PREDICTION OF THE COMPACTION PARAMETERS FOR COARSE-GRAINED SOILS WITH FINES CONTENT BY MLR AND GEP

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abstract

The determination of the compaction parameters of soils, the maximum dry unit weight (γ_{dmax}) and the optimum water content (w_{opt}), at various compaction energy (E) levels is an important process. The aim of this study is to develop correlations in order to estimate the compaction parameters dependent on the compaction energy for coarse-grained soils with various fines contents on which limited studies exist in the literature. Genetic Expression Programming (GEP) and Multi Linear Regression (MLR) analyses are used in the derivation of the correlations for the prediction of γ_{dmax} and w_{opt} obtained from Standard Proctor (SP) and Modified Proctor (MP) tests with the index properties of coarse-grained soils with various fines contents. To develop the models, a total of 86 data sets collected from university laboratories in Turkey and six parameters, such as gravel content (G %), sand content (S %), fines content (FC %), liquid limit (w_L %) and plasticity index (I_P %) of fines content and compaction energy (E Joule), are used. The performance of the models is comprehensively examined using several statistical verification tools. The results revealed that the GEP and MLR models are fairly promising approaches for the prediction of the maximum dry unit weight and the optimum water content of cohesionless soils with various fines contents at SP and MP compaction energy levels. The proposed correlations are reasonable ways to estimate the compaction parameters for the preliminary design of a project where there are financial and time limitations.

keywords

coarse-grained soils, compaction, MLR, GEP

1 INTRODUCTION

The structures on fills and embankments should be constructed with caution. Unless the fill, the embankment and the foundation soil satisfy the design criteria, the structures on them both can fail due to an insufficient soil strength. Thus, it causes environmental disaster, affects lives and causes economic losses. Therefore, fills and embankments should be constructed under control using specified methods and codes. Soil improvement can be carried out by compacting the soil to enhance the soil characteristics, such as an increase in the soil modulus, a reduction in the hydraulic conductivity and an increase in the shear strength. Field compaction is required when constructing fills or embankments under required specifications. In this context, mechanical compaction is the most commonly used method in surface ground improvement. Mechanical compaction is generally considered to be more economical than the other soil-stabilization techniques.

Compaction is involved in various commonly performed earthwork projects, such as highways, railway subgrades, airfield pavements, earth dams and landfill liners, which require a degree of compaction of the soil to a desired dry unit weight and water content. In the field, soils are usually compacted using tampers, sheepsfoot rollers, rubber-tired rollers, and various other equipment. In the laboratory, soil compaction is usually performed with the Proctor compaction apparatus. The Proctor compaction tests provide a standard method for a standard amount of compaction energy.

The most important parameters obtained from the compaction curve are two important compaction characteristics, i.e., the maximum dry unit weight (γ_{dmax}) and the optimum water content (w_{opt}), representing the compaction behavior. The behavior of the compacted soils depends on the dry unit weight, the water content, the compaction energy level, the soil type and their gradation.

Indirect correlative approaches are necessary or inevitable for estimating the engineering properties of soils, particularly for a project where there is a financial limitation, a lack of test equipment or a limited time frame. Thus, it is useful to estimate the engineering properties of soils, by using other soil parameters that can be obtained easily [1, 2]. Correlations are frequently used in the preliminary design stage of projects [3]. However, many of the correlations in the literature are not well defined or clear enough to be applied to field data. Thus, their usage results in confusions or erroneous conclusions. Some uncertainties, such as whether the correlation has a statistical meaning, which test results, are used in the correlation and what type of soil the correlation is valid for, have considerable effects on the correlation equations. Therefore, the correlation equations with compaction parameters should be used cautiously by taking these uncertainties into consideration.

Approaches such as GEP, Artificial Neural Networks (ANNs) and Adaptive Network Based Fuzzy Inference Systems (ANFISs) which allow developing a spatial model for complex systems have recently emerged as promising approaches in engineering tasks. These modelling techniques are also becoming more popular and have been used commonly as a tool in geotechnical engineering applications.

The compaction characteristics of soils are primary tools for the effective control of field compaction. The determination of compaction parameters (w_{opt} and γ_{dmax}) is a time-consuming process and a considerable effort is required to obtain them. Therefore, it is useful and sometimes inevitable to employ indirect methods, such as correlative equations. The aim of the current study is to develop MLR and GEP models from the statistical point of view to estimate the maximum dry unit weight and the optimum water content using Standard Proctor (SP) and Modified Proctor (MP) compaction test data and index the properties of coarse-grained soils with fines contents (percentage passing 75μm), and to present simple models to estimate w_{opt} and γ_{dmax} for an arbitrary compaction energy.

1.1 MULTIPLE LINEAR REGRESSION (MLR)

The MLR is a method for obtaining an equation to predict one variable using several other variables. The significance tests for each statistical parameter and the resulting lines are made with a 5 % confidence level. The significance of the regression coefficients (a, b, c, d, e, f and g) is examined by means of a t-test and it is found that the regression coefficients have significant dependence on the developed models.

In this study, a relationship is sought using all six independent variables (G, S, FC, I_p, w_L and w_P) to establish the best accurate and precise equations for predicting the optimum water content and the maximum dry unit weight for the SP and MP compaction data. In order to develop the relationships of the dependent variables (w_{opt} and γ_{dmax}) with each independent variable (energy E, gravel content G, sand content S, fines content FC=clay + silt content, liquid limit w_L and plasticity index I_p), Multi Linear Regression (MLR) analyses are performed using the method of least squares, as follows:

$$f(w_{opt}, \gamma_{dmax}) = a + b \cdot G + c \cdot S + d \cdot FC + e \cdot I_p + f \cdot w_L \quad (1)$$

where G, S, FC, w_L and I_p are in percent, and the unit of γ_{dmax} and w_{opt} is kN/m^3 and %, respectively. The correlation coefficient (R) and standard errors (SEs) have been determined for each regression equation obtained with a statistical approach. In addition, the models were developed based on the energy level.

