FINITE ELEMENT ANALYSIS OF CONCRETE BLOCK PAVING

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ABSTRACT

Two and Three-dimensional finite element analyses were conducted on concrete block paving. In order to verify the calculated results, a case study was analysed. Good agreement was observed between the measured and the calculated results. Based on the Finite Element (FE) analysis results and available failure models, comprehensive design charts were developed which can take into account; the subgrade and pavement layers properties as well as the tyre pressure and the number of repetitive loads.

1. INTRODUCTION

For many years design of block pavements has been based upon experimental methods and experience gained from behaviour of previous pavements. However, in recent years the finite element method has increasingly been used for structural analysis of pavements. The method is especially attractive when the nonlinear behaviour of granular and cohesive materials used in pavements is to be considered in mechanistic modeling.

Elastic analyses, which are based on linear behaviour, may offer some understanding of strains and stresses, however such analyses have limitations. This is because soil behaviour cannot usually be described in terms of a linear stress-strain relationship.

A comprehensive analysis of block paving was conducted using the following models:
- Two-dimensional linear analysis;
- Two-dimensional nonlinear analysis;
- Three-dimensional linear analysis and;
- Three-dimensional nonlinear analysis.

In order to determine the accuracy of above analyses a comparison was made between the vertical stresses obtained from analysis with those measured from a case study which are discussed in the following sections. In addition, the finite element analysis was incorporated in design charts developed in this study. The analyses were carried out using the ANASYS (Moaveni, 1999) finite element package.

2. BACKGROUND

Three general methods to the analysis of block pavements have been introduced. These include modified slab analysis (Marias,1967 & Dutruel, 1984), layered elastic analysis (Barber, 1980 & Shackel, 1984) and finite element analysis (Houben, 1984 & Nishizawa et al., 1984).

The criticism with two former methods is that they ignore the discrete discontinuous nature of paving blocks but, rather, assume the block course can be modeled in terms of an equivalent continuous elastic layer.

However, finite element techniques can model the blocks as an articulated having defined loads or displacement transference at the joints between neighboring paving units. Furthermore, nonlinearity of materials behaviour (i.e. base and subgrade layers) can also be considered by this technique.

The analysis presented by Nishazaw et al (1984) was restricted solely to a consideration of the block surfacing but was valuable in providing theoretical confirmation of the difference in performance of pavement installed in different lying patterns. The study conducted by Molenaar et al. (1984) and Houben et al. (1984) demonstrate that finite element analysis were capable of modeling the observed load/deflection behaviour of block pavements more accurately than elastic layer theory.

3. CASE STUDY

In order to evaluate the analysis results, a carefully instrumented accelerated trafficking tests of prototype block pavements was selected as a case study (Shackel, 1979) to be analysed. Figure 1 illustrates the vertical stress at various depths of pavement. From this figure it may be seen the principal reduction in stress occurs within the blocks themselves but the some further substantial decrease occur within the bedding sand layer. The reason of selecting this test as case study was that the vertical stress does not change significantly at any depth with number of load repetitions due to stiffening of block pavement under simulated trafficking (see Figure 1).

