ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20220130202020
Preliminary communication

Evaluation of the Resilient Modulus of the Dunaújváros Loess Soil According to the MEPDG

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Abstract: The resilient modulus (M_R) of the earthworks is a basic input parameter of the new alternative design method of pavement structures. Its value depends on the stress state and the properties of the soil. In the literature several models are available that are based on directly measured results, thus they make possible to determine the value of the resilient modulus in case of different stress levels. Thanks to these models, the resilient modulus could be determined on stress levels that are not possible to make direct measurement on. It enables also to choose a correct M_R value even if the expected stress state changes during the design procedure. The most widely applied model is the universal model recommended by the Mechanistic-Empirical Pavement Design Guide that can be fitted to a certain soil by regression coefficients. Several researches were conducted to determine these regression parameters to many types of soils, most of them produced the coefficients as simple numbers. However, some literature recreates the regression parameters as functions of basic soil properties, making a more complex attempt to fit the model to a given soil type. In this paper the parameters of the MEPDG model were examined and fitted to a typical soil type: the loess soil origins from Dunaújváros in Hungary. Equations were established to determine the regression coefficients as function of more simple parameters the determination of which requires simpler and less costly tests than that of the direct cyclic triaxial resilient modulus measurements.

Keywords: loess soil; MEPDG; resilient modulus

1 INTRODUCTION

As in many other countries in the Hungarian practice, the design of pavement structures is based on the module pavement structures. This method takes into consideration the expected permanent bearing capacity as the single parameter describing the earthwork. Its disadvantage is that it cannot take into account a higher bearing capacity; therefore the advantages of a better earthwork are lost. Recently initiatives were started to change this design procedure to be able to find more appropriate pavements for different loads in Hungary. The new procedure to be elaborated is based on detailed numerical analyses [1, 2]. The development of measuring techniques for dynamic soil properties has evolved, therefore those properties should be included in design instead of previously used static soil properties. It makes possible to directly determine the input parameters of the new design method and decrease the uncertainty of the parameters used for the design. On the other hand, new design procedures must allow taking into consideration the increase of the bearing capacity of the earthworks and thus creating pavement structures with augmented lifetime and more economical construction [3].

2 BACKGROUND

According to its general definition the resilient modulus (M_R) is the quotient of the applied deviatoric stress and the elastic strain. It characterizes the soil in those conditions that do not result in the failing of the pavement structure. Therefore, it describes the stiffness of the soil, rather than its strength. Its value could be determined applying different combinations of loading and confining pressure, hence the question emerges which resilient modulus should be used for the design procedure. To determine the resilient modulus in given stress conditions, it is indispensable to know the relationship between the M_R value and the stress state. With this intention, firstly the k-θ model was elaborated that is widely used in practice to calculate the resilient modulus of non-cohesive soils [4].

$$M_R = k_1 \cdot \theta^{k2} \tag{1}$$

where M_R is the resilient modulus, θ is the bulk stress, k_1 and k_2 are parameters determined by the regression analyses. The k_1 and k_2 coefficients signify the interception of the bulk stress resilient modulus relationship and the y axis, and the slope of the regression line respectively in case the regression graph is plotted in a logarithmic coordinate system. After the determination of the regression relationship of the examined soil, the resilient modulus belonging to a certain stress state could be chosen easily.

Since the introduction of the k-θ model several similar models have been established. The new Mechanistic-Empirical Pavement Design Guide (MEPDG) recommends the following equation to determine the resilient modulus:

$$M_R = k_1 \cdot P_a \cdot \left(\frac{\theta}{P_a}\right)^{k_2} \cdot \left[\left(\frac{\tau_{oct}}{P_a}\right) + 1\right]^{k3} \tag{2}$$

where k_1, k_2 and k_3 are regression parameters depending on the material, θ is the bulk stress, P_a is the atmospheric pressure (100 kPa) and τ_{oct} is the octahedral shear stress. In case of triaxial tests the bulk stress and the octahedral shear stress could be calculated according to these equations:

$$\theta = \sigma_1 + 2 \cdot \sigma_3 \tag{3}$$

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{4}$$

This model is called k_1 - k_3 or universal model in practice, and its main advantage is that it could take into consideration the change of the stress state [4-6].