1.2 GENETIC EXPRESSION PROGRAMING (GEP)

GEP was presented by Ferreira [4] for first time. Its evaluation system is similar to the biological evaluation. It is a computer program that is encoded in linear chromosomes of fixed-length. The GEP algorithm (Fig. 1) uses five major preliminary steps for solving a problem. These are named as "the function set", where arithmetic operations, testing functions (such as IF and CASE statements) and Boolean functions are defined, "the terminal set" where independent variables of the problem are stated, "the fitness function" where the evaluation of the solving is made, "control parameters" where the qualitative numerical values that control the run are declared and “the stop condition” where the announcement of a result and the termination criteria of the run is set. The GEP algorithm starts by the random generation of an initial chromosome (the initial population) that is represented by a mathematical function. Then these chromosomes are converted into an expression tree (ET). In the next step a comparison is made between the predicted values and the actual values. The GEP process stops when the desired results fulfil the initially stated error criteria.

If the initially stated error criteria are not fulfilled, some chromosomes are chosen by a method that is referred to as roulette-wheel sampling and they are mutated to obtain new chromosomes. The process is repeated for a certain number of generations or until a solution has been found [4]. After the desired fitness score is obtained, this process terminates and then the knowledge is coded in genes and chromosomes are decoded for the best solution to the problem [5].

GEP is composed of two main elements that are referred to as the chromosomes and the expression trees (ETs). In GEP, the chromosome consists of one or more genes in which there is some coded information about the

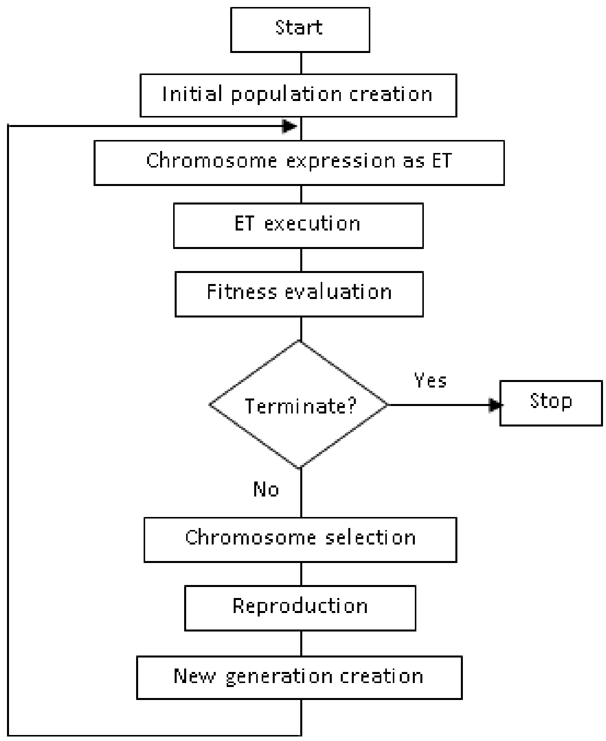

Figure 1. GEP algorithm [5].

problem. The mathematical information is translated to the ET using a bilingual and conclusive language called Karva Language (the language of the genes) and by means of the language of ET. The genotype is accurately derived by using Karva Language. GEP genes are made up of two parts that are named as the head and the tail. The head of a gene has some functions, variables and constants. This part is used for encoding a function for the expression. The variables and constants in the tail are used as supplementary terminal symbols and they are needed for additional terminal symbols only if the variables in the head are not sufficient to encode a function. The head of a gene includes arithmetic, trigonometric or any other mathematical or user defined functions, like (+, -, ·, /, √ , *sin*, *cos*). The terminal symbols in the tail are composed of the constants and the independent variables of the problem like (1, a, b, c).

At the beginning of the model construction the user specifies the length of the head (i.e., the number of symbols) which is the significant parameter in the GEP process. The encoding process takes place by reading the ET from left to right in the top line of the tree and from the top to the bottom and the ET is converted to Karva Language. The GEP genes include a non-coding part similar to the coding and non-coding sequences of biological genes.

The GEP operators are implemented by operator rate, which indicates a certain probability of a chromosome. Users decide the operator rate before the analysis. The mutation rate is recommended to be between 0.001 and 0.1. On the other hand, it is suggested that the transposition rate and cross-over rate are 0.1 and 0.4, respectively [5].

1.3 PREVIOUS STUDIES ON COMPACTION PARAMETERS

Many attempts have been made to obtain the optimum water content and maximum dry unit weight of compacted fine-grained soils. The correlation equations for fine-grained soils relate the optimum water content and the maximum dry unit weight to factors using soil classification descriptors, index properties (liquid limit w_L, and plastic limit w_P), the specific gravity of solids (G_s), and the grain-size distribution. Sivrikaya [2] developed the correlations with the SP compaction test data for fine-grained soils used as mineral liner for solid waste, and concluded that the optimum water content has a good correlation with the plastic limit in comparison with the liquid limit and the plasticity index. For the estimation of w_{opt} in fine-grained soils, Gurtug and Sridharan [6], Sivrikaya et al. [1] and Sivrikaya and Soycan [7] also attempted to develop an empirical correlation that consists of w_p and the compaction energy (E).

In the literature, there are fewer studies on the compaction of coarse-grained soils than the compaction parameters for fine-grained soils. Wang and Huang [8] developed correlations for estimating the optimum water content and the maximum dry unit weight for synthetic soils consisting of mixtures of bentonite clay, silt (limestone dust), sand and fine gravel. In their non-linear models, while w_{opt} is estimated from the plastic limit (w_p), finess modulus (F_m) and uniformity coefficient (U) of soils, γ_{dmax} is estimated using the solid unit weight (γ_s), effective grain size (D_{10}), F_m and w_p. In addition, Sivrikaya and Olmez [9] improved the correlations, where the gravel content (G), sand content (S), fine-grained content (FC), plasticity index (I_p), w_L and w_P are used as independent variables for coarse-grained soils employing SP compaction parameters. In their models, w_{opt} and γ_{dmax} are estimated from the combination of independent parameters by performing multi-linear analyses. To the best of the authors' knowledge, there is no available study to estimate the maximum dry unit weight and the optimum water content of coarse-grained soils with various fines contents at any compactive effort from the index properties.

There are a great many studies on the determination of compaction parameters of fine-grained soils using MLR and ANN approaches in comparison with coarse-grained soil. However, studies using the MLR and GEP models on the determination of compaction parameters based on the compaction energy of coarse-grained soils with fines contents of more than 5 % do not appear to exist in the literature as far as the authors are concerned. The main purpose of this paper is to present new correlations based on GEP and MLR for the prediction of the compaction parameters based on the compaction energy of coarse-grained soils with fines content.