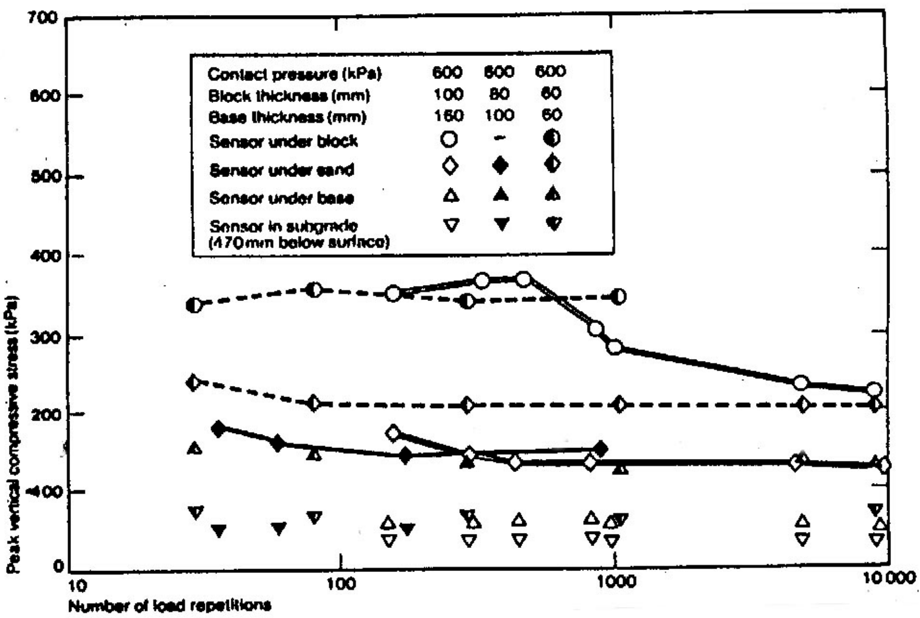
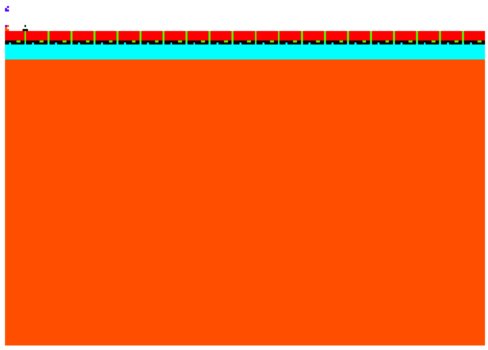


Figure 1. Measured vertical stress at various depths against number of load repetitions (Shackel, 1979).

4. FINITE ELEMENT MODEL CONFIGURATION

Two-dimensional plain strain and three-dimensional meshes are shown in Figures 2 and 3.

In the case of two-dimensional analysis, the height and width of mesh are 4.6m and 3m, respectively. In consists of 21 rectangular blocks with 20 Cm. in width, 10 Cm in thickness. The thickness of bedding sand, was selected to be 2 Cm. and that of the base layer is 16 Cm. The depth of subgrade to the bottom of the mesh is 122 Cm.



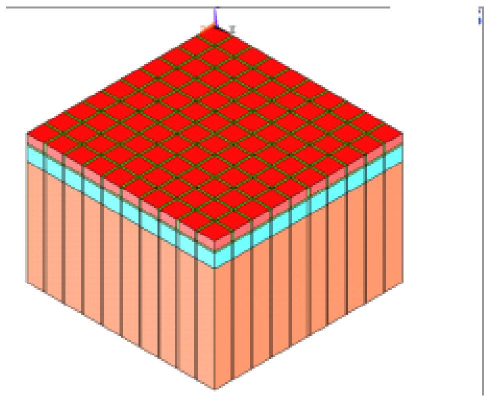


Figure 2. Two-dimensional mesh. **Figure 3. Three-dimensional mesh.**

In the case of three-dimensional analysis the height, length and width of mesh are 2.18m, 2.18m and 1.5m, respectively. It consists of 100 blocks having 20Cm. width, 20Cm. length and 10Cm. thickness.

The mesh dimensions were determined so that its boundaries do not have any effect on the analysis results and this became possible by several trial and error analyses.
The contact pressure is 600 kPa in the both cases. In the case of three-dimensional analysis, load is applied on one block surface area.

5. MATERIAL PROPERTIES

Since, for the case study being analysed, no material properties were reported, the properties recommended by Shackel (1990) were used. The layers properties are presented in Table 1.

Table 1. Material properties (Shackel, 1979).

Layer	E (Mpa)	ρ (kN/m^3)	ν	C (kN/m^2)	φ (Deg.)
Concrete block	2500	20	0.3	--	--
Bedding and jointing sand	350	18	0.35	10	30
Base layer	225	18	0.35	10	30
Subgrade	225	18	0.35	10	30

For the non-linear two and three-dimensional analyses, concrete blocks is considered to be elastic. Bedding sand, base and subgrade layers were assumed to have elasto perfectly plastic behaviour and the Drucker-Prager model (Drucker & Prager, 1952) was utilized as their failure criteria. The layers were assumed to have full contact with no relative displacement between.

