Development of Subgrade Parameter Prediction Model Using FE.

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Abstract

A new numerical approach has been undertaken to derive simple models to estimate subgrade parameters K_1, K_2, and K_3 as functions of vertical deflections and light falling weight deflectometer (LFWD) loads using FE analysis. Resilient modulus, Mr, at each element in the FE mesh was computed by incorporating a stress state dependent nonlinear material model in the FE analysis. Multiple regression analyses were performed to develop the models based on the FE outputs. The proposed study promises to be a feasible method for subgrade characterization, considering significant stress-state dependent material properties of the subgrades.

Key words: FWD, Subgrade parameters, FE

Introduction

The resilient modulus has been used to describe the nonlinear characteristics of unbound soil materials. Resilient modulus testing procedure designed to predict the response of soils under various stress levels is a difficult and time consuming testing. M_R, resilient modulus, values are generally obtained by at laboratory conditions under cyclic loadings by conducting complex triaxial tests on cylindrical specimens, according to TP46 procedure [1, 2, 3]. The test requires expensive laboratory equipment, disturbed samples and is considered relatively time-consuming.

The complexity of the laboratory test procedures has prompted highway engineers to use in-situ field tests such as FWD.

FWD (falling weight deflectometer) is preferred because it is non-destructive testing technique and can simulate the stress state in the soil material in the field better than the laboratory testing [4,5]. The FWD, deflection-based characterization, allows much higher number of tests to be conducted, compared to sampling for laboratory testing, resulting in reduced time and field testing costs. In particular, the light falling-weight deflectometer, LFWD, is an effective device due to their simplicity and ability to provide rapid measurements of in-situ strength of compacted embankment soils.

The resilient modulus in granular materials has been known to be stress-state dependent due to nonlinear behavior of soil [6, 7, 8, 9, 10]. The stress-state dependent universal model introduced by Witczak and Uzan [8] is applicable to a wide range of unbound materials. The model is expressed in terms of both deviator and bulk stresses and can account for the shear stress effect on the resilient modulus. The general form of the universal model is shown as follows:

$$Mr = K_1 Pa(\theta/Pa)K_2(\tau_{oct}/Pa+1)^{K3} \qquad \text{.............................(1)}$$

Where,

Mr: resilient modulus

K_1, K_2 and K_3 = regression constants.

Pa = atmospheric pressure, 101.3 kPa (14.7 psi)

θ = bulk stress (sum of three principle stress) = s1 + s2 + s3

τ_{oct} = octahedral shear stress = $(1/3)[(s1 - s2)^2 (s1 - s2)^2 + (s1 - s2)^2]^{1/2}$

Significant errors can be introduced in predicted values of M_R in the universal model. Since K_2 and K_3 is exponent, small change in K_2 and K_3 can make large difference in predicted M_R, which may be the primary reason for the significant prediction errors of the universal model. This is true even for moderate changes in K_1 parameters.

Objective

The primary objective of this study was to develop an analysis method that predicts compacted unbound soil parameters, K_1, K_2, K_3 as a function of peak displacements D_0, D_1, D_2 and varying peak loading pressures. It is hoped that, this simplified approach can help to produce accurate soil parameter values that will be used in the universal resilient modulus model.

Method of Analysis

Stress state dependent resilient modulus shown in equation 1 was incorporated into a finite element analysis. The model was then utilized to predict the deflection under varying load conditions. Based on the deflection database generated from the finite element analyses, a number of relationships were developed using multiple regression approach to predict the K_1, K_2 and K_3 regression parameters.

