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Predictive modeling of sandy subgrade soil's resilient modulus using cyclic and static triaxial test variables and results

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ABSTRACT

To design a pavement the mechanical properties of it need to be determined, one of them is the resilient modulus (E_r), which is a measure of the ability of a material to resist deformation under repeated loading. The prediction of resilient modulus using different types of parameters is a well-known and commonly used practice. Three static and one cyclic triaxial tests were conducted with variously graded sand (SP) and the same type and number of tests were conducted with the well-graded sand (SG). Two dependencies were observed during the analysis of the tests results: 1) the power dependency between the resilient modulus and a ratio of maximum and minimum values of deviatoric stress, and 2) natural logarithmic dependency between the ratio of resilient modulus to maximum and minimum values of deviatoric stress, and a ratio of secant modulus from the static triaxial tests to a maximum and minimum value of deviatoric stress. Developed prediction dependencies showed a good agreement compared to the resilient modulus values received from the direct test results.

KEYWORDS

Resilient modulus; cyclic triaxial test; static triaxial test; predictive models; sand.

1. INTRODUCTION

To design a pavement the mechanical properties of it need to be determined, one of them is the resilient modulus (E_r), which is a measure of the ability of a material to resist deformation under repeated loading (Transportaions officials, 1993; Transportaions officials, 2008; EN 13286-7, 2004). It provides a measure of the stiffness of the pavement material and its ability to resist rutting and fatigue (Behiry, 2012; Sas et al., 2016), so it is commonly used in the design of flexible pavements. There are several factors affecting the resilient modulus such as the type and amount of loading, the temperature, and the moisture content of the material (Jin et al., 1994; Filotenkovas and Vaitkus, 2022). The cyclic triaxial pressure tests are performed in the laboratory to determine the resilient modulus. These tests are difficult to perform due to several reasons, such as the duration of the tests, expensive equipment, and a need for highly qualified specialists which makes these tests relatively expensive (Tamošiūnas and Skuodis, 2023; Tilti et al., 2006). To solve this issue a predictive modeling of resilient modulus has been introduced (Tamošiūnas et al., 2022; Fathi et al., 2021; Pahno et al., 2021). The purpose of this research work is to find the dependencies between soil parameters that were used and received during the static and cyclic triaxial test campaign and the resilient modules that were received after the performance of the cyclic triaxial tests.

2. TEST PROCEDURE

To determine the secant modulus (E_{50}) the static isotropic consolidated drained (CD) triaxial compression tests were conducted for every type of soil according to the procedure described in LST EN ISO 17892-9. Three different values of confining stress σ_3 were applied during the consolidation and loading phases: 20 kPa, 50 kPa, and 70 kPa. To determine the resilient modulus the isotropic unconsolidated drained cyclic triaxial tests were performed according to the low-stress test program provided in EN 13286-7 (method B), which was adjusted using three different values of confining stress, 20 kPa, 50 kPa, and 70 kPa, the same values as for static isotropic consolidated drained triaxial compression tests. The minimum value of the deviator σ_d was fixed at the limit of 10 kPa due to the limitations of the test apparatus. The number of cycles and the maximum deviator stress for a particular state of specimen loading are described in Table 1. The loadings of the specimen were performed at a frequency of 1 Hz with data recording intervals ranging from 100 to 150 times per second. Conditioning of specimens was performed with 20’000 periodic cyclic loadings at the same frequency of 1 Hz with variable stress deviator ranging from 10 to 200 kPa as described in EN 13286-7 (lowest 10 kPa stress deviator was applied due to limitations of the equipment). The dimensions of the samples for static and cyclic triaxial tests were the same, 100 mm in diameter and 200 mm in height. Both types of tests were performed using Wille Geotechnik cyclic triaxial apparatus.