6. RESULTS AND DISCUSSION

Figures 4 and 5 illustrate the variations of vertical stress against depth for linear and non-linear two-dimensional analysis.

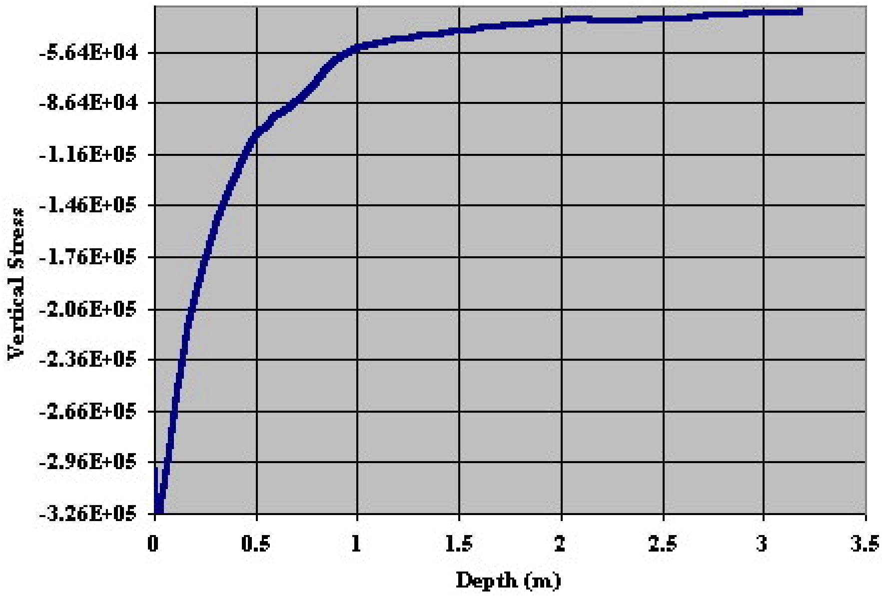


Figure 4. Vertical stress versus depth (Linear two-dimensional analysis).

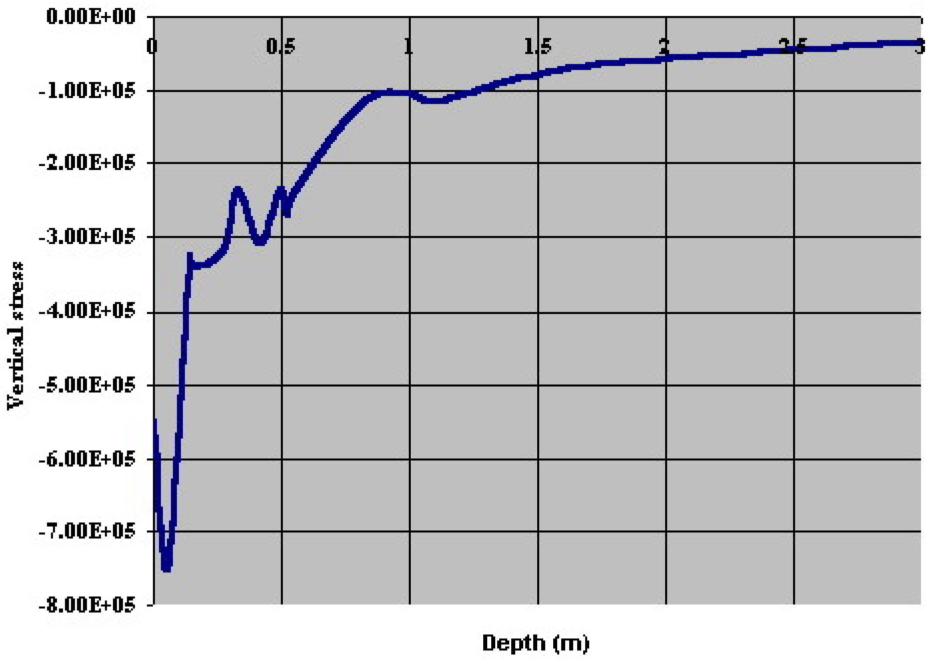


Figure 5. Vertical stress versus depth (nonlinear two dimensional analysis).