In the literature, several researches were conducted about the examination of the parameters that affect mostly the value of the resilient modulus [7-9]. According to the results of [7], one of the most essential parameters is the water content, because its growth leads to the diminution of the M_R value. The change of the water content affects the resilient modulus in two ways. On the one hand it influences the stress state because of the change of the suction or the pore pressure. Researchers examined the necessity of the application of both parameters in the same model, since they are in relationship with each other through the soil-water characteristic curve [7]. On the other hand, the water content can affect the structure of the soil and disrupt the cementation between the soil grains. In case of low moisture content and small volume density, the resilient modulus is small, while higher moisture content also results in small resilient modulus even in high volume density. But the volume change results in the change of the saturation which has strong relation with suction. Therefore, the void ratio has to be applied as input parameter as well. To determine the resilient modulus with the convenient accuracy, the water content, void ratio and unit weight are necessary to be measured [7].

The k_1, k_2, k_3 parameters essential for the MEPDG model are determined by regression analysis based on the resilient modulus values measured using different confining and deviatoric stresses. These coefficients can be determined as plain numbers; however, some tests explained in the following were carried out to establish them as functions of other soil parameters. Authors of [8] created such functions for six types of soils, classified by the AASHTO system. The soil properties included in the regression analysis were the water content, the optimum water content, the maximum dry density, the actual dry density, liquid limit, plastic limit, silt content, clay content, and different percentages of the grain size distribution, such as the percentages passing a given diameter's sieve. They refined the equations for optimum and in-situ water contents, including the appropriate quantity in the given function [8]. Authors of [9] carried out their research for Wisconsin fine-grained soils. They established equations for the different soils classified by the AASHTO system, but they applied far less variables than [8]. The functions include the maximum dry unit weight, the water content, the liquid limit, the liquidity index, the specific gravity, and the coefficients of uniformity and curvature [9]. Authors of [10] investigated the effect of soil type, deviatoric stress, confining stress, moisture content and the unit weight on the resilient modulus of South Carolina soils. Based on the results they established model parameters for the bulk stress model and the generalized constitutive resilient modulus model to use in MEPDG. They carried out the resilient modulus tests on undisturbed soil samples. Different equations were developed for granular and silt-clay soils. The variables included in the equations were the in-situ dry density, in-situ water content, maximum dry density, optimum moisture content, different percentages of the grain size distribution, diameters belonging to 60%, 50%, 30% and 10% of passing material, coefficient of uniformity and curvature, liquid and plastic limit, plasticity and liquidity index, specific gravity, sand, silt, and clay content [10].

Authors of [11] elaborated equations separately for cohesive and granular soils examining fourteen cohesive and fifteen granular data sets. The research points out that k values of both granular and cohesive soils are highly various. This was the first model to recognize that the k values are depending on the moisture and other material parameters of the soil. The equations established included variables as the moisture content, the optimum moisture content, the saturation, the compaction, the density, the silt and clay content, the percent passing the #40 and #60 sieves, the percent of swelling, the percent of shrinkage, the maximum dry unit weight and the California Bearing Ratio [11].

3 MATERIAL

The resilient modulus tests were conducted on very common soil, which covers app. 10% of the earth's land surface [14]. This soil is one of the most typical in Hungary. In the Carpathian Basin this type of soil was formed during the Pleistocene era. It covers nearly 1/3 of the country's surface which makes it the most typical and widespread formation of the Pleistocene. This eolic formation is represented by several loess versions, whether in its original position or in a moved state. It can be found on the lower levels of Hungarian hills and mountains as well as on the lowlands. The loess was formed in a cold and dry climate; its thickness varies in different regions of Hungary [12].

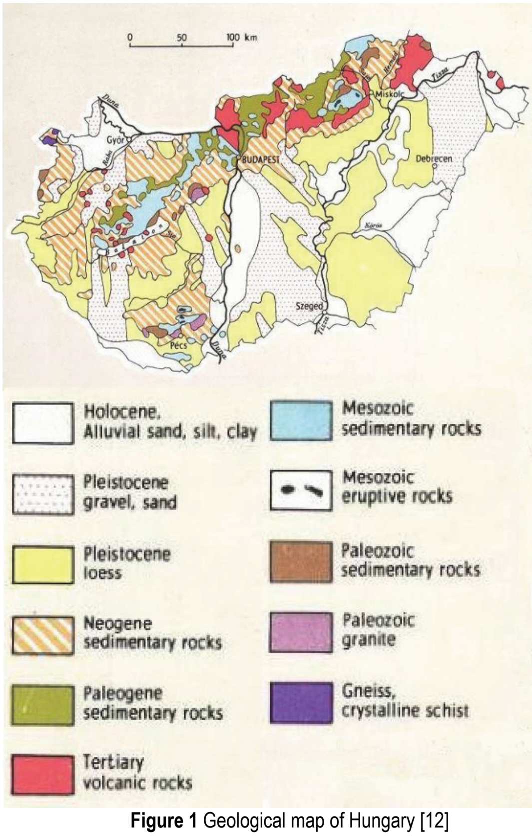

Figure 1 Geological map of Hungary [12]