Table 1. Test program for cyclic triaxial test after the conditioning phase

Confining stress σ_3, kPa	Deviator stress σ_d, kPa	
constant	min	max
20	10	20
20	10	35
20	10	50
20	10	70
50	10	50
50	10	70
50	10	90
50	10	120
50	10	160
70	10	70
70	10	90
70	10	120
70	10	160
70	10	200

3. MATERIALS

Static and cyclic triaxial tests were performed with two types of soils which were classified according to the LST 1331 standard. The first one is variously graded sand (SP), and the second one is well-graded sand (SG). Additionally, the classification according to the Unified Soil Classification System (USCS)(Daryati et al., 2019) was performed on the soils mentioned above, and the resulting types can be seen in Table 2, as well as coefficients of curvature (C_c), and uniformity coefficients (C_u).

Table 2. Classification of soils

Type of specimen	C_u	C_c	Soil Classification	
			LST 1331	USCS
SP	4.74	0.75	Variously graded sand (SP)	Poorly graded sand (SP)
SG	6.23	1.07	Well-graded sand (SG)	Well-graded sand (SW)

4. PREDICTIVE MODELS

The prediction of resilient modulus using different types of parameters is well-known and commonly used in practice. There are many predictive models that help to predict the values of residual modulus using the mechanical and physical properties of the soil (Zhang et al., 2021a; 2021b; Hanandeh et al., 2020). Another group of predictive models that are commonly used are models based on the stress state of the soil. The universal Witczak model (Yoder and Witczak, 1975; Al-Dulaimi et al., 2022), the Uzan model (Uzan, 1985; Hopkins et al., 2020), the K-θ model (Hicks, 1970; Adomako et al., 2022; Chowdhury, 2021), and the Rahim and George model (Rahim and George, 2005; Fedakar et al., 2022) can be taken as an example of such type of models. A new Octahedral Shear Stress (OSS) predictive model based on the stress state of the soil was developed (Tamošiūnas and Skuodis, 2023) by the current article authors:

$$E_r = K_1\tau_{oct} - K_2, \tag{2}$$

where (τ_{oct}) is the octahedral shear stress equal to ($\sqrt{2}/3$)(σ_1- σ_3), and $K_{1\text{-}2}$ are regression coefficients. This new model predicts resilient modulus with a regression coefficient K_1 ranging from 15.58 to 16.24 depending on the soil type, regression coefficient K_2 ranging from 19.46 to 77.73, also depending on the soil type, and a coefficient of determination (R^2) ranging from 0.85 to 0.99.

5. RESULTS AND DISCUSSION

Three static and one cyclic triaxial tests were conducted with variously graded sand (SP) and the same type and number of tests were conducted with the well-graded sand (SG). The results for variously graded sand (SP) are presented in Tables 3-4.

Table 3. Cyclic triaxial test results for variously graded sand (SP)

Cyclic triaxial						
Number of cycles	$\sigma_{3,max}$	$\sigma_{d,min}$	$\sigma_{d,max}$	E_r	$\sigma_{d,max} / \sigma_{d,min}$	E_r / $(\sigma_{d,max} / \sigma_{d,min})$
20'000 - 20'100	20.7	10.5	21.0	125.8	2.0	63.2
20'100 - 20'200	20.6	11.5	35.9	211.4	3.1	67.4
20'200 - 20'300	20.5	12.4	51.2	315.8	4.1	76.3
20'300 - 20'400	23.6	12.7	67.5	437.5	5.3	82.7
20'900 - 21'000	50.8	10.7	51.9	355.7	4.9	73.2
21'000 - 21'100	50.8	11.3	73.2	507.0	6.5	78.1
21'100 - 21'200	50.9	11.8	92.8	653.5	7.8	83.4
21'200 - 21'300	51.0	12.3	123.2	881.1	10.0	87.7
21'300 - 21'400	52.5	13.2	150.2	1066.5	11.3	94.0
21'400 - 21'500	71.0	10.5	71.8	516.6	6.8	75.5
21'500 - 21'600	71.0	10.7	92.8	674.3	8.7	77.6
21'600 - 21'700	70.7	11.1	123.8	886.9	11.1	79.6
21'700 - 21'800	70.9	11.6	163.5	1186.4	14.1	84.3
21'800 - 21'900	71.1	12.6	199.0	1440.5	15.7	91.5