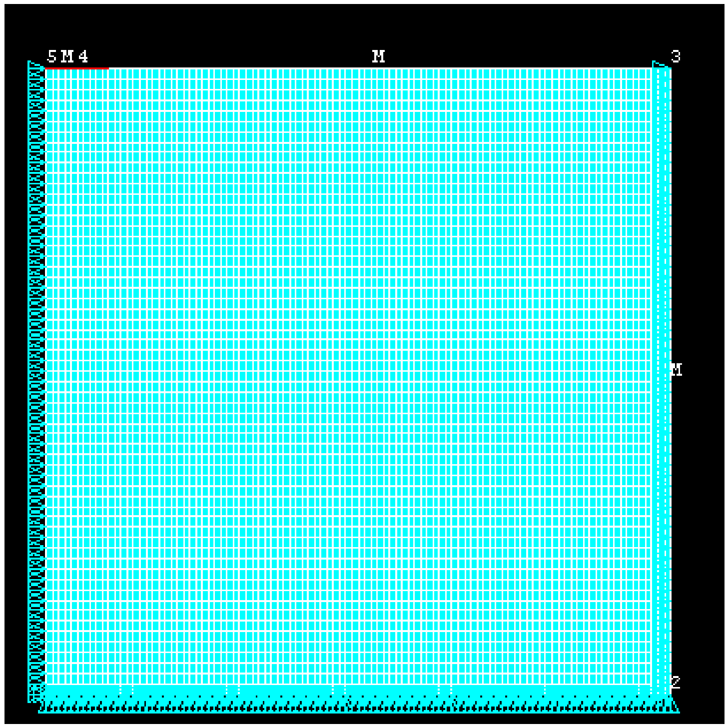


Figure 1. Subgrade finite element mesh used for generating the runs.

In this research the general purpose finite element method ANSYS version 8 [12] was selected as a numerical tool which was used to calculate the bulk and octahedral stresses. Finite element analyses were successfully used to model road pavements to determine the critical stress at varying depths [12-17]. The FE analysis was performed with axisymmetric finite element representation of a subgrade structure consisted of 10,000 (100 x 100) elements. A 2-D FE structure similar to Figure 1 was constructed. Thickness of soil layer was assumed to be 152.4 cm overlying on a rigid layer. The length in the horizontal direction was 152.4 cm. Poisson's ratio of 0.4 was used for all elements generated from meshing. Generally, Poisson's ratio will be less than 0.5, usually thought to be between 0.35 and 0.45 for most unbound materials.

The subgrade layer was represented by PLANE82 as an axisymmetric element. Four node quadrilaterals and 8 node hexahedra are generally more accurate than 3 node triangles and tetrahedra, respectively [12]. PLANE82 is a higher order version of the two-dimensional, four-node PLANE42 element. Higher order elements can be more efficient and therefore require fewer elements than do lower order elements for comparable accuracy. The 8-node element is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

Mesh size and configuration was an important part of finite element modeling. One of the main concerns in the analysis was the adequacy of the finite element mesh. Effort and time was spent in meshing procedure to avoid creating ill-conditioned elements.

The boundary conditions were important to simulate the vertical deflection under loading. The boundary conditions of the model were as follows: nodes along the outer edges the meshes were allowed to move in vertically but were restrained from horizontal displacements. The nodes located at bottom of the mesh were restricted from horizontal and vertical displacements, as shown in Figure 1.

The LFWD operates by applying a load to the structure surface and measuring the resulting surface deflections using geophones. Light falling weight deflectometer load magnitudes are available with peak rated loadings from 1 kN to 15 kN. Loading plate size diameters varying between 100 mm and 300 mm are used for various models. In this study loads of 6.89, 13.78, and 20.67 kPa were applied on axis symmetric. The diameter of the loading plate used in this study was 300 mm.

The resilient modulus at a given point within the soil structure was related to the state of stress by varying the material properties. After assigning the atmospheric pressure value and subgrade soil parameter values K_1, K_2, and K_3 and incorporating the formula into the FE model the resilient modulus values in each element were generated starting from top to bottom over the meshed structure.