The typical loess is yellow and has a lime content of 20% - 25%. It is also known as wind-blown loess with a microporous structure that has a porosity of 50% - 55%. Thanks to its characteristic structure it conserves its stability even in steep slopes or nearly vertical walls. The typical loess is not formed in homogeneous facies because of its segmented settlement. It is divided by darker clayey zones that are paired with the eras of the formation of the loess. According to this, "old" and "young" Pleistocene loess soils are distinguished in Hungary and the neighbour countries as well. The strength of the loess is favourable, but in saturated state it can collapse under loading. Nevertheless, damage cases are rare comparing to the spread of this soil [12].

The so-called "infusion loess" is the loess soil of the floodplains. It was formed of the dust fallen on wet, flooded lowlands.

The loess, independently of its type, is a transition between the cohesive and non-cohesive soils. It contains approx. 80% of fine grains and 20% of sand. This grain size distribution characterizes the majority of the sediments formed in the surroundings of the main rivers in Hungary and also the wind-blown loess. The infusion loess can be mixed with clay, forming the clayey loess. Usually, it contains less lime, and it is formed of less strata. The loess of the regions characterized by mainly sand dunes has more sand grains, or even whole sand layers settled between the loess strata. Hungarian terminology can differentiate between the sandy loess, silty loess and clayey loess depending on the small differences grain size distribution. However, it is remarkably similar in all kinds of loess soils, even if the geological formation is completely different [12].

The loess soil used for the testing series discussed herein was collected in Dunaújváros that is located in the center region of Hungary. In this area, named Mezőföld, the loess soil was formed in the highest thickness (40 m - 65 m) regarding the surface of Hungary. It represents the typical loess formed in high banks [12].

Since the loess soil is so widespread in the country as the geological map represents (Fig. 1), it is advantageous for use in the earthworks and construction. Thus, the cost efficiency of projects could be optimized, and the environmental effects could be significantly decreased. Because of the water sensitive bearing capacity of the loess soil, the method of application must be examined. For example, soil stabilization could improve the strength and the bearing capacity of the loess even in saturated state.

4 TESTING PROCEDURES

The aim of the research was to establish an applicable correlation between basic soil properties and the k_1-k_3 regression parameters of the universal model defined by the Mechanistic-Empirical Design Guide. For this purpose, the resilient modulus was determined by the so-called direct method, namely cyclic triaxial tests.

The cyclic triaxial tests were carried out according to the recommendation of the AASHTO. A loading cycle consisted of a loading and a resting phase that lasted 0.1 s and 0.9 s, respectively. The loading involved a conditioning of 1000 cycles to eliminate the effect of the period between the preparation of the sample and the tests. It also reduces the difference between the initial loading and the reloading and minimizes the possible inaccurate contact between the loading apparatus and the top of the specimen. After the conditioning, 5 different deviatoric stresses were applied during 100 - 100 cycles. The tests were performed with 3 different water contents: 7.5%, 11.5% and 15.0%. These selected water contents were chosen based on the results of the Proctor tests. The 11.5% represents the optimum moisture content, thus the state in which the compaction is at maximum. The lower and higher water contents were selected in order the degree of compaction does not decrease under 95%.

For the resilient modulus 10 tests were performed on each water content because 10 can be considered as the minimum amount of data required for a statistical analysis.

From the triaxial tests the stress parameters of the MEPDG model are easily obtained. Since the goal was to recreate the regression coefficients as functions of basic soil parameters, grain size distribution and Proctor tests were carried out to determine the soil properties applicable in those equations. The research results that can be found in the literature [5, 6] indicate well what are those parameters that are worth trying to assemble such equations, and what is the logic behind the assessment.

For the determination of the necessary soil parameters grain size distribution test and CBR tests, for the optimum moisture content and maximum dry density Proctor test were carried out.