Table 4. Static triaxial test results for variously graded sand (SP)

Static triaxial		
σ_3	E_{50}	E_{50} $(\sigma_{d,max} / \sigma_{d,min})$
20.0	14.0	27.9
20.0	14.0	43.9
20.0	14.0	57.9
20.0	14.0	74.1
50.0	34.9	169.6
50.0	34.9	226.5
50.0	34.9	273.4
50.0	34.9	350.4
50.0	34.9	395.8
70.0	42.2	288.8
70.0	42.2	366.6
70.0	42.2	470.4
70.0	42.2	593.7
70.0	42.2	664.2

The results for variously well-graded sand (SG) are presented in Tables 5-6. The picture of well-graded sand (SG) after the static and cyclic triaxial tests is presented in Figures 1-2.

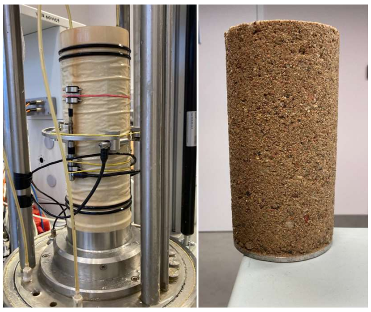

Figure 1. Well-graded sand (SG) after the cyclic triaxial test

Table 5. Cyclic triaxial test results for variously well-graded sand (SG)

Cyclic triaxial

Number of cycles	$\sigma_{3,max}$	$\sigma_{d,min}$	$\sigma_{d,max}$	E_r	$\sigma_{d,max}/\sigma_{d,min}$	$E_r / (\sigma_{d,max} / \sigma_{d,min})$
20'000 - 20'100	20.1	9.0	22.5	75.3	2.5	30.2
20'100 - 20'200	20.2	10.4	36.5	150.2	3.5	42.7
20'200 - 20'300	19.9	11.2	51.7	255.7	4.6	55.3
20'300 - 20'400	23.0	12.0	68.1	411.0	5.7	72.5
20'900 - 21'000	49.8	11.1	52.6	281.6	4.7	59.5
21'000 - 21'100	50.9	11.0	73.6	489.0	6.7	73.3
21'100 - 21'200	50.5	11.5	92.8	601.6	8.1	74.5
21'200 - 21'300	50.3	12.5	123.8	816.2	9.9	82.3
21'300 - 21'400	52.9	13.3	150.8	1016.5	11.3	89.9
21'400 - 21'500	70.7	10.3	72.3	386.5	7.0	55.3
21'500 - 21'600	71.0	11.0	93.0	606.0	8.4	71.9
21'600 - 21'700	71.0	11.9	124.1	906.9	10.4	87.0
21'700 - 21'800	71.2	12.9	163.6	1223.3	12.7	96.3
21'800 - 21'900	71.1	13.5	200.0	1403.8	14.8	94.8

Table 6. Static triaxial test results for variously well-graded sand (SG)

Static triaxial		
σ_3	E_{50}	E_{50} $(\sigma_{d,max} / \sigma_{d,min})$
20.0	11.8	29.4
20.0	11.8	41.5
20.0	11.8	54.6
20.0	11.8	66.9
50.0	24.4	115.6
50.0	24.4	162.8
50.0	24.4	197.0
50.0	24.4	242.1
50.0	24.4	275.9
70.0	38.9	272.0
70.0	38.9	327.9
70.0	38.9	405.7
70.0	38.9	494.1
70.0	38.9	576.1

Figure 2. Well-graded sand (SG) after the static triaxial test

After receiving the results of cyclic triaxial tests, a power dependence was observed between resilient modulus and a ratio of maximum and minimum values of deviatoric stress. The dependency can be seen in Figure 3.