2 MATERIALS AND METHODS

The laboratory test results used for this study were obtained from samples that were recovered from the field in different regions of Turkey. The laboratory tests include index and Standard Proctor (SP) and Modified Proctor (MP) compaction tests. The data consist of consistency parameters (liquid limit, plastic limit, and plasticity index), grain size distribution (gravel, sand and fines content %) and compaction parameters (optimum water content and maximum dry unit weight).

Sieve and hydrometer analyses were performed taking ASTM D-221 and D-422 into consideration [10, 11]. The Atterberg (consistency) limit tests were determined by considering ASTM D-4318 [12]. The compaction tests were conducted by using the SP and MP compaction method in accordance with ASTM D-698 and D-1557, respectively [13, 14]. The soils are classified as coarse-grained soils according to the Unified Soil Classification System (USCS) [15].

The input parameters used herein were selected in such a manner that the compaction is defined by these parameters in accord with the methods used practically in engineering situations. Therefore, E, G, S, FC, w_L and I_p were chosen as the inputs parameters. The number of data pairs for the SP and MP compaction was 63 and 23, respectively. The statistical parameters of the soils studied are also determined and presented in Table 1 and Table 2.

Table 1. Statistical parameters of the soils studied for the SP compaction tests.

	Grain size distribution							
	Gravel (%)	Sand (%)	FC* (%)	w_L	w_P	I_P	w_{opt} (%)	γ_{dmax} (kN/m^3)
Maximum	89.00	79.00	49.00	83.00	44.00	40.00	32.00	22.60
Minimum	0.00	4.00	5.00	19.00	10.00	5.00	6.50	12.70
Range	89.00	75.00	44.00	64.00	34.00	35.00	25.50	9.90
Average	46.79	33.73	19.56	31.71	17.78	14.46	13.18	18.96
Median	50.00	30.00	17.00	29.00	16.00	14.00	11.50	19.20
St. Deviation	23.95	17.20	11.61	10.74	7.18	5.47	5.60	2.08
Variance	573.75	295.82	134.88	115.35	51.60	29.93	31.34	4.34
Skewness Coeff.	-0.36	0.65	0.88	2.30	1.91	1.81	1.93	-1.14
Kurtosis Coeff.	-0.82	-0.20	-0.02	7.74	3.93	6.74	3.83	1.49

*FC represents fines content percentage that is passing 75 μm diameters.

Table 2. Statistical parameters of the soils studied for the MP compaction tests.

	Grain size distribution							
	Gravel (%)	Sand (%)	FC* (%)	w_L	w_P	I_P	w_{opt} (%)	γ_{dmax} (kN/m^3)
Maximum	84.00	64.00	43.00	49.00	35.00	29.00	17.00	23.30
Minimum	3.00	9.00	6.00	17.00	11.00	6.00	4.50	17.20
Range	81.00	55.00	37.00	30.00	24.00	23.00	12.50	6.10
Average	53.35	31.35	16.61	32.09	17.65	15.78	9.25	20.81
Median	61.00	26.00	12.00	29.00	16.00	15.00	7.50	21.70
St. Deviation	20.87	15.20	11.62	9.67	5.21	6.52	3.68	1.99
Variance	435.44	230.92	134.93	93.56	27.18	45.52	13.56	3.94
Skewness Coeff.	-0.75	0.71	1.09	0.15	1.57	0.15	0.63	-0.38
Kurtosis Coeff.	0.17	-0.34	0.05	-1.48	3.86	-0.91	-0.76	-1.45

*FC represents fines content percentage that is passing 75 μm diameters.

3 RESULTS AND DISCUSSION

This paper intends to investigate the potential use of GEP and MLR in predicting the compaction parameters of coarse-grained soils with fines contents that have great significance on soil compaction based on the compaction energy. For quantitative assessments of the model's predictive abilities, the results obtained from these correlations are comprehensively evaluated in terms of statistics.

In order to see the accuracy of the results obtained through the proposed MLR models, the coefficient of correlation (R) and the standard errors (SEs) are used as statistical verification tools. The standard error (SE) of the estimate is a measurement of the deviation around the regression line. It is well known that the correlation equation obtained from the MLR method is accurate and precise as long as its coefficient of correlation value reaches 1 or close to 1 and the standard deviation is 0 or close to 0.

In order to analyse the performance of the developed GEP models several statistical verification criteria are used such as the coefficient of correlation (R), the root-mean-square error ($RMSE$) and the standard deviation (σ) of the errors. The definitions of these evaluation criteria are given below

$$R=\frac{\sum_{i=1}^{n}\left(u_i^m-\overline{u}^m\right)\left(u_i^p-\overline{u}^p\right)}{\sqrt{\sum_{i=1}^{n}\left(u_i^m-\overline{u}^m\right)^2}\sqrt{\sum_{i=1}^{n}\left(u_i^p-\overline{u}^p\right)^2}} \qquad (2)$$

$$RMSE=\sqrt{\frac{\sum_{i}^{n}\left(u_i^m-u_i^p\right)^2}{n}} \qquad (3)$$

$$\sigma=\sqrt{\frac{\sum_{i=1}^{n}\left(e-\overline{e}\right)^2}{(n-1)}} \qquad (4)$$

where u_i^m and u_i^p are the measured and predicted values, respectively, $\overline{u}^m$ and $\overline{u}^p$ are the mean of the measured and predicted values, e is the absolute error ($\left|u_i^m-u_i^p\right|$), $\overline{e}$ is the mean of the absolute error, n is the number of the sample.

Of the 86 data sets in this study, 69 are used for training the models and 17, which are not used in the training stage, are presented for testing of the GEP models. In the MLR analyses all the data are used.

3.1 DEVELOPED MLR MODELS

In this study, the correlations have been improved between the optimum water content and maximum dry unit weight obtained from the SP and MP compaction tests and the index properties of coarse-grained soils with fines contents of more than 5 % by attempting different combinations of soil index parameters (G %, S %, FC %, w_L, w_p, I_p) as independent parameters. The

Table 3. Correlation equations obtained from the MLR analyses according to the SP compaction data.

Model number	Correlation equation	*R*	*SE*
SP-1	w_{opt} = -0.032G-0.009S+0.046FC+0.659w_L-0.473I_p	0.987	± 2.37 %
SP-2	w_{opt} = 0.420w_L	0.982	± 2.71 %
SP-3	γ_{dmax} = 0.253G+0.236S+0.218FC-0.234w_L+0.161I_p	0.999	± 0.89 kN/m^3
SP-4	γ_{dmax} = 23.673-0.357w_{opt}	0.960	± 0.59 kN/m^3

Table 4. Correlation equations obtained from the MLR analyses according to the MP compaction data.

