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COMPARISON OF SOIL DEFORMATION PARAMETERS DETERMINED BY OEDOMETER AND TRIAXIAL TESTS

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One of the main parameters characterizing soil deformations is the deformation modulus, which can be determined in the laboratory with an oedometer or a triaxial test device. The authors conducted experimental tests with the oedometer and triaxial test apparatuses with eight different type soils. Experimental data for eight types of sands, clays, silts with specially mixed grain size distribution curves, having different non-plastic fines contents, mean grain sizes and uniformity coefficients, were analyzed. In general, the deformation modulus obtained from the triaxial test is higher than that obtained from the oedometer test, due to the difference in loading conditions. It is important to take into account the specific properties of the soil, like particles form, and test conditions when comparing the values of the deformation modulus obtained by performing different laboratory tests. Also, it is very important to know the magnitude of the loads and the type of foundation when assessing ground deformations.

Keywords: Deformation modulus, Secant modulus, Oedometric modulus, Compression parameter, Stress, Compressibility.

1 INTRODUCTION

Evaluation of soil deformation is essential for many geotechnical tasks. Soil compression parameters are required for geotechnical calculations related to sediments and horizontal deformations. These parameters can be determined in the laboratory and/or under field conditions. One of the main parameters characterizing soil deformations is the deformation modulus, which can be determined in the laboratory with an oedometer or a triaxial test devices.

The purpose of soil oedometer testing is to determine a soil porosity changes with external vertical loading. The soil sample is tested in a rigid ring, where deformations in the horizontal direction are not possible. Normally, the test specimen is loaded by gradually increasing the load. The oedometric deformation modulus E_0 is the relationship between stress and relative strain changes. Under natural conditions, the soil below the foundation deforms differently than in the oedometer apparatus. Since the rigid steel ring does not constrain, the soil under the foundation is deformed not only in the vertical but also in the horizontal direction as well. Therefore, another index of compressibility is used to describe the actual deformation of the soil under the foundation – the deformation modulus E. The deformation of the oedometer specimen is different from the triaxial pressure test. When testing compressibility with a triaxial pressure machine, three perpendicular stresses are applied to the soil sample: vertical σ_1 and horizontal σ_2 and σ_3. These stresses create a three-dimensional stress state in the soil specimen. Determined secant modulus

E_{50} is a modulus of elasticity at 50% strength. The state of soil stresses and deformations under the foundation where soil is undisturbed (natural conditions) is simulated more accurately than the odometer.

Under different loads, when tested with different devices, different deformation modulus is obtained (Tamošiūnas *et al.* 2020, Tamošiūnas *et al.* 2022). Due to the different loading conditions, the deformation modulus obtained in the triaxial test is higher than in the oedometer test (Feeser and Bruckmann 1995, Molla 2017). However, the difference in deformation modulus between the two tests may vary depending on the type and properties of the soil. Therefore, it is important to take into account the specific properties of the soil, like particles form, and test conditions when comparing the values of the deformation modulus obtained by performing different laboratory tests (Šlečkuvienė 2013, Statkus and Martinkus 2013, Berre 2014, Skuodis *et.al.* 2017). It is very important to know the magnitude of the loads and the type of foundation when assessing ground deformations.

This paper presents and discusses the results of experimental tests performed with an oedometer and a triaxial test apparatus to determine the deformation modulus of soils and compare the obtained results.

2 EXPERIMENTAL SETUP

2.1 Oedometer Test

Rings with an inner diameter of 71.4 mm and a height of 25.0 mm were used for the oedometer soil samples. The initial volume of all samples was 100 cm^3. The samples were loaded in stages by increasing the load, the load steps are: 20, 40, 70, 100, 120, 140, 160 kPa. The load is not increased until settlement stabilization is reached. Stabilization is achieved when the soil sample height change is less than 0.01 mm over a certain time for each soil type.

Disturbed structures and compacted specimens were used for the tests. The soil samples were prepared by compacting them to Proctor density with the optimal soil moisture. Each soil was tested three times and the average values were derived from the results. Deformation moduli are calculated when stresses increased from 0 to 20 kPa; from 0 to 40 kPa; from 0 to 70 kPa; from 0 to 100 kPa; from 0 to 120 kPa; from 0 to 140 kPa; from 0 to 160 kPa, respectively.

2.2 Triaxial Test

In the triaxial test, the cylinder-shaped soil samples were used. The diameter of the soil sample was 100 mm, the height was 200 mm. A consolidated – drained test was performed where water was allowed to drain from the specimen during consolidation and shearing. The specimen is loaded with a vertical load as soon as the deformation of the specimen stabilizes due to hydrostatic pressure. With vertical loading, the sample is loaded at such a rate that the redistribution of soil particles does not cause an increase in pore pressure.

Tests were performed under constant lateral pressure σ_3 of 20, 50 and 70 kPa, with the vertical deformation of the specimen increased at a constant rate. During the test, axial deformations and the vertical force compressing the specimen were measured. The shear test is completed when the axial relative deformations reached 15%.