Figures 6 and 7 illustrate the variation of vertical stress against depth for linear and non-linear three-dimensional analysis.

Vertical stresses at various depths obtained from the analyses as well as the measured stresses (from Fig.1) are given in Table 2 for comparison.

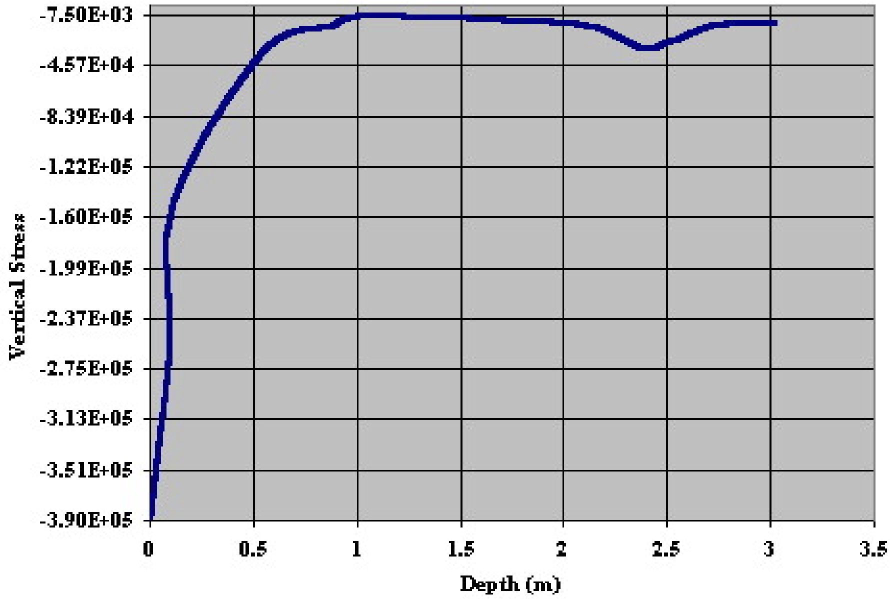


Figure 6. Vertical stress against depth (Linear three dimensional analysis).

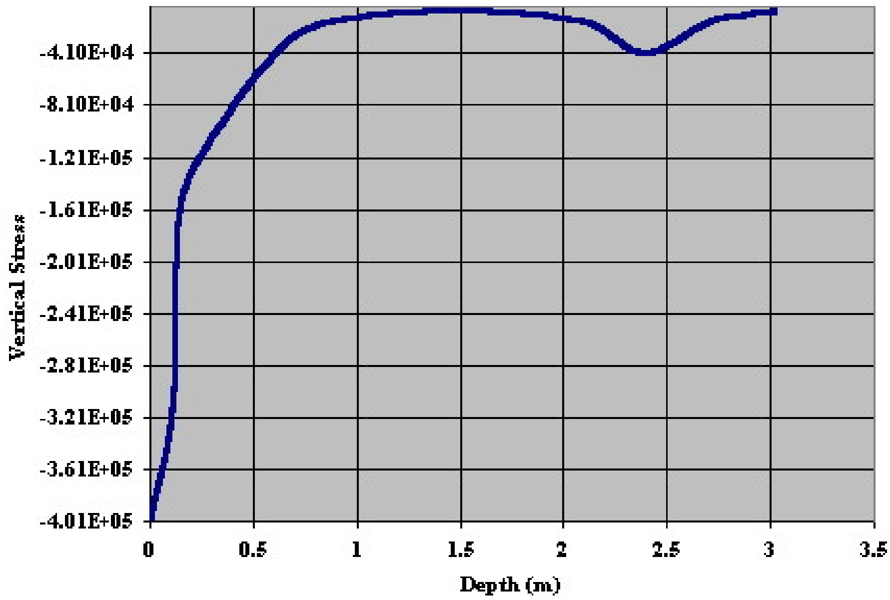


Figure 7. Vertical stress against depth (non linear three-dimensional analysis).

