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Numerical Simulation of an Idealized Road Structure

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Abstract: This study deals with the behaviour of an idealized road structure observed using a numerical simulation. The investigated layered structure is constituted by the asphalt layer commonly called the road made of bituminous material, a layer of clean aggregate (gravel) and a foundation layer of soil mass. The numerical model was developed with respect to the geometry, dimensions, boundary and loading conditions of a physical model investigated by a previous researcher. After validation, the numerical model was used in a parametric study to show the effect of different parameters as the Young's modulus of the materials, the temperature effect and the type of loading. Emphasis was put upon the behaviour of the structures when subjected to static and cyclic loadings induced by the normalized stress of a wheel. The irreversible deformation of the road surface, usually called rutting was investigated. Out of this numerical exercise it was found that the deflection associated with rutting, considered as a residual displacement, is mainly due to the effect of the cyclic loading of the structure.

Key words: Road structure, numerical model, plaxis code, cyclic loading, rutting

INTRODUCTION

Road pavement is a structure that is mainly designed to carry traffic safely, conveniently and economically during its lifespan. Experience shows that increase in traffic density leads more often to the speeding of the deterioration of the pavement structure. The design methods of pavements have always been inspired from empirical approaches based on experimental observations. Early research on the analysis and simulation of pavement response due to traffic loading were based on linear elastic material model considered under static loading conditions, Although this approach can produce estimates of the static deflection with the proper choice of a secant elastic modulus, it cannot predict the permanent deformation (Brown and Bell, 1977).

Modern numerical methods and the fast growing development in computers performances have opened new horizons for investigating the behaviour of road structures by means of simulations techniques. Development of powerful numerical methods has made it possible to perform complicated simulations of the degradation process induced to the road surface and to have a close look on the response of the structure when subjected to different type of loadings (Kettil *et al*., 2007). Numerical investigation remains reliable enough to be representative of the real behaviour of the structure, but they need to be continuously fully validated against reliable data.

One of the common forms of deterioration mechanism is the permanent deformations, associated with an irreversible deformation of the road surface, usually called rutting. Rutting is governed by the type of traffic loading and the material properties. Analysis and simulation of asphalt material due to wheel-loads are still based on linear elastic model (Ullidtz, 1987). Research work has shown that this approach can produce reasonable estimates of the static deflection with an adequate choice of the secant modulus, but, it cannot produce predictions of the residual deformation causing the rutting.

Considering a linear elastic law for all the materials constituting the structure investigated (asphalt, Gravel and the soil), a numerical model was developed using the Plaxis program with respect to the geometry, dimensions, boundary and loading conditions of a physical model investigated by a previous researcher. The numerical model was then was used to investigate the effect of many parameters that are known to affect the behaviour of the road structure. The parameters considered are: dimension (thickness) effect of the asphalt layer, temperature dependant Young's modulus for the asphalt material, the variation of the rigidity of the aggregate layer and the effect of the type of loading applied to the road surface.

IDEALISED STRUCTURE

The road structure considered in the present simulation is presented in Fig. 1. As can bee seen three

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Table 1: Material properties

Mohr-Coulomb	BB	GNT-1	GNT-2	GNT-3	Soil
γ_{unsat}	1500,00	2000,00	2000,00	2000,00	2300,00
γ_{sat}	1500,00	2100,00	2100,00	2100,00	2600,00
k_x	0,000	0,000	0,000	0,000	0,000
k_y	0,000	0,000	0,000	0,000	0,000
e_{init}	0,500	0,500	0,500	0,500	0,500
c_k	1E15	1E15	1E15	1E15	1E15
E_{ref}	5400,000	400,000	200,000	100,000	50,000
ν	0,350	0,350	0,350	0,350	0,350
G_{ref}	2000,000	148,148	74,074	37,037	18,519
E_{oed}	8666,667	641,975	320,988	160,494	80,247
$R_{inter.}$	1,00	1,00	1,00	1,00	1,00

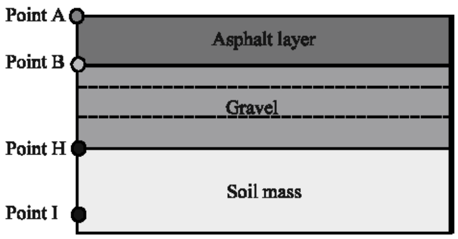

Fig. 1: Idealised road structure

layers are considered in the model. The top or first layer is the asphalt layer which is made of bituminous concrete; the sub grade layer is made of gravely aggregate which rest on a supposed infinite soil mass. To investigate the deformation mechanism of the layered structure 4 reference points are considered. The point A represents the deformation of the road surface under the wheel-weight; the rutting will be investigated by the vertical displacement of this point. Point B indicates the unbound interface between the asphalt layer and the gravel layer. The point H represents the interface between the aggregate and the soil. The point I give an indication on the stress strain behaviour of the soil mass. The most important material properties considered and the soil are presented in Table 1.