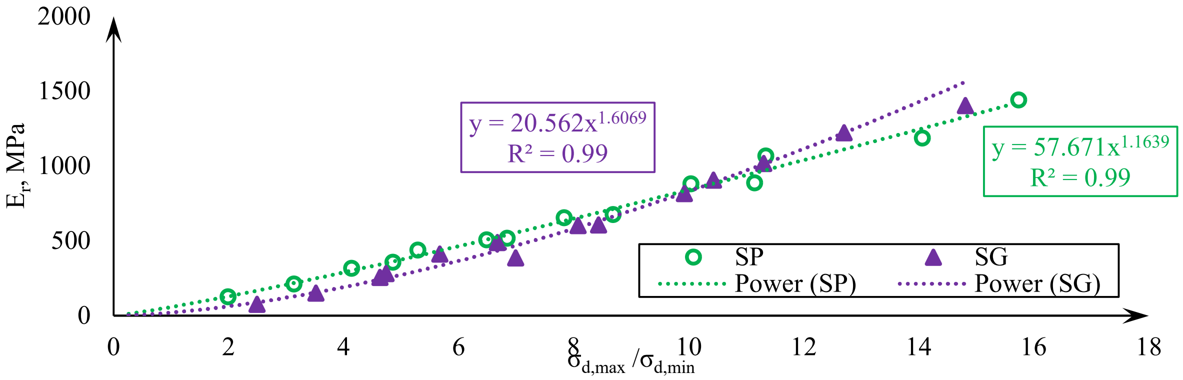

Figure 3. A power dependency between resilient modulus and a ratio of maximum and minimum values of deviatoric stress

As can be seen from Figure 3 the power dependence between resilient modulus and a ratio of maximum and minimum values of deviatoric stress has a coefficient of determination of 0.99. Based on these results, the authors of the paper propose the following dependency equations (3) and (4):

$$E^{SP}_{r,p} = 57.671 \left(\frac{\sigma_{d,max}}{\sigma_{d,min}}\right)^{1.1639}, \tag{3}$$

$$E^{SG}_{r,p} = 20.562 \left(\frac{\sigma_{d,max}}{\sigma_{d,min}}\right)^{1.6069}, \tag{4}$$

where $E^{SP}_{R,p}$ is a predictive value of resilient modulus for variously graded sand (SP), and $E^{SG}_{r,p}$ is a predictive value of resilient modulus for well-graded sand (SG). After receiving the results of cyclic and static triaxial tests, a natural logarithmic dependence was observed between the ratio of resilient modulus to maximum and minimum values of deviatoric stress and a ratio of secant modulus from the static triaxial tests to a maximum and minimum values of deviatoric stress. The dependency can be seen in Figure 4.