Model number	Correlation equation	*R*	*SE*
MP-1	w_{opt} = -0.005G-0.007S+0.141FC+0.267w_L-0.073I_p	0.992	± 1.40 %
MP-2	w_{opt} = 0.292w_L	0.983	± 1.88 %
MP-3	γ_{dmax} = 0.265G+0.278S+0.127FC-0.213w_L+0.166I_p	0.998	± 1.65 kN/m^3
MP-4	γ_{dmax} = 25.702-0.528w_{opt}	0.980	± 0.41 kN/m^3

obtained best accurate and precise equations with the correlation coefficients and standard errors of estimate from the MLR analyses for SP and MP compaction data are presented in Tables 3 and 4, respectively.

MODELS ON SP COMPACTION PARAMETERS

The correlations have been improved between the optimum water content and the maximum dry unit weight obtained from SP compaction tests and index properties by using 63 data sets for the regression analyses (Table 3).

The analyses results have shown that the SP-1 model including the input data of all the index properties without a plastic limit are observed to give the best w_{opt} results with R = 0.987 and SE = ± 2.37 % (Table 3 and Fig. 2). In addition, it is found that the correlation (w_{opt} = 0.41w_L with R = 0.982 and SE= ± 2.71 %) of the optimum water content with liquid limit (SP-2 model) gives the best results among the consistency index parameters (Table 3 and Fig. 3). However, it is stated in the previous studies that the correlation of the optimum water content with plastic limit gives better results than the correlation of the optimum water content with the liquid limit for fine-grained soils [2, 6].

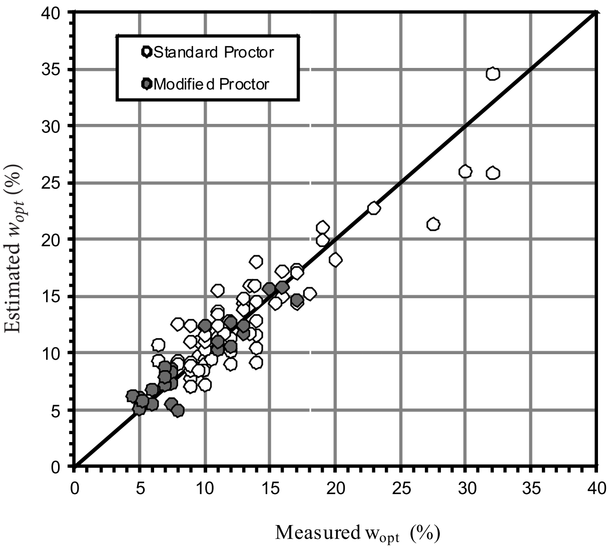

Figure 2. Comparison of optimum water contents obtained from the SP and MP compaction tests with values estimated from Model SP-1 and MP-1.

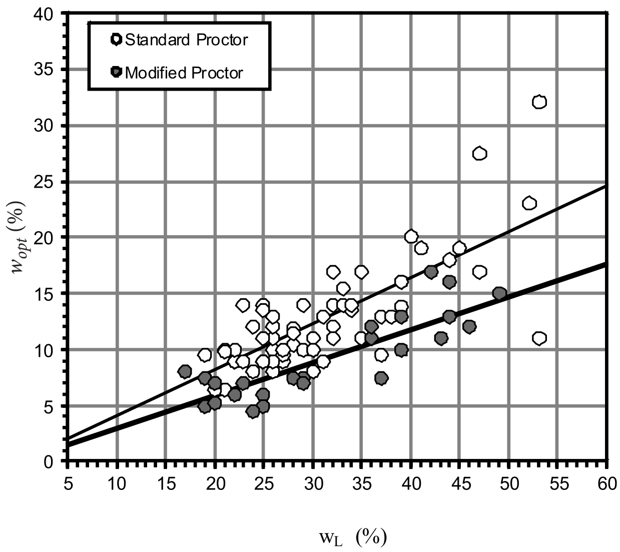

Figure 3. Relationships between the optimum water content obtained from the SP and MP compaction tests and the liquid limit.

For the correlations between the maximum dry unit weight obtained from the SP compaction tests and the index properties, it was found that the SP-3 model with R = 0.999 and SE = ± 0.89 kN/m^3 gave the best results for all the parameters (Table 3 and Fig. 4). The correlations were also attempted only for the consistency parameters. The results of the regression analyses have shown that it is not likely to estimate the maximum dry unit weight only from the consistency indices, as expected. Furthermore, the results reveal that γ_{dmax} can be estimated very precisely from w_{opt} using the SP-4 model with R = 0.960 and SE = ± 0.59 kN/m^3 instead of the index properties of the soils (Table 3 and Fig. 5)

MODELS ON MP COMPACTION PARAMETERS

Twenty-three data sets were used for the regression analyses on w_{opt} and γ_{dmax} obtained from the MP compaction tests with the index properties of coarse-grained soils. A large number of models were attempted, but the only MLR models with w_{opt} estimating best results are given in Table 4. The MP-1 model including input data of all the index properties without the plasticity index were observed to give the best results with R = 0.992 and SE = ± 1.40 % due to the minimum SE and the maximum R value (Table 4 and Fig. 2). The correlation of the optimum water content with the liquid limit gives better results than the plastic limit and the plasticity index. As far as the regression analyses are concerned, the dominant input parameter affecting the optimum water content appears to be the liquid limit for coarse-grained soils with fines contents of more than 5 % instead of the plastic limit in fine-grained soils [1, 2, 6]. Fig. 2 shows a plot of the optimum water content versus the liquid limit. The optimum water content increases with the increasing liquid limit. It was found that the correlation of w_{opt} with w_L (MP-2 model) has R of 0.983 and SE of ± 1.88 % (Table 4 and Fig. 3).

As can be seen in Table 4, the MP-3 model including the input data of G, S, FC, w_L and I_P were found to give the best result. Fig. 4 shows a plot of MP-3 with R = 0.998 and SE = ± 1.65 kN/m^3. It is observed from the regression analyses that while the correlation of γ_{dmax} with the consistency index parameters is not accurate, the correlation of γ_{dmax} with the grain distribution ratios gives better results. γ_{dmax} can be estimated easily and precisely from w_{opt} instead of the index properties of the soils using MP-4 model with R = 0.980 and SE = ± 0.41 kN/m^3 (Table 4 and Fig. 5).