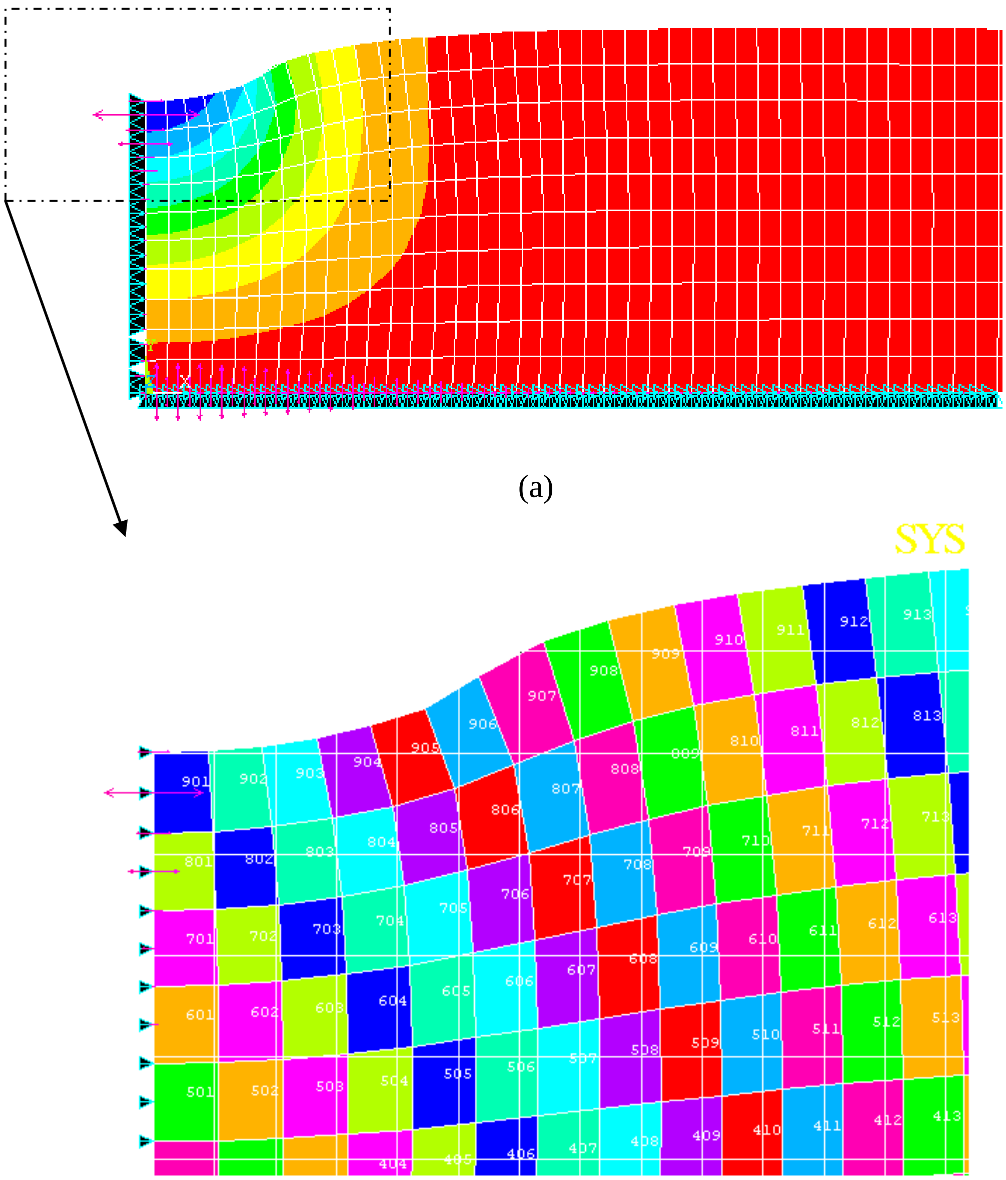
Typical subgrade parameter values were introduced to the equation 1 in the FE analysis. Positive numbers of 1500, 1000, 500, 250, and 100 were assigned for K_1 subgrade parameters since they were proportional to Mr which could not be negative. Positive values of 0.45, 0.3, 0.2, and 0.1 were entered for K_2 subgrade parameters. Negative values of -4, -3, -2, -1 were introduced as K_3 values to the model regarding that the soil exhibits deviator stress softening due to increased octahedral shear stress.

Results and Discussion

The PLANE 82 quadratic element showed very good performance under the loading and geometries. The good performance was attributed to the ability of the elements to properly handle bending and shear energy, in contrast to the linear elements. Changing the element from Plane 82 to Plane 42 in the FE analysis did not have effects on the displacement values.

The surface deflections generated by the imposed load were computed on the surface elements 0, 200, and 300 mm, away from the center of load. Figure 2 displays the vertical deformations computed from the FE analysis for the given element properties. Higher deflection values under the load center (D_0) and lower deflection values under the elements that were located far from load center (D_1, D_2) were computed. The majority of D_0 values fall between 0.076 and 5 cm, D_1 ranged from 0.043 to 2.18 cm, and D_2 between 0.024 and 0.99 cm.