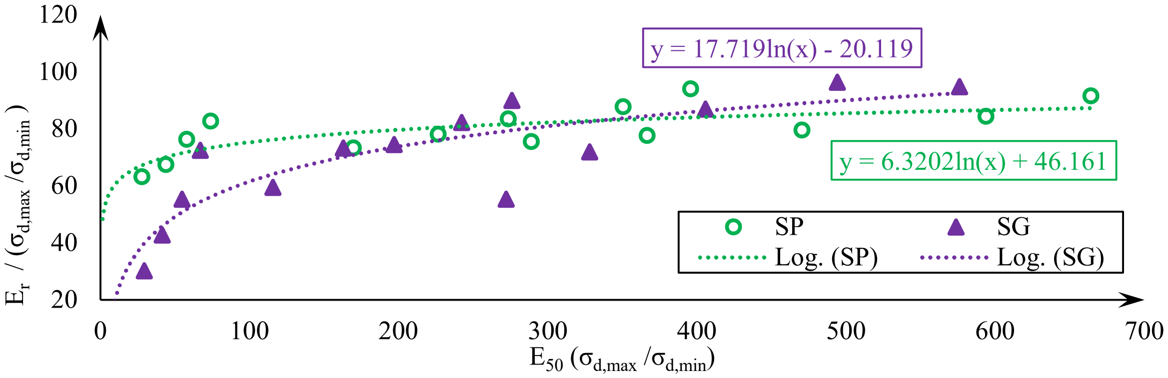

Figure 4. A natural logarithmic dependency between the ratio of resilient modulus to maximum and minimum values of deviatoric stress and a ratio of secant modulus from the static triaxial tests to a maximum and minimum values of deviatoric stress

Based on a natural logarithmic dependence between the ratio of resilient modulus to maximum and minimum values of deviatoric stress and a ratio of secant modulus from the static triaxial tests to a maximum and minimum values of deviatoric stress, the authors of the paper propose the following dependency equations (5) and (6):

$$E^{SP}_{r,p} = \left[6.3202 \ln\left(E_{50}\frac{\sigma_{d,max}}{\sigma_{d,min}}\right) + 46.161\right]\left(\frac{\sigma_{d,max}}{\sigma_{d,min}}\right), \tag{5}$$

$$E^{SG}_{r,p} = \left[17.719 \ln\left(E_{50}\frac{\sigma_{d,max}}{\sigma_{d,min}}\right) - 20.119\right]\left(\frac{\sigma_{d,max}}{\sigma_{d,min}}\right). \tag{6}$$

All four proposed equations (3), (4), (5), and (6) for predicting the resilient modulus were used and the results can be seen in Tables 7-8.

Table 7. Prediction results using power dependence equations (3) and (4)

Number of cycles	SP				SG			
	$\sigma_{dmax}/\sigma_{dmin}$	$E_{r,p}$	E_r	$1 - (E_{r,p} / E_r)$	$\sigma_{dmax}/\sigma_{dmin}$	$E_{r,p}$	E_r	$1 - (E_{r,p} / E_r)$
20'000 - 20'100	2.0	128.7	125.8	-2.2%	2.5	89.3	75.3	-18.6%
20'100 - 20'200	3.1	218.1	211.4	-3.2%	3.5	154.9	150.2	-3.1%
20'200 - 20'300	4.1	301.3	315.8	4.6%	4.6	241.1	255.7	5.7%
20'300 - 20'400	5.3	401.1	437.5	8.3%	5.7	334.1	411.0	18.7%
20'900 - 21'000	4.9	363.1	355.7	-2.1%	4.7	250.3	281.6	11.1%
21'000 - 21'100	6.5	508.5	507.0	-0.3%	6.7	434.1	489.0	11.2%
21'100 - 21'200	7.8	633.2	653.5	3.1%	8.1	589.5	601.6	2.0%
21'200 - 21'300	10.0	845.1	881.1	4.1%	9.9	821.2	816.2	-0.6%
21'300 - 21'400	11.3	973.9	1066.5	8.7%	11.3	1013.0	1016.5	0.3%
21'400 - 21'500	6.8	541.0	516.6	-4.7%	7.0	468.0	386.5	-21.1%
21'500 - 21'600	8.7	714.0	674.3	-5.9%	8.4	632.1	606.0	-4.3%
21'600 - 21'700	11.1	954.4	886.9	-7.6%	10.4	889.7	906.9	1.9%
21'700 - 21'800	14.1	1251.4	1186.4	-5.5%	12.7	1221.2	1223.3	0.2%
21'800 - 21'900	15.7	1426.1	1440.5	1.0%	14.8	1562.9	1403.8	-11.3%

After the predictive modeling of resilient modulus using power dependence equations (3) and (4), it can be seen in Table 7 that the predicted resilient modulus had a good agreement compared to the resilient modulus value received from test direct test results, error margin ranging from -7.6% to 8.7% for variously graded sand (SP), and error margin ranging from -18.6% to 18.7% for well-graded sand (SG).