CORRELATIONS ON W_{OPT} AND γ_{DMAX} WITH E

Correlations based on the compaction energy on the compaction parameters were also developed and given in Table 5. Even though the correlations appear to be satisfactory in terms of R, they are good at SE except for the SMP-3 model. Therefore, a new approach for estimating the compaction parameters of coarse-grained soils with fines contents of more than 5 % are introduced for the SP and MP compaction energy levels.

Considering the correlations between w_{opt} and the consistency parameters of soils for both SP and MP compaction data, it is found that the most appropriate

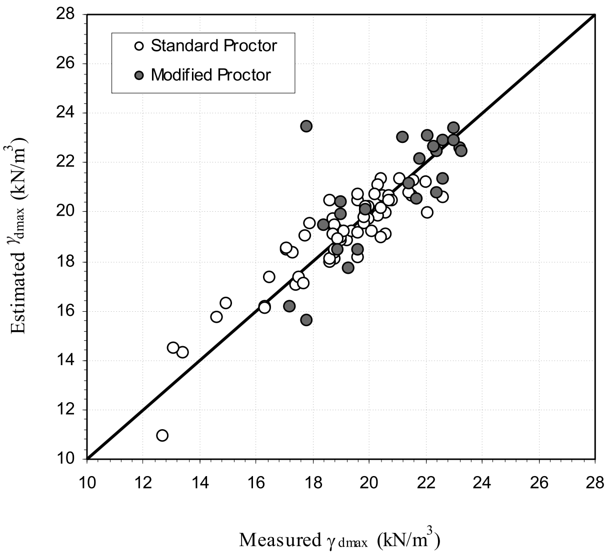

Figure 4. Comparison of maximum dry densities obtained from the SP and MP compaction tests with the values estimated from Model SP-3 and MP-3.

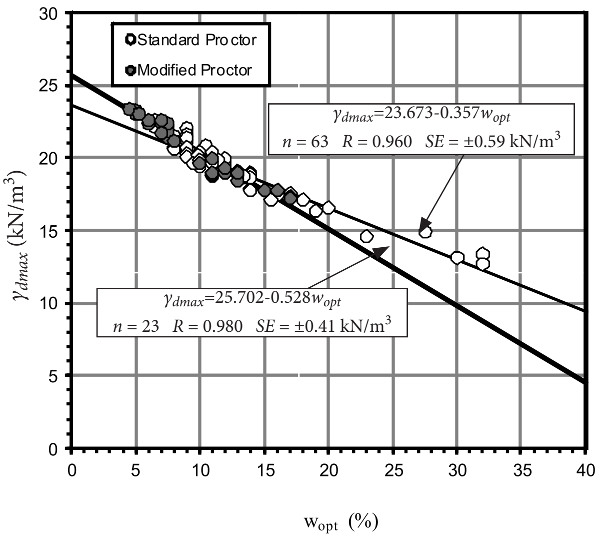

Figure 5. Linear relationships between the optimum water content and the maximum dry unit weight obtained from the SP and MP compaction tests.

Table 5. Correlation equations obtained from the MLR analyses based on the SP and MP compaction data.

Model number	Correlation equation	*R*	*SE*
SMP-1	$w_{opt} = 0.447w_L\text{-}0.002E$	0.982	± 2.55 %
SMP-2	$w_{opt} = \text{-}0.002E\text{-}0.011G\text{-}0.001S+0.072FC+0.61w_L\text{-}0.421I_p$	0.986	± 2.26 %
SMP-3	$\gamma_{dmax} = 0.006E+0.875w_{opt}$	0.924	± 7.58 kN/m^3
SMP-4	$\gamma_{dmax} = 0.001E+0.251G+0.241S+0.194FC\text{-}0.228w_L+0.146I_p$	0.998	± 1.15 kN/m^3

correlation is between the optimum water content and the liquid limit, as proved and mentioned before (Table 3, Table 4 and Fig. 3). Fig. 3 shows the variation of the optimum water content with the liquid limit for the Standard and Modified Proctor compaction energy level. From Fig. 3 it is clear that:

$$w_{opt} = \mathrm{K}w_L \qquad (5)$$

where w_{opt} is the optimum water content, w_L is the liquid limit and K is a coefficient depending on *E*. K decreases from 0.420 for Standard Proctor to 0.292 for Modified Proctor (Fig. 6a). On the other hand, the K values for the fine-grained soils were found to be 0.94 and 0.28 for the SP and MP compaction energy levels, respectively [1]. The variation in K shows that the optimum water content is significantly affected by the change in the compaction energy level. As seen in Fig. 6a, the variation of K with ln*E* is linear, as expected [1, 6, 16]. The developed empirical equations are as follows:

$$\mathrm{K} = 0.90\text{-}0.077\ln E \qquad (6)$$

$$w_{opt} = (0.90\text{-}0.077\ln E)w_L \qquad (7)$$

where the unit of w_{opt} and E is in percent (%) and in kilojoules per cubic meter (kJ/m^3), respectively.

There is a possibility that γ_{dmax} can be estimated using either w_{opt} or other index parameters. However, it has been observed in this study and stated in previous studies that the estimation of γ_{dmax} using w_{opt} is more reliable than using consistency parameters in the light of statistical parameters (n, R, SE) [2, 6, 16, 17, 18].

