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Models to predict the deformation modulus and the coefficient of subgrade reaction for earth filling structures

İsmail Dinçer *

Adıyaman University, Vocational High School, Department of Drilling Technology, 02040 Adıyaman, Turkey

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ABSTRACT

Determination of deformation modulus and coefficient of subgrade reaction of soils have major importance, whether the projects are in design, and construction or compaction assessment stage of earth filling structures. Plate load test is one of the frequently used method to directly determine the parameters but the method is both costly and time consuming. For this reason, this paper is concerned with the applications of artificial neural networks (ANN) and simple–multiple regression analysis to predict deformation modulus and coefficient of subgrade reaction of compacted soils from compaction parameters (such as maximum dry density (MDD) and optimum moisture content (OMC), field dry density (FDD), and field moisture content (FMC)). Regression analysis and artificial neural network estimation indicated that there are acceptable correlations between deformation modulus and coefficient of subgrade reaction and these parameters. Artificial neural networks model exhibits higher performance than traditional statistical model for predicting deformation modulus and coefficient of subgrade reaction.

1. Introduction

Soil compaction is one of the most efficient and practical soil improvement techniques. Soil compaction is carried out at three main stages which are design, construction and compaction assessment. Assessment of compaction performance is the most important steps of these works. It is commonly carried out by different test methods such as sand-cone and nuclear gauge tests. These tests are intended to determine optimum water content and dry unit weight. Furthermore, the deformation modulus and coefficient of subgrade reaction are widely used to measure degree of compaction. Therefore, determination of these parameters has to be done in an easy and reliable manner. Commonly, these parameters can be obtained from plate load test which is both costly and time consuming. Thus, engineers have had to use various guidelines charts [1–4] and numerical methods [5,6] for design of earth structure. These guidelines, charts and methods are highly complex. Engineer also needs shear strength parameters, subgrade resilient modulus and soil elastic modulus for using the guidelines, charts and methods. Obtaining of these parameters is difficult as much as performing plate load test. Estimating of the deformation modulus and coefficient of subgrade reaction of soils using soil properties is more practical than suggested guideline charts and methods.

In the literature, a number of studies have been undertaken to evaluate the coefficient of subgrade reaction [5,7–9]. However, deformation modulus studies are limited. Recently, Pantelidis [10] studied based on numerical analysis using finite element software for the correlation of the Modulus of Elasticity (tangent modulus) with the deformation modulus (secant modulus). According to this, correlation related to the shear strength parameters of soils the radius of the rigid loading plate and the magnitude of applied pressure.

In recent years, estimation models obtained from statistical and artificial neural networks methods, widely used in geotechnical engineering instead of performing difficult laboratory and field tests [11–23]. In this study, similar models were developed and evaluated for estimating of deformation modulus and coefficient of subgrade reaction of compacted soils. Also, availability of these models were discussed for engineering applications.

2. Materials and methods

This study was undertaken to develop and evaluate statistical and neural networks models for predicting deformation and coefficient of subgrade reaction (EV1: fisrt loading, EV2: second loading and ks) of compacted soils using the maximum dry density (MDD) and optimum moisture content (OMC), field dry density (FDD), and field moisture content (FMC). For this purpose, 143 plate load, proctor and sand-cone test results of six different soil types

* Tel.: +90 416 2232125; fax: +90 416 2232129.
E-mail address: idincer@adiyaman.edu.tr

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Table 1
Geotechnical properties of used soils types.

Soil type	Sieve analysis (passing percent%)				Atterberg limits		Soil class (USCS)
	No. 4	No. 10	No. 40	No. 200	Liquid limit (%)	Plastic limit (%)	
1	81.30–99.40	75.30–99.00	66.40–98.40	59.10–96.30	58.00–67.00	21.00–22.00	CH
2	85.35–99.80	84.10–99.30	81.50–98.10	65.00–93.70	35.00–40.00	17.00–21.00	CL
3	–	–	–	11.60–18.20	23.30–36.80	15.50–20.50	GM-SM
4	40.50–63.30	26.60–58.20	16.20–51.90	11.70–47.10	41.00–72.00	17.00–33.00	GC
5	36.90–52.00	26.10–45.30	13.90–31.70	10.20–20.30	–	–	GP-GM
6	32.80–49.00	16.40–32.00	7.10–14.80	2.50–5.60	–	–	GW

Table 2
Statistical results of geotechnical properties used analysis.

Parameters	Minimum	Maximum	Mean	Standard deviation
MDD (gr/cm^3)	1.41	2.33	2.21	0.24
OMC (%)	2.94	26.70	7.49	5.23
FDD (gr/cm^3)	1.40	2.37	2.15	0.27
FMC (%)	0.65	25.30	6.89	5.89
ks (Mpa/m)	114.50	496.56	298.16	89.78
Ev1 (MN/m^2)	42.00	133.85	93.20	22.64
Ev2 (MN/m^2)	91.00	276.08	210.21	39.09

which are commonly used in earth filling constructions, were gathered from the constructed different earthwork project in Turkey (Table 1). Tests results and their basic statistical evaluations such as average, maximum, minimum values and standard deviations of different parameters are given in Table 2.