Table 8. Prediction results using natural logarithmic dependence equations (5) and (6)

Number of cycles	SP					SG				
	$\sigma_{dmax}/\sigma_{dmin}$	E_{50}	$E_{r,p}$	E_r	$1 - (E_{r,p} / E_r)$	$\sigma_{dmax}/\sigma_{dmin}$	E_{50}	$E_{r,p}$	E_r	$1 - (E_{r,p} / E_r)$
20'000 - 20'100	2.0	14.0	133.9	125.8	-6.4%	2.5	11.8	99.3	75.3	-31.8%*
20'100 - 20'200	3.1	14.0	219.7	211.4	-4.0%	3.5	11.8	161.2	150.2	-7.3%
20'200 - 20'300	4.1	14.0	297.3	315.8	5.9%	4.6	11.8	234.9	255.7	8.1%
20'300 - 20'400	5.3	14.0	388.3	437.5	11.2%	5.7	11.8	308.2	411.0	25.0%*
20'900 - 21'000	4.9	34.9	381.9	355.7	-7.4%	4.7	24.4	303.3	281.6	-7.7%
21'000 - 21'100	6.5	34.9	522.0	507.0	-3.0%	6.7	24.4	467.8	489.0	4.3%
21'100 - 21'200	7.8	34.9	639.5	653.5	2.1%	8.1	24.4	593.3	601.6	1.4%
21'200 - 21'300	10.0	34.9	835.3	881.1	5.2%	9.9	24.4	765.4	816.2	6.2%
21'300 - 21'400	11.3	34.9	952.3	1066.5	10.7%	11.3	24.4	898.4	1016.5	11.6%
21'400 - 21'500	6.8	42.2	561.0	516.6	-8.6%	7.0	38.9	553.8	386.5	-43.3%*

21'500 - 21'600	8.7	42.2	725.2	674.3	-7.5%	8.4	38.9	695.7	606.0	-14.8%
21'600 - 21'700	11.1	42.2	948.1	886.9	-6.9%	10.4	38.9	899.9	906.9	0.8%
21'700 - 21'800	14.1	42.2	1217.2	1186.4	-2.6%	12.7	38.9	1140.3	1223.3	6.8%
21'800 - 21'900	15.7	42.2	1373.0	1440.5	4.7%	14.8	38.9	1369.9	1403.8	2.4%

After the predictive modeling of resilient modulus using natural logarithmic dependence equations (5) and (6), it can be seen in Table 8 that the predicted resilient modulus had a good agreement compared to the resilient modulus value received from test direct test results, error margin ranging from -8.6% to 11.2% for variously graded sand (SP), and error margin ranging from -14.8% to 11.6% for well-graded sand (SG). In Table 8 values marked with the symbol (*) can be held as outliers due to human and machine error while performing the tests.

6. CONCLUSIONS

After the determination and investigation of the static and cyclic triaxial tests results of variously graded sand (SP) and well-graded sand (SG), the following conclusions can be drawn:

- The power dependence equations (3) and (4), proposed by the authors of the paper, for predictive modeling of resilient modulus, showed a good agreement compared to the resilient modulus values received from direct test results. The error margin ranges from -7.6% to 8.7% for variously graded sand (SP), and from -18.6% to 18.7% for well-graded sand (SG).
- The natural logarithmic dependence equations (5) and (6), proposed by the authors of the paper, for predictive modeling of resilient modulus, showed a good agreement compared to the resilient modulus values received from test direct test results. The error margin ranges from -8.6% to 11.2% for variously graded sand (SP), and from -14.8% to 11.6% for well-graded sand (SG).
- The developed equations can serve as a two-step method predicting the values for resilient modulus for variously graded sand (SP) and well-graded sand (SG).

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