Fig. 5 shows the correlation of γ_{dmax} with w_{opt} for the Standard and Modifed Proctor compaction energy levels. As seen from Fig. 5, the correlations are found to be satisfying. Therefore, γ_{dmax} is described as a function of *E* and w_{opt} instead of other index properties due to the high R and low *SE* values in this study. The model is developed in order to estimate the maximum dry unit weight in terms of the optimum water content based on the SP and MP compaction energy levels. The model is in the form of

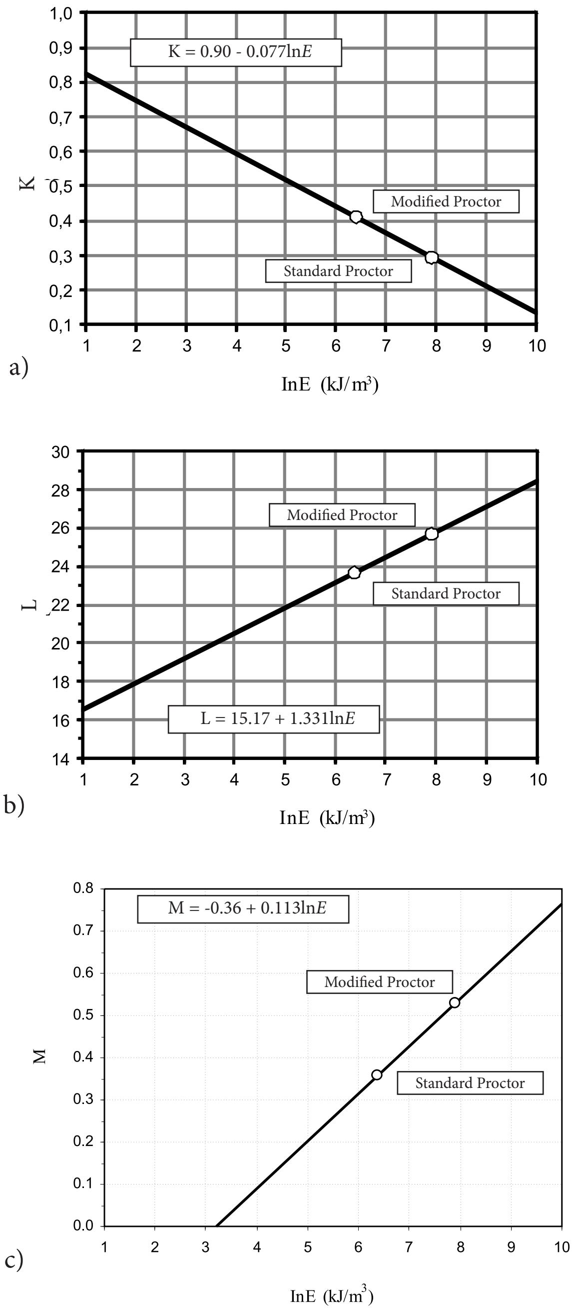

Figure 6. Variations of K, L and M coefficients with compaction energy.

$$\gamma_{dmax} = \text{L-M}w_{opt} \qquad (8)$$

Both coefficients L and M are described as a function of E in this model. Figs. 6b and 6c show the variation of the L and M coefficients with ln$E$, respectively. The L and M coefficients vary with ln$E$ linearly as found before [1, 16]. The L and M values are obtained as 23.673 and 0.357, respectively, for the SP compaction energy level and 25.702 and 0.528, respectively, for the MP compaction energy level, respectively (Figs. 6a,b). However, the L and M values for fine-grained soils were found to be 21.97 and 0.27, respectively, for the SP compaction energy level and 23.78 and 0.38, respectively, for the MP compaction energy level [1]. While the K coefficient increases with increasing ln$E$, the L and M coefficients increase with decreasing of ln$E$, which was also shown and proved for fine-grained soils by Blotz et al. [16], Gurtug and Sridharan [6] and Sivrikaya et al. [1]. The developed empirical equations are presented as

$$\text{L} = 15.17+1.331\ln E \qquad (9)$$

$$\text{M} = -0.36+0.113\ln E \qquad (10)$$

$$\gamma_{dmax} = (15.17+1.331\ln E)-(-0.36+0.113\ln E)w_{opt} \qquad (11)$$

where the unit of γ_{dmax} and E is in kilonewtons per cubic meter (kN/m^3) and in kilojoules per cubic meter (kJ/m^3), respectively.

Even though some scattering in the data distribution may exist (Figs. 3 and 5), the methods proposed to estimate the optimum water content and the maximum dry unit weight at any compaction energy can have some errors, which are insignificant and within the acceptable range (in w_{opt} for SP and MP compaction SE = ±2.71 and ±1.88 %, respectively; in γ_{dmax} for SP and MP compaction SE = ±0.59 and ±0.41 kN/m^3, respectively). Therefore, the developed methods could be very useful during the preliminary design stage in practice. They could be used to predict the optimum water content of soil samples for a comparison with the natural moisture content in a preliminary assessment of earthwork materials.

3.2 DEVELOPED GEP MODELS

The GEP models developed here are mainly aimed to generate the mathematical functions for the prediction of the compaction parameters based on the compaction energy of coarse-grained soils with fine grains. In this study, four GEP models (GEP-1, GEP-2, GEP-3 and GEP-4) are developed. To predict w_{opt} GEP 1 and 2, in which two and six input parameters such as E, w_L and E, G, S, FC, w_L, I_P are employed, respectively, are developed. In the GEP-3 and GEP-4 models, different two (E, w_{opt}) and six (E, G, S, FC, w_L, I_P) input parameters are used respectively. Thus, four mathematical functions are generated in the form of w_{opt}=f(E, w_L), w_{opt}=f(E, G, S, FC, w_L, I_P), γ_{dmax}=f(E, w_{opt}) and γ_{dmax}=f(E, G, S, FC, w_L, I_P) for the prediction of compaction parameters based on the compaction energy in coarse-grained soils with fine grains. Table 6 presents the model parameters used for both models. DTREG software is used for the GEP algorithm [19]. The functions for the compaction parameters in coarse-grained soils with fine grains based on the compaction energy are generated as below:

GEP-1

$$w_{opt} = \sin(\sqrt{w_L}) - \cos(w_L) - \cos((w_L)^2) + \left[\frac{w_L}{E}(\sqrt[3]{w_L})(w_L+E)w_L\right]^{1/3} + \left[\frac{(w_L-E)}{E}\right]^3 \frac{1}{[\cos(E)+1]} \qquad (12)$$

GEP-2

$$w_{opt} = \cos\left[\cos(\sqrt{w_L}) - G + I_P\right] + \sin(E) + 0.12\left[w_L - \sqrt{G^{1/3} I_P}\right] + \sin(E) - \cos\left[I_P - FC + w_L + E + S\right] \qquad (13)$$

GEP-3

$$\gamma_{d\max} = \left[\frac{\log(E)}{w_{opt}} + \log(E)\right]\sin[\log(w_{opt})] + \sqrt{a\tan(w_{opt})} + \sin(E) + \log(E+w_{opt}) + a\tan(w_{opt})^2 + \sin(E) + \log\sqrt{E} \qquad (14)$$

GEP-4

$$\gamma_{d\max} = \frac{(FC+2G+S-7.8)}{w_L} + 8.09 + \sin\left[\frac{w_L}{\left(-7.1 - a\tan\left(\frac{\log(S)}{-8.39}\right)\right)}\right] + \log\left[E - 4.78w_L - \sqrt[3]{I_P * G}\right] \qquad (15)$$

Table 6. GEP parameters of the models developed.