NUMERICAL MODEL

Finite element model: The geometry of the finite element model was constructed using the graphical input procedure of the Plaxis program. At this stage, the geometry of the numerical model, the material properties and the boundary conditions were specified. The numerical analysis was carried out in plane strain, as presented in Fig. 2, the layout of the numerical model extends 8 m horizontally and 6 m vertically, these boundary limits were assumed to be sufficient to avoid border disturbances. Conditions of plain strain were assumed throughout; the vertical boundaries of the model were pinned in the horizontal direction but free to move vertically and the horizontal boundary at the base of the model was assumed to be pinned in both vertical and the horizontal directions. Following the setting of the finite element computation parameters, the Plaxis input programme is used for the generation of the model's finite element mesh; developed with respect to validation model. A typical finite element mesh is shown in Fig. 3. The model was run with a fine mesh, 6 nodded triangular elements, leading to 342 elements, with 733 nodes and 1026 stress points.

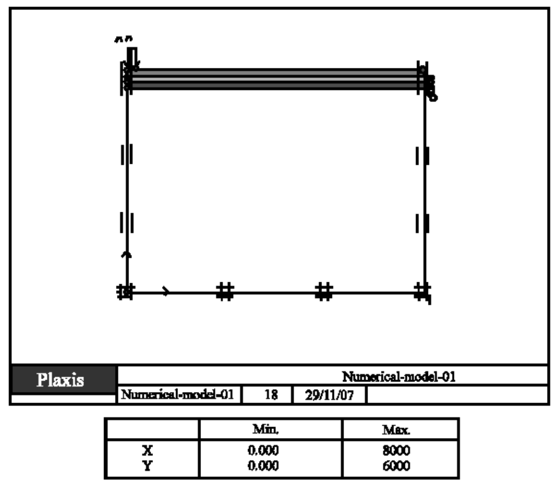

Fig. 2: Geometrical layout of the numerical model

Loading conditions: To simulate the effect of the tire on the asphalt surface s static load of 650 kN m^{-2} was supposed to be statically applied over a width of about 0.125 m to simulate the tire's impact. At the first stage of modelling the load is assumed to remain monotonic. For the static application of the considered loading, the calculation phase was run in a monophase. Plastic calculation was considered in the present exercised, as it is assumed that the displacements of the elements remain small compared to the dimensions of the model. During the calculation the load was applied in steps in which the loading was increased uniformly by increasing the value of a multiplier of the final load applied (the maximum value

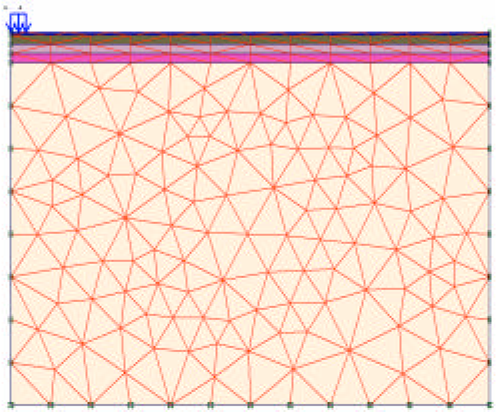

Fig. 3: Finite elements meshes

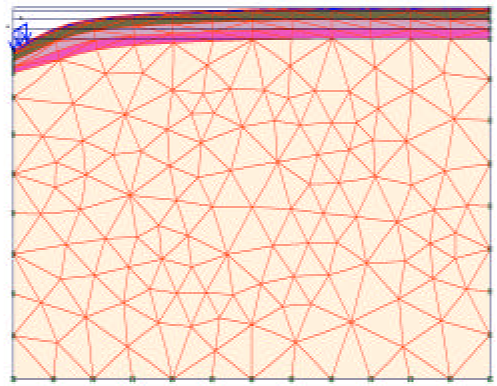

Fig. 4: Typical deformed mesh

of the multiplier is unity and correspond to the total value of the load considered). To model the cyclic effect, the model was run following a multiphase calculation process, where the applied loading was activated and deactivated simultaneously until the desired number of cycle (loading-unloading) was reached.

NUMERICAL ANALYSIS

Deformation under static loading: The numerical model was first run in one calculation phase, in which the load was maintained applied statically on the impact surface. The action of the load on the behaviour of the structure is clearly visible. Figure 4 shows in a typical deformed mesh of the numerical model. The vertical displacement of the layers is also shown in the shading plot of the Fig. 5. From this figure it is clear, that the static load induces to the layers verticals displacements effect, this effect is shown to spread out and decreases in effect following a nearly circular shape. The vertical displacements of the reference points are plotted in Fig. 