The grain size distribution of the examined soil is shown in Fig. 2. According to the Eurocode 7, the loess soil can be qualified as clayey silt.

Based on the results of the Proctor test, the optimum moisture content of the soil is 11.6%, and the maximum dry density is 1.90 t/m^3. The Proctor curve is represented in Fig. 3.

Similar to the resilient modulus tests the California Bearing Ratio tests were conducted on 10 samples for each water content.

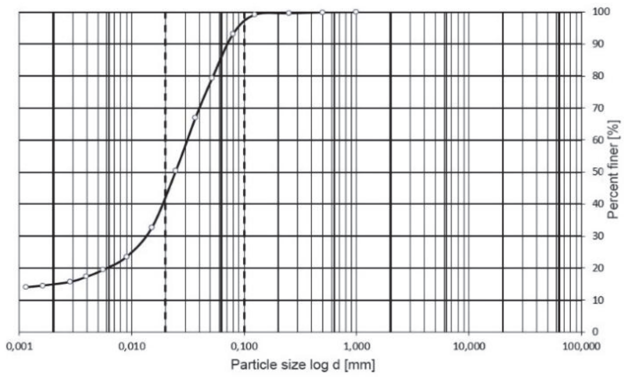

Figure 2 Grain size distribution of the examined soil

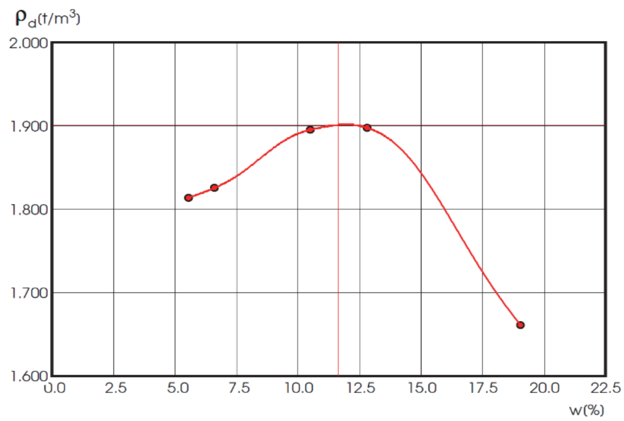

Figure 3 Proctor curve of the examined loess soil

5 TEST RESULTS AND ANALYSES

The resilient modulus can be determined directly by cyclic triaxial test. By its general definition, the resilient modulus is the quotient of the deviatoric stress and the recoverable strain. Fig. 4 represents the stress-strain curve of one of our resilient modulus tests. Since the calculation of the resilient modulus takes into consideration only the elastic strain, the resilient modulus can be obtained as the slope of the straight connecting the point of maximal strain, maximal stress and the point where the hysteresis loop reaches the axe of the axial strain (where the deviatoric stress becomes zero at the end of the loading cycle).

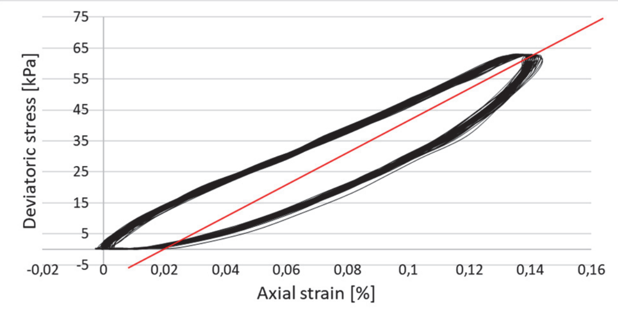

Figure 4 Hysteresis loops of an examined sample and the visual representation of the resilient modulus value

To elaborate the model, firstly the characteristic values of the resilient modulus were calculated in accordance with the method suggested by the [15].

The first step was to choose those measured values that are susceptible to be incorrect because of an error in the measurement process or in the sample preparation. These values were eliminated from further calculations. From the remaining results, the characteristic values were determined by statistical method applying the following formula:

$$X_k = X_m \cdot (1 - k_n \cdot v_x) \tag{5}$$

where X_m is the expected value that is defined as the average of the measured values, k_n is a statistical parameter, v_x is the relative standard deviation obtained from the measured results [15].

Using the results of the 10 samples on each water content the characteristic values of the resilient modulus were determined at each deviatoric stress level. The calculated characteristic resilient modulus values depending on the deviatoric stress level in different moisture content are given in Tab. 1.