FEM calculated Do deflections at the center of loading for the contact pressures of 68.9, 137,8, and 206 kPa are shown in Figures 3, 4, and 5 respectively.



(a)

(b)

Figure 2. Deformation due to LFWD loading displayed in a) contour and b) elements.

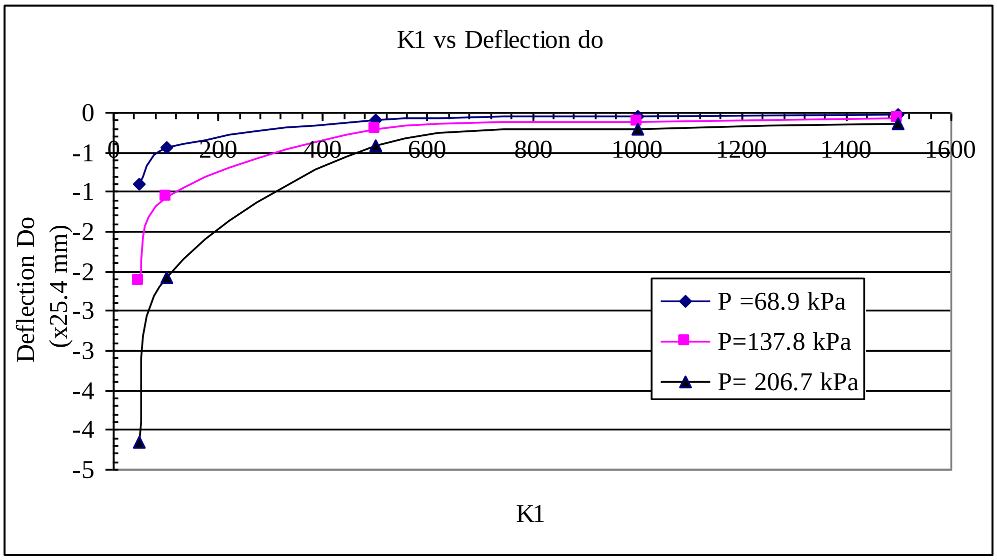


Figure 3. Soil Parameter K1 vs Do deflection.

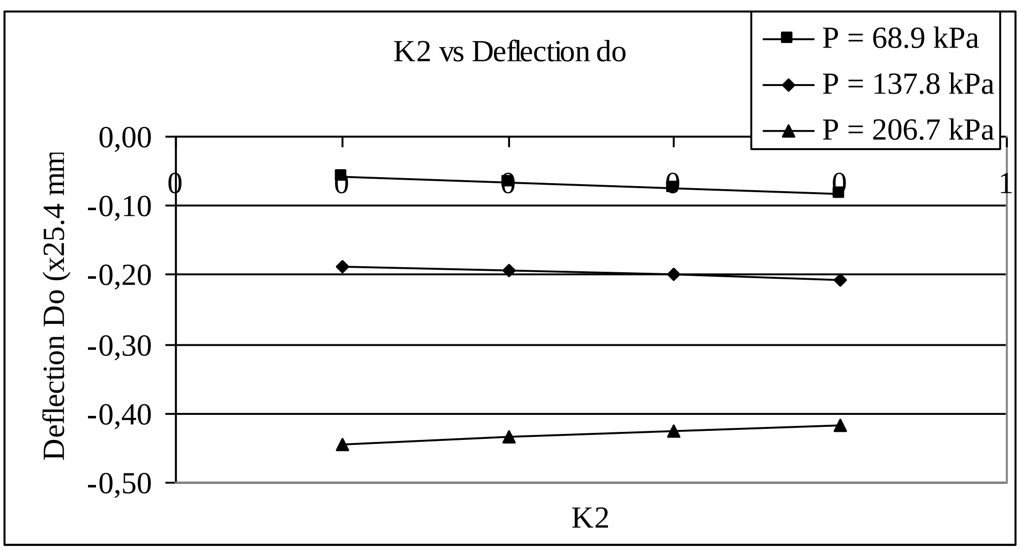


Figure 3. Soil Parameter K2 vs Do deflection.