3 SOIL PROPERTIES

For the purposes of scientific testing different soils were used: poorly graded sand; uniformly graded sand; clay; well graded sand; silt; silty sand; clayey sand and low clayey sand. These soils were classified according to LST 1331:2022 – the primary Lithuanian road construction classification (Lithuanian Standards Board 2022). Determined physical and mechanical characteristics of all investigated soils in laboratory are presented in Table 1.

Table 1. Physical and mechanical properties of soil.

Soil parameters	Poorly graded sand	Uniformly graded sand	Clay	Well graded sand	Silt	Silty sand	Clayey sand	Low clayey sand
Optimal soil density ρ, g/cm^3	1.655	1.746	1.958	1.984	2.081	1.928	1.900	2.172
Optimal soil moisture w, %	14.30	8.00	11.00	8.80	8.00	11.80	10.70	6.00
Angle of internal friction φ, °	43.9	43.5	27.9	48.3	33.0	39.0	39.9	43.8
Cohesion c, kPa	0.0	1.0	39.0	0.0	40.0	1.0	14.0	8.0
Initial porosity coefficient, e_0	0.664	0.652	0.553	0.464	0.386	0.566	0.573	0.318

4 INTERPRETATION OF RESULTS

4.1 Results of Oedometer Testing

Examining the results obtained by the odometer shows that the oedometric deformation modulus E_0 at both 20 kPa and 70 kPa stresses is not much different compared to the triaxial test results in the same stress range, the difference is up to 30%. The highest difference (30%) is obtained for sandy soils, the lowest difference (14%) for clay soils.

The initial porosity coefficient of poorly graded sand was the highest e_0 = 0.664 compared to other soils, during the compression test the porosity of the soil varied from 0.664 to 0.650, the sample did not compress much (Table 2). Low clayey sand and silt had the lowest initial porosity coefficient respectively e_0 = 0.318 and e_0 = 0.386, the samples compressed moderately. Well graded sand with e_0 = 0.464 deformed at least, the change of specimen height was Δh = 0.177 mm. The most deformed clay had the change in specimen height Δh = 1.127 mm, with the initial porosity coefficient e_0 = 0.553.

Table 2. Summary of results obtained with the oedometer.

Soil	e_0	e	Δh
Poorly graded sand	0.664	0.650	0.193
Uniformly graded sand	0.652	0.639	0.187
Clay	0.553	0.483	1.127
Well graded sand	0.464	0.454	0.177
Silt	0.386	0.372	0.250
Silty sand	0.566	0.510	0.893
Clayey sand	0.573	0.528	0.717
Low clayey sand	0.318	0.300	0.333

Examining the deformation moduli of all soils, it can be seen that the well graded sand has the highest deformation modulus when the vertical stress is 160 kPa (Fig. 1). The clay has the lowest value of the deformation modulus and its change in all stages of loading. The values of the deformation modulus change up to 34% in all stages under vertical stresses from 20 kPa to 160 kPa. The uniformly graded sand and the poorly graded sand have very similar deformation moduli at vertical stresses of 40–160 kPa, the deformation modulus change range till 33%. There is a similar increase in the deformation modulus in silty sand and clayey sand, and the deformation modulus increases similarly in both soils as the load increases.

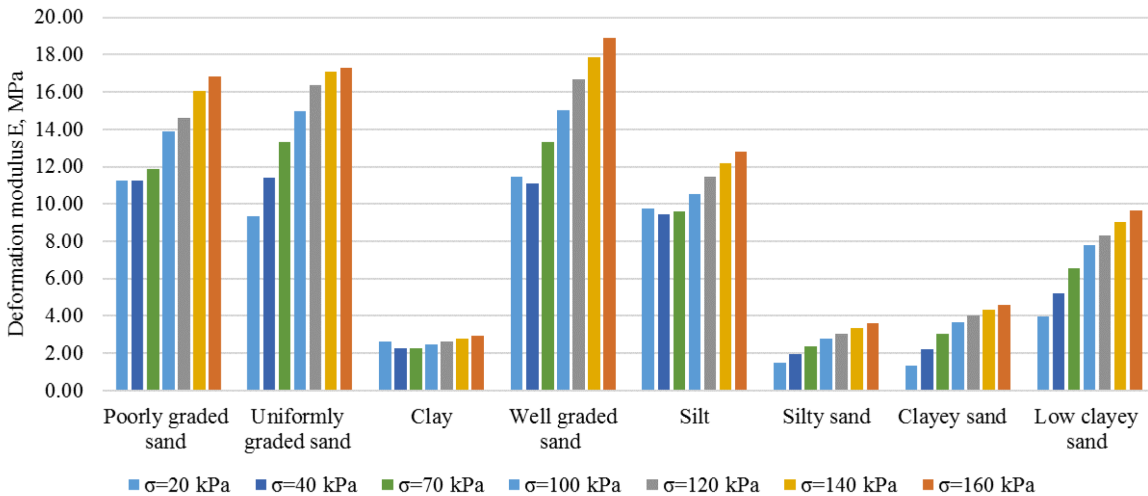

Fig. 1. Deformation modulus determined by oedometer.