Table 1 Characteristic M_R values in MPa depend on the deviatoric stress and the moisture content

Deviatoric stress / kPa	Moisture content		
	7.5%	11.5%	15.0%
13.8	28.5	38.5	12.0
27.6	38.9	39.3	14.4
41.4	40.9	39.0	13.3
55.2	43.1	39.1	11.0
68.9	45.7	39.8	11.4

The results show that the resilient modulus is highly sensitive to the moisture content. Even if the moisture content does not change radically (3.5% - 4.0%), the difference between the measured resilient modulus values could be significant as shown in Fig. 5.

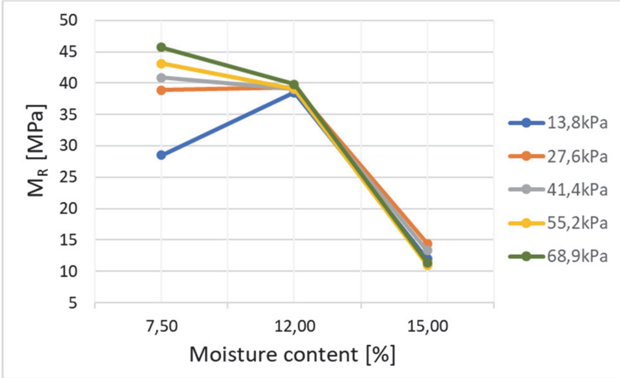

Figure 5 Resilient modulus values depending on the moisture content

Based on the results, higher water content gives a lower resilient modulus value. The resilient modulus was measured at the same deviatoric stress, but a higher water content could decrease to 1/3 - 1/4 of the value obtained at the lowest water content. In case of the measurements where the deviatoric stress was 13.8 kPa and 27.6 kPa, the resilient modulus was higher if the water content approximated the optimum moisture content. It must be taken into consideration that these deviatoric stresses are lower or equal to the deviatoric stress applied during the conditioning process.

It is also noticeable that the deviation between the resilient moduli measured at the same water content is higher in case of the driest samples. At 7.5% moisture content the resilient modulus increases significantly with the increase of the deviatoric stress. In contrast, the results at 15% moisture content show a slight decrease of the resilient modulus with increasing deviatoric stress. The variation is less noticeable in case of the optimum moisture content, where only a slight increasing tendency could be observed, but the difference between the measured values is almost negligible (Fig. 5).

Authors of [16-18] conclude that the increase of the deviatoric stress results in the decrease of the resilient modulus. It must be noted that most of these researchers examined cohesive soils, and there are few results about non-cohesive soils that show the increase of the resilient modulus with increasing deviatoric stress [13].

The same procedure was followed for the CBR values belonging to the given water contents as presented in case of the triaxial resilient modulus tests. The characteristic CBR values were calculated also from the measured 10 samples on each water content. The CBR values are shown in Tab. 2.

Table 2 Measured CBR values

	Moisture content		
	7.5 %	11.5 %	15,0 %
CBR / %	46	34	4

The results show that the CBR value decreases with the increase of the moisture content. The difference between the drier samples and those compacted at optimum moisture content is ~25%. In contrast the decrease experienced between the CBR of the specimens compacted at optimum moisture content and the wettest samples is more significant. This phenomenon demonstrates well the sensitivity of the loess soil to the change of the water content that was discussed in section 3.

The creation of the k_1, k_2 and k_3 equations was proceeded from the functions given by [11], since this research operated with the widest data range, and the results of other researches were limited to a local soil type. The regression analyses were executed in a single step using the Solver plug-in module of the Excel program. During the calculation, the factors belonging to the variables were modified in order to determine the resilient modulus as close as possible to the measured value.

The equations obtained from the regression analysis are the following:

$$\begin{aligned}\log k_1 &= 0.006 - 0.08\cdot w + 0.22\cdot w/w_{opt} + \\ &+7.33\cdot COMP + 0.006\cdot SI + 0.006\cdot CL - \\ &-0.2564SW - 0.03\cdot \rho_{d,\max} + 0.004^2\cdot SW^2/CL + \\ &+0.002\cdot \rho^2{}_{d,\max}/S40\end{aligned} \tag{6}$$

$$\begin{aligned}k_2 &= 23.8\cdot 0.045\cdot w_{opt} + 5.52\cdot COMP - \\ &-0.00005\cdot S_r + 0.0055\cdot CL + 0.0088\cdot SW - \\ &-0.007SH + 0.00007\cdot CBR + 0.003\cdot SW^2/CL - \\ &-0.303\cdot(SW + SH)/CL\end{aligned} \tag{7}$$