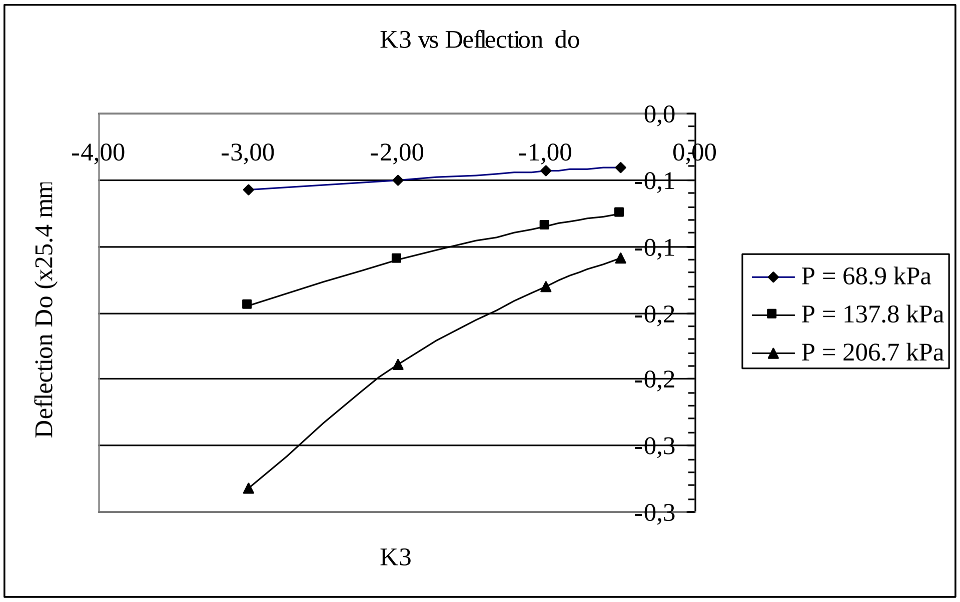


Figure 3. Soil Parameter K3 vs Do deflection.

Multiple Regression Analysis

Multiple regression analysis were used to discover the relationship between the D_0, D_1, D_2 peak displacements and LFWD pressure independents or predictor variables and the dependent variables K_1, K_2, K_3, and then finding an equation that satisfies that relationship. All variables were entered into the regression equation according to the standard regression method. Three separate regression equations relating subgrade parameters to displacement and pressure values were developed. In all three deflection models independent variables were significant ($p<0.005$). R^2 values of the three regression equations were 0.8.

Based on the best possible correlation to the FE results, the following three regression equations can be derived to estimate subgrade parameters:

$$\mathrm{Log}(K_1)= 10.62*\mathrm{Log}(D_0)-34.65*\mathrm{Log}(D_1)+23*\mathrm{Log}(D_2)+0.055*P+3.2 \quad \text{............(1)}$$
$$K_2 = 9.53*\mathrm{Log}(D_0)-33.3*\mathrm{Log}(D_1)+23.81*\mathrm{Log}(D_2)+0.038*P+3.66 \quad \text{........... (2)}$$
$$K_3 = -81*\mathrm{Log}(D_0)+233.3*\mathrm{Log}(D_1)-152.4*\mathrm{Log}(D_2)-0.123*P-20.66 \quad \text{. ....(3)}$$

The compaction control of different soils used in the construction of highways and embankments is needed for enhancing their engineering properties.

The current methods for assessing the quality control for construction of highways is based on determining the field unit weight measurements and comparing that to the maximum dry unit weight obtained in the standard or modified Proctor tests that are conducted in the laboratory. The field dry unit weight measurement is determined using either destructive tests, which include the sand cone, the rubber balloon, and the core cutter methods; or other non-destructive tests such as the nuclear density gauge.

Conclusion

The main purpose of this study was to develop a method that predicts subgrade parameters as a function of vertical displacements and loading pressures. From the results the following conclusions were drawn.

1. The principle benefit of the statistical model developed in this research resides in being able to compute the subgrade parameters K_1, K_2, and K_3 from the applied load and the measured peak displacements using the equations found in this study.
2. Based on the results of this research the tentative procedure given below is recommended for using the PFWD to monitor compaction of granular base courses.

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