Table 2. Vertical stresses at various depths (analyses and measured results).

Depth	Two-dimensional analysis (kPa)		Three-dimensional analysis (kPa)		Measured vertical stress (kPa)
	Linear	Non linear	Linear	Non linear	
Under block	300	328	257	302	300
Under bedding sand	330	340	146	164	150
Under base layer	208	232	100	108	100
470mm below surface	109	113	47	48	45

In case of two-dimensional analyses, even though there is reasonable agreement between numerical and the experimental results for stresses below the block, however the analysis overestimates the stresses at other depths. The reason for such disagreement is probably that the two dimensional analysis cannot model three-dimensional discrete discontinuous nature of blocks.

In case of three-dimensional analysis, there is a good agreement between the results calculated with the linear and non-linear FE models and the measured results. Furthermore, linear three-dimensional analysis gives reasonable answers (except below the block layer). Since the non-linear analysis is time consuming and cumbersome the linear three-dimensional analysis, particularly at lower layers, may be used for design purposes.

The vertical stresses with depth are illustrated in Fig. 8.

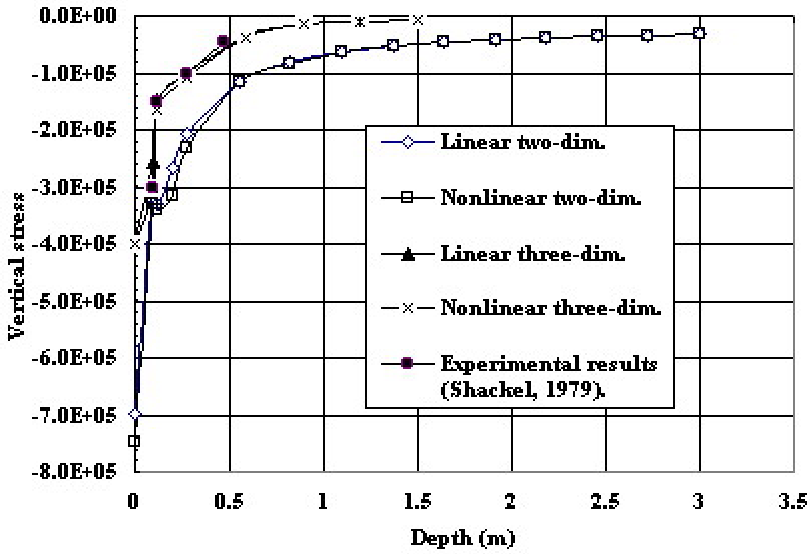


Figure 8. Vertical stresses against depth.

7. BLOCK PAVEMENT DESIGN

Based on the analyses results, a series of design charts were developed for common axle loads in Iran.

7.1 Subgrade Characterisation

Subgrade material is characterised in terms of the California Bearing Ratio (CBR). Hence, the elastic modulus of subgrade must be evaluated from the CBR value. Among a variety of correlations, the following widely accepted relation was selected:

$$E=10.\ CBR \tag{1}$$

Where the modulus, E, is in Mpa and the CBR is in percent.

7.2 Characterization of pavement response

For design of pavement, the overall response of a pavement to traffic is necessary to be assessed. To accomplish this task, Miner's linear cumulative damage hypothesis was adopted. The miner hypothesis state that, irrespective of the magnitude of the stress each stress repetition is responsible for a certain amount of fatigue damage. It is assumed that there is a linear rate of fatigue damage irrespective of the order of load application and that fatigue occurs when the sum of the damage increment at each level of stress accumulates to unity. The law can be expressed in the form:

$$\sum_{N=1}^{n} \frac{n_i}{N_i} = 1 \tag{2}$$

Where N_i is the number of cycles to failure level i and n_i is the number of cycles actually applied at stress level i.