	GEP-1	GEP-2	GEP-3	GEP-4
Generation	118333	150552	7854	8702
Program size	37	34	32	35
Number of the genes	3	3	3	4
Length of the gene head	7	8	7	8
Max. fitness	1000			
Linking function	+			
Function set	+, -, *, /, √ , exp, log, sin, cos, arctan			
Mutation rate	0.044			
One-point recombination rate	0.3			
Two-point recombination rate	0.3			
Inversion rate	0.1			
Transposition rate	0.1			

The compaction parameters estimated from all the GEP models are graphically compared with the measured values in Fig. 7 and Fig. 8. It clearly appears that the results from the GEP are in good agreement with the measured values. This also shows that all the models are found to be able to learn a complex relationship between the input parameters relating to the soils and the compaction parameters.

In addition, the values of the compaction parameters estimated from the GEP models are graphically compared with those from the MLR models in Fig. 9 and Fig. 10. Table 7 presents the statistical performances of the MLR and GEP models. As far as this table is concerned, all the models for the compaction parameters, except for MLR-SMP-3, give satisfactory agreement in terms of the statistical evaluation criteria. The best results in terms of the *R*, *RMSE* and σ values are obtained for MLR-SMP-2 (R=0.94, $RMSE$=2.69, σ=1.84) among the MLR models and GEP-2 (R=0.95, $RMSE$=3.11, σ=2.29) among the GEP models to estimate w_{opt}, and for MLR-Eq. 11 (R=0.97, $RMSE$=0.57, σ=0.42) among the MLR models and GEP-3 (R=0.98, $RMSE$=0.42, σ=0.20) among the GEP models to estimate γ_{dmax}. These models have fairly high *R* values and low *RMSE* values, which are a measurement of the deviation around the regression line.

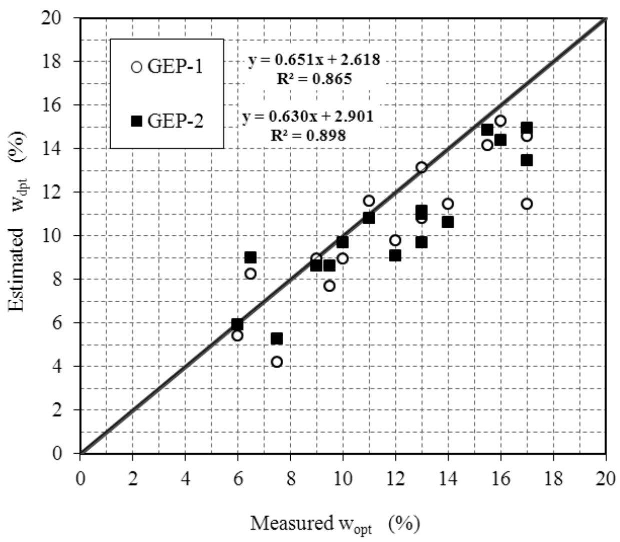

Figure 7. Comparison of measured and estimated w_{opt} based on *E* from the GEP-1 and GEP-2 models.

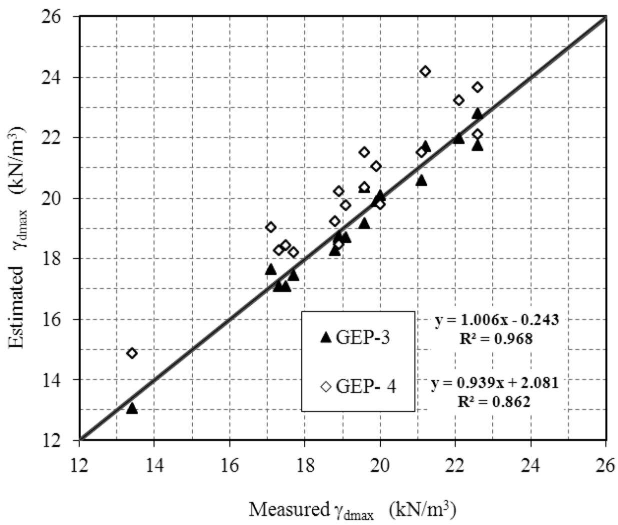

Figure 8. Comparison of measured and estimated γ_{dmax} based on *E* from the GEP-3and GEP-4 models.

The overall error performances of the relationship between the two groups (predicted and actual values) can be interpreted from the *R* values. If the *R* value of a relationship between two groups is as high as 0.8, it is accepted from the statistical point of view that this correlation is satisfactory [20]. The *RMSE* value also has great significance for the statistics as well as the *R* value, because although a relationship provides high *R* value, it may give a high *RMSE* value.

When the models are compared in terms of the types of analyses (MLR and GEP) it can be seen that the MLR model (MLR-SMP-2) gives better results to estimate w_{opt} and the GEP model (GEP-3) gives better results to estimate γ_{dmax}. However, MLR-Eq. 11 can be used for esti-

Table 7. Performance statistics of the models.

	R	*RMSE*	σ
MLR-SMP-1	0.92	3.09	2.23
MLR-SMP-2	0.94	2.69	1.84
MLR-Eq. 7	0.94	3.05	2.43
GEP-1	0.93	3.18	2.33
GEP-2	0.95	3.11	2.29
MLR-SMP-3	-0.44	7.30	5.06
MLR-SMP-4	0.94	1.09	0.53
MLR-Eq. 11	0.97	0.57	0.42
GEP-3	0.98	0.42	0.23
GEP-4	0.95	1.05	0.51

