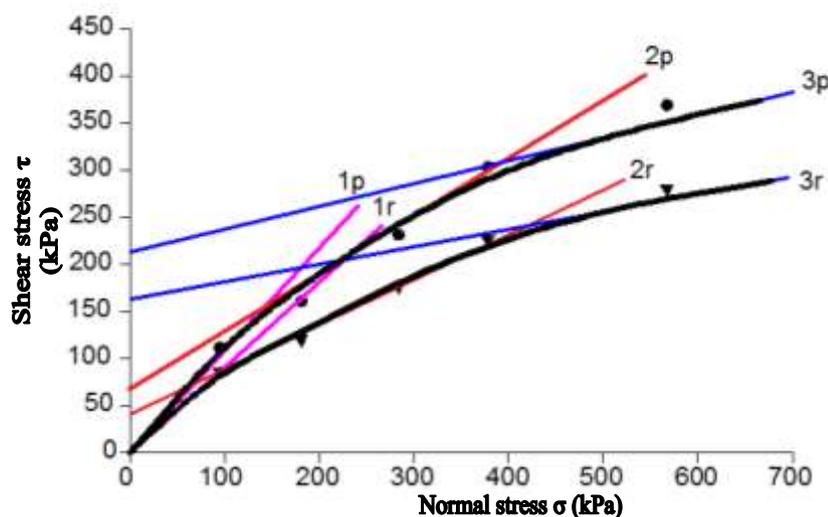


Figure 3. Peak and residual cohesion and shear strength angle

By reading the values of peak and final cohesion as well as the shear angle, the values were obtained as follows in the table 1 and table 2.

Tabela 1. Vrijednosti vršne kohezije i ugla otpornosti na smicanje u zavisnosti od primjenjenog napona  
Table 1. Values of peak cohesion and shear strength angle depending on the applied stress

Tangent	$C_p$ [kPa]	$\varphi_p$ [°]
1	0	45
2	68	31
3	212	17

Tabela 2. Vrijednosti rezidualne kohezije i ugla otpornosti na smicanje u zavisnosti od primjenjenog napona  
Table 2. Values of residual cohesion and shear strength angle depending on the applied stress

Tangent	$C_r$ [kPa]	$\varphi_r$ [°]
1	0	42
2	40	25
3	162	19

By analyzing the research results shown on the diagram of the ratio of normal and shear stress, it can be concluded that there is a nonlinear relationship that depends on the applied normal stresses in the failure plane (Figure 3). Since the material embedded in the cells is a loose material of the landfill composed of individual unconnected pieces of rock material, it is to be expected that at low values of normal stress in the slopes there is no cohesion, because there is no fracture in the pieces of rock mass and the slope is formed at the angle of friction of the material or the angle of shear resistance (due to the influence of dilation) which depends on the grain size and type of material.

Under such conditions, there is no failure within the pieces of rock material, so cohesion does not exist as a resistance parameter. With an increase in the value of the normal stress, in the failure plane, pieces of rock material are crushed in which there is cohesion as a resistance parameter, and dilatation is prevented. At this stress ratio, the shear strength angle approaches the value of the internal friction angle in the pieces of rock material, so that the size of the piece of rock material in the slope has less and less influence on the values of the shear resistance angle.

Small particles inside individual pieces of rock material in the sample, which are smaller in size, have an increasing influence on the angle of shear resistance, which leads to a decrease in the angle of shear resistance. The shear strength angle slowly decreases to the value of the base friction angle of the material, which is essentially the angle of internal friction of the material. It is important to note that with increase of normal stress, the difference in the shear strength angle between the peak and residual values decreases, due to the decreasing influence of the size of the piece of rock material on the friction angle.

Theoretically, if the normal stress were to increase further, at some point the material would plasticize and the value of the friction angle would be equal to zero, that is, the material would behave as an ideally plastic material. Of course, this is impossible to achieve in the slopes of landfills or dams, but due to the large loads due to the increase that can prevail in such structures, the nonlinear stress ratio in the failure plane must be taken into account when choosing the final slope geometry.

It is especially important to further study the phenomenon recorded in the shear diagrams that with increasing deformation there is a constant decrease in the value of the shear stress in the part of the residual displacement of the sample along the formed sliding plane. This phenomenon is more pronounced at shear planes at high normal stresses. This means that the residual resistance of the material is not a constant value and depends on the size of the dilatation. The rate of slope fracture could also depend on this phenomenon, which may be the subject of further research.

## CONCLUSION

Based on the stated risk due to insufficient data on the resistance of the landfill material that is planned to be used for the construction of the dam on the river Ribnica and which will represent the foot part of the Ribnica landfill, tests were conducted to define the shear resistance of the deposited material. These tests, due to the heterogeneity of the lithological composition as well as the variable granulometric composition and water content, required the production of larger shear cells than usual and the conduct of tests at higher normal loads.

Based on the tests performed on the deposited materials from the Ribnica landfill, which do not represent “freshly” disposed materials, tests were performed to determine the optimal water content and maximum dry bulk density. These tests served as a basis for the preparation of test samples granulation less than 63 mm on which it is necessary to determine the shear strength, i.e. to determine the parameters of cohesion and shear resistance angle, which can be expected during the construction of the dam, depending on the elements of the formed slopes.

Based on the results, it can be concluded that although it is a material tested at the same compaction and water content, there are changes in the resistance parameters of the material due to changes in stresses acting in the failure plane (primarily when changing the normal stress).

Tests show that with an increase in normal stress there is an increase in the share of cohesion as a resistance parameter and a decrease in the shear strength angle. The angle of shear resistance slowly decreases towards the angle of internal friction inside the piece of rock material, while due to the increasing presence of failure in the pieces of rock material within the failure plane, the cohesion of the material increases.

The test results show that it is necessary to analyze in detail the obtained data on the shear resistance of materials and based on the performed stability analyzes, define the optimal geometric parameters of the slopes formed in these materials.

Tests have shown that with increasing deformation there is a constant decrease in the value of shear stress in the part of residual displacement of the sample along the formed sliding plane, which indicates that the residual resistance of the test material is not a constant value and depends on dilatation. The velocity of the slope fracture could also depend on this phenomenon, which is more pronounced in the case of shear planes at high normal stresses, which may be the subject of further research.

The presented test results represent the first phase of the testing, after which tests for fully saturated samples will be performed, based on which the shear resistance of the material will be determined in case of complete flooding, i.e. in cases of high waters when an accumulation on the river Ribnica may form.

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