$$\begin{aligned}k_3 &= 0.823 - 0.2\cdot w + 0.156\cdot w/w_{opt} - \\ &-0.007\cdot SI + 0.0051\cdot CL + 0.026\cdot SH - \\ &-0.142\cdot \rho_{d,\max} - 0.0009\cdot SW^2/CL + \\ &+0.00001\cdot S^2{}_r/SH - 0.003\cdot(CBR\cdot SH)\end{aligned} \tag{8}$$

where w is the water content of the soil (%), w_{opt} is the optimum moisture content (%), $COMP$ (%) is the degree of compaction, SI is the silt content (%), CL is the clay content (%), SW is the swelling (%), SH is the shrinkage of the soil (%), $\rho_{d,\max}$ the maximum dry density (pcf), $S40$ is the percentage passing the #40 sieve (0.42 mm), Sr is the saturation (%) and CBR is the California Bearing Ratio.

The comparison of the resilient modulus values calculated by applying these functions and those measured directly by cyclic triaxial tests is shown in Fig. 6. As shown the calculated M_R values show minimal difference comparing to the measured ones, therefore, the established equations could be applied accurately enough to estimate the resilient moduli even in case of different stress states.

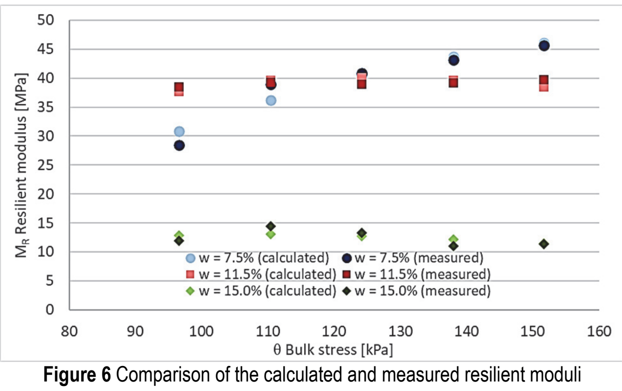

Figure 6 Comparison of the calculated and measured resilient moduli

6 CONCLUSION

In this research the possibility of the determination of the resilient modulus was examined in case of different stress states. The calculations were performed according to the MEDG that determines the resilient modulus depending on the expected stress state and applying different regression parameters. As literature data show, these coefficients can be elaborated as plain numbers, or as functions of simpler soil parameters. The advantage of the functions is that they can include the change of the basic soil parameters, thus they can provide a better accuracy. Plain numbers might not be applicable even in case of a slightly different soil, or the accuracy of the results could not be guaranteed.

Based on the results of research found in the literature, Eq. (6) to Eq. (6) were developed to elaborate the k_1 - k_3 regression parameters of the universal model, which thus was fitted to the loess type of soil of Dunaújváros. The calculated resilient modulus values are in good correspondence with the directly measured ones, hence the equations could be used to determine the resilient modulus for the desired stress state.

Since the base of the equation established were functions found in the literature [11], it could be examined in future researches that every parameters are essential to an accurate estimation, or some coefficients could be eliminated. However, it should be checked to what extent the elimination changes the accuracy of the calculated values.

Equations were established to one type of soil, but it would be favourable to fit the MEPDG universal model to other common soil types by elaborating these functions, such as Holocene sandy soils, that is also a very frequent soil type in Hungary and all around the world too.

Laboratory results indicate that the resilient modulus is strongly sensitive to the change of the water content. Since the procedure of stabilization improves the strength parameters of soils, it should be examined how it could improve the resilient modulus of this type of soil. The main question in this case is that the significant sensitivity to the change of the moisture content remains even after the stabilization is performed.

Soil stabilization is a commonly used technology in Hungary. Therefore, it would also be advantageous to execute the same procedure to establish the k_1 – k_3 functions for stabilized soils, all the more so as they are more commonly used in road construction than natural state soils.

Water content changes can occur because of floods, but even because of meteorological or climatic reasons. Since the sensibility of the resilient modulus is pointed out in the research, it should also be examined how the decrease of the resilient modulus affects the pavement structure. The influence should be determined on levels of permanent and elastic strains, because even if the failure of the pavement structure does not occur, the usability greatly depends on the strains that develop as a result of the change in the stress state.

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