In order to predict Ni (service life of pavement) in above equation, a mechanism of failure must be postulated. Where unbound materials such as crushed rocks and gravel are used, the pavement is assumed to be failed by gradual accumulation of permanent rutting deformation. It is commonly accepted that rutting deformation is related to the vertical compression strain at the top of the subgrade. The criterion used in this study was the model developed by Claessen et al. (1977). This criterion has been most widely used in block pavement design. It can be written as:

$$S_v = \frac{2800}{N^{0.25}} \tag{3}$$

Where Sv is the permissible subgrade compression strain (microstrain) and N is the number of strain repetition.

Fig. 9 illustrates a typical design charts for various axle load categories (Wheel loads) available in Iran (See Table 3).

Table 3. Wheel contact pressures used in design charts.

Graph Label	Wheel load (KN)
A	65
B	55
C	40
D	30
E	25
F	20
G	15
H	10
K	5

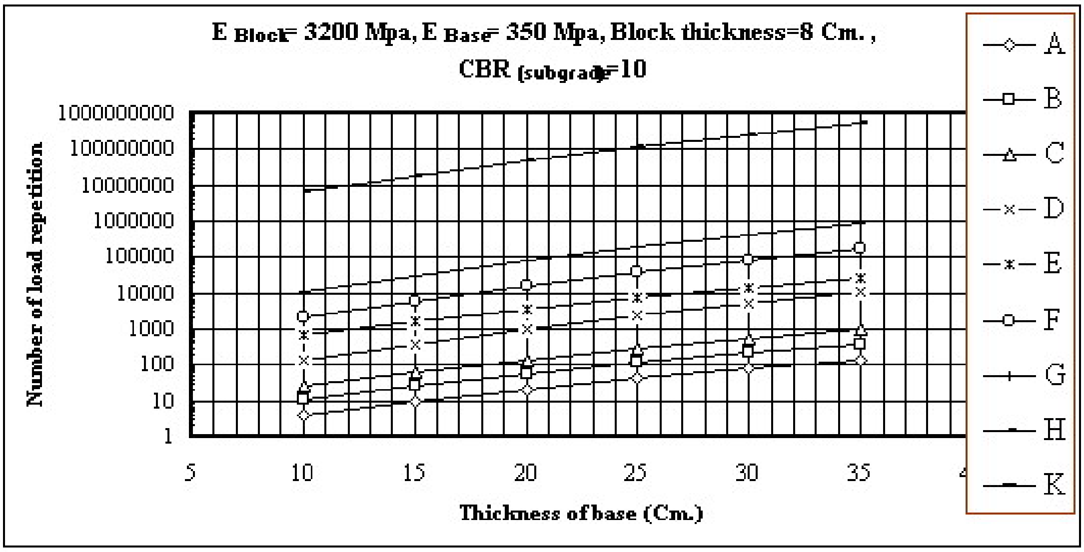


Figure 9. A typical design chart.

8. CONCLUSION

- According to the experimental and numerical results the principal reduction in stress occurs within the block layer and this fact shows that the block layer is not only a wearing surface but represent one of the main structural layers.
- Two-dimensional analysis cannot predict the accurately the block pavements behaviour due to three-dimensional discrete discontinuous nature of blocks.
- Apart from the stress below the block layer, linear three-dimensional analysis may predict the block pavements response with reasonable accuracy.
- Since the non-linear analysis is time consuming and cumbersome, linear three-dimensional analysis, particularly at lower layers, can be used for design purposes.

9. ACKNOWLEDGEMENTS

Financial support for the work presented in this paper was provided by Iran Center for Road and Transportation Researches. This support is gratefully acknowledged. The author also appreciates the contribution from formerly graduate student Mr. Mohamadpour and gratefully acknowledges the value of discussion with Dr. M. Fakhri.

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