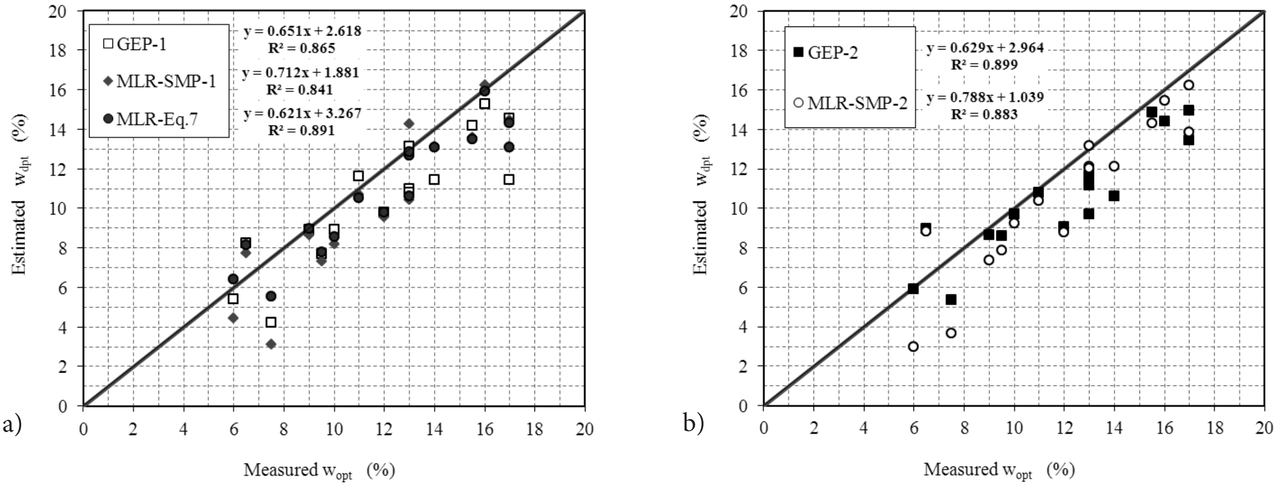

Figure 9. Comparison of estimated w_{opt} from the MLR and GEP models.

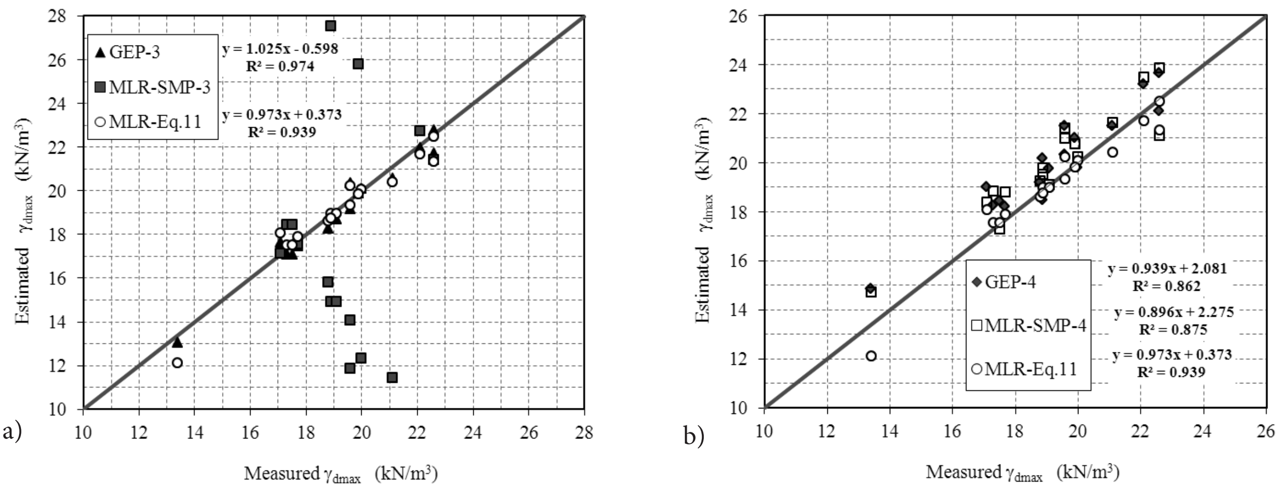

Figure 10. Comparison of estimated γ_{dmax} from the MLR and GEP models.

mating γ_{dmax} due to its simplicity and ease in practice. The evaluations given above reveal that the MLR-SMP-2, MLR-Eq. 11, GEP-3 and MLR-Eq. 11 generated by the GEP and MLR models provide a good prediction ability. The prediction accuracy of the models appears to be sufficient from statistical point of view in the prediction of the compaction parameters.

4 CONCLUSIONS

The optimum water content, w_{opt} and the maximum dry unit weight, γ_{dmax} are the principle parameters to control field compaction in which the applied compaction energies may vary depending on the field requirements and the soil type. A determination of these properties plays an important role in the design of compaction projects. In this study, the correlations between the compaction and index properties of coarse-grained soils with fines contents of more than 5 % are developed by performing MLR analyses using 63 SP compaction data and 23 MP compaction data. The MLR and GEP models that include compaction energy have also been described for estimating w_{opt} and γ_{dmax} for SP and MP compaction energy levels. The MLR and GEP models are found to give very reliable results for predicting both w_{opt} and γ_{dmax} for the SP and MP compaction test data.

It is concluded from this study that w_{opt} has a much better correlation with w_L than w_P, and γ_{dmax} can be estimated more precisely from w_{opt} instead of the index properties of soils. Thus, two mathematical equations (Eq. 7 and Eq. 11) are generated and proposed for estimating w_{opt} using w_L and E, and γ_{dmax} using w_{opt} and E from the MLR models. The correlations are formed as w_{opt} = Kw_p and γ_{dmax}= L-Mw_{opt} where the coefficients of K, L and M are introduced as a function of E. As w_L and E are known, at first w_{opt} could be obtained from Eq. 7 then γ_{dmax} could be obtained by substituting w_{opt} into Eq. 11 for any compaction energy levels.

In addition, four GEP models are developed. A satisfactory agreement is obtained as a result of the testing procedures of the GEP-2 and GEP-3 models. This is evidenced by some statistical performance criteria used for evaluating the models. The overall evaluation of the results obtained throughout the paper revealed that the MLR and GEP computing techniques used here are very encouraging for the data used. The author recommends that the models developed for estimating the compaction parameters for any compaction energy level could be used in a preliminary design stage due to laborious, time-consuming and costly tests. Additional important parameters in the compaction are the roughness of the surface of the grains, the shape of grains, and the composition of minerals, etc. Though a great effort was made to use unbiased and heterogeneous media the conclusions introduced in this study are significant for the coarse-grained soil samples taken from particular sites with the same geological history. Future studies are needed to expand these results in order to be internationally valid.

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