4.2 Results of Triaxial Testing

At the beginning of the test, the sand samples become denser, and with the further increase of the vertical displacements, a plane of failure begins to form. Dense sands have a clearly expressed peak strength corresponding to the maximum value of stress deviator ($\sigma_1 - \sigma_3$). Only after the peak strength, as the relative deformations increase, the strength of the soil begins to decrease, the sample swells (expands), dilatancy occurs, and the vertical component of stresses decreases slowly. As the horizontal stress component σ_3 increases, the shear strength reaches its minimum value at different axial deformations. Determined secant moduli E_{50} by triaxial test of all investigated soils are presented in Table 3.

Table 3. Summary of results obtained with the triaxial apparatus.

Soil type	**E_{50}, kPa**		
	σ_3 = 20 kPa	**σ_3 = 50 kPa**	**σ_3 = 70 kPa**
Poorly graded sand	17.6	34.0	43.4
Uniformly graded sand	21.9	45.32	50.3
Clay	7.4	6.4	5.1
Well graded sand	14.8	26.2	35.5
Silt	15.7	10.6	13.7
Silty sand	2.9	2.5	7.8
Clayey sand	1.7	3.4	6.5
Low clayey sand	11.5	14.4	16.9

When testing clay, silty sand, and clayey sands samples, the samples are densified throughout the test, they do not have a clear peak strength. Stresses $\sigma_1 - \sigma_3$ increase during the entire test, in most cases they do not stabilize. The maximum strength in the specimens is achieved at much higher axial relative strains than in the dense sand specimens. In some clay specimens, no shear plane is visually formed, in some, many shear planes are formed.

5 INTERPRETATION OF RESULTS

After all the tests with the oedometer and the triaxial pressure apparatus, comparisons of the soil deformation moduli results are made. The compared deformation moduli were obtained at stress levels of 20 and 70 kPa.

Examining the results obtained with the oedometer shows, that the deformation modulus E_0 at both 20 kPa and 70 kPa stresses is different, the difference is up to 56%. The highest difference (56%) is obtained for sandy soils, the lowest difference (15%) for clayey soils. Analyzing the results of the triaxial test in the same stress range, the differences are significantly larger: for sandy soils, the secant modulus E_{50} is higher and reaches 32–73%, for clay, silt reaches 12–31%. The difference between the oedometer and triaxial results is due to the fact that the soil sample cannot deform horizontally in the oedometer ring and it can be in the triaxial test. A summary of the obtained results is presented in Table 4.

Table 4. Summary table of comparison of soil deformation moduli.

Soil type	σ, kPa	E_0, MPa	E_{50}, MPa	%
Poorly graded sand	20	14.1	17.6	20
	70	14.9	43.4	65
Uniformly graded sand	20	11.7	21.9	46
	70	16.7	50.3	66
Clay	20	3.3	7.4	55
	70	2.8	5.1	44
Well graded sand	20	18.1	14.8	18
	70	16.6	35.5	53
Silt	20	12.2	15.7	22
	70	12.0	13.7	12
Silty sand	20	1.9	2.9	36
	70	2.9	7.8	61
Clayey sand	20	1.6	1.7	3
	70	3.8	6.5	41
Low clayey sand	20	4.9	11.5	56
	70	8.2	16.9	51

When all differences were examined, a wide spread of study results was found. The deformation moduli determined by the triaxial pressure apparatus are even higher, up to 66%.

8 CONCLUSIONS

After the analysis of literature sources, experimental tests results, the following conclusions can be drawn:

1. Examining the results obtained by the oedometer shows that the deformation modulus E_0 both at 20 kPa and at 70 kPa stress is different, the difference is up to 56%. The highest difference (56%) is obtained for sandy soils, the lowest (15%) for clayey soils and silt.
2. Analyzing the results of the triaxial test in the same stress range, the differences are significantly larger: for sandy soils, the secant modulus E_{50} is higher by 32–73%, for clay and silt by 12–31%.

3. The initial porosity coefficient of poorly graded sand was the highest $e_0 = 0.664$ compared to other soils, during the compression test, the porosity of the soil varied from 0.664 to 0.650 with the oedometer, the sample did not compress much. Low clayey sand had the lowest initial porosity coefficient $e_0 = 0.318$ and silt $e_0 = 0.386$, the samples compressed moderately. The well graded sand with $e_0 = 0.464$ deformed at least $\Delta h = 0.177$ mm. The most deformed clay was $\Delta h = 1.127$ mm, with initial porosity coefficient $e_0 = 0.553$.
4. In all cases, larger deformation moduli were determined by testing with a triaxial pressure apparatus. The differences in the deformation moduli of all the tested soils in the oedometer and the triaxial pressure apparatus at stresses of 20 and 70 kPa range from 3 to 66%. The largest difference of 53–66% is obtained for poorly, uniformly and well graded sands at 70 kPa loading, the smallest difference of 12–44% is obtained for clay, silt and clayey sand at 70 kPa.

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