2.1. Geotechnical tests

Proctor tests were performed based on ASTM D698 [24] standards. The test covers the determination of the relationship between the moisture content and density of soils compacted in a mold of a given size with a 2.5 kg rammer dropped from a height of 30 cm. Using the test data, OMC is determined from achieved MDD. A small hole (6″ × 6″ deep) is dug in the compacted material for sand-cone test [25]. The soil is removed and weighed, then dried and weighed again to determine its FMC. A soil's moisture is figured as a percentage. The hole filled by opening valve of cone device and the specific volume of the hole is determined by filling with calibrated dry sand from a jar and cone device. Dry weight of the soil removed is divided by the volume of sand needed to fill the hole. This gives us the FDD of the compacted soil. This density is compared to the maximum proctor density obtained earlier.

The plate loading test is an in situ test. The test is commonly used for determination of bearing capacity and compaction check in earth filling and foundation engineering. Namely, the aim of this test is determination of the relationship between the applied pressure and the displacements (pressure–displacement curve) occurring under the load plate. (Fig. 1A). The plate load test consists of applied load with hydraulic jack to the steel rigid plates. In general, plate load test is performed based on ASTM D 1194 [26], AASHTO [27], and DIN 18134 [28] standards for earth works. These test methods cover a procedure of repetitive static plate load tests on subgrade soils and compacted pavement components, in either compacted or natural condition, and provides data for use in the evaluation and design of rigid and flexible pavements. In this study, plate of 300 mm in diameter was used and the test carried out in accordance with DIN 18134 [28]. The test procedure consists of two loading phase and one load removal phase. The modulus of deformation is calculated from both the first (EV1) and the second loading phase (EV2). The Modulus of Deformation has also been calculated according to the mathematical formula (Eq. (1)) used in DIN 18134 [28].

$$\mathrm{EV} = 0.75 \times D\frac{\Delta\sigma}{\Delta S} \tag{1}$$

where EV: deformation modulus, D: diameter of plate, $\Delta\sigma$: applied stress and ΔS: measured deflection based on selected stress values.

Firstly, coefficient of subgrade reaction was put forward by Winkler [29] assumed the soil medium as a system of identical but mutually independent, closely spaced, discrete and linearly elastic springs and ratio between contact pressure, $\Delta\sigma$, at any given point and settlement, s, produced by load application at that point, is given by the coefficient of subgrade reaction (ks):

$$\mathrm{ks} = \frac{\Delta\sigma}{s} \tag{2}$$

This model is based on some approximations. One of the basic limitations of it lies in the fact that this model cannot represent the shear stresses in the ground and its foundation interface due to the lack of spring coupling. Also, linear stress–strain behavior is assumed. Generally, the value of subgrade modulus can be obtained from the plate load test, consolidation test, triaxial test, and CBR test. In this study, subgrade modulus was obtained from plate load test. A graph is plotted with mean settlement versus bearing pressure (load per unit area) as shown in Fig. 1B. The pressure $\Delta\sigma$ (kPa) corresponding to a settlement = 0.00125 m was obtained from the graph. The coefficient of subgrade reaction (ks) is calculated from Eq. (2).

3. Statistical analysis

3.1. Simple regression analysis

Regression analysis is commonly used to put forward estimating models among the connected parameters in geotechnical engineering. Regression analyses were conducted to investigate the relationships between EV1 and EV2, ks and MDD, OMC, FDD, and FMC. Thus, the regression analyses were performed for the pairs of EV1–MDD, EV1-OMC, EV1-FDD, EV1-FMC, EV2-MDD, EV2-OMC, EV2-FDD, EV2-FMC, ks-MDD, ks-OMC, ks-FDD, and ks-FMC. In this study, statistically significant correlations were observed for EV1 and EV2 of earth structure. Figs. 2 and 3 show the plots of the EV1 and EV2 versus MDD, OMC, FDD, and FMC. When considering number of data, the test results have shown good correlations with the respective coefficient of determination (R^2) of 0.46, 0.41, 0.51, 0.60, 0.68, 0.65, 0.57 and 0.62. Plots of ks versus MDD, OMC, FDD, and FMC are shown in Fig. 4. According to this, deficient correlations were observed with correlation coefficient of (R^2) of 0.24, 0.21, 0.26 and 0.37.

Reasonable correlations were also obtained from the regression analyses performed for the estimation of EV1 and EV2 using FDD and FMC as independent variables. But correlations are not strong for the estimation of ks. Therefore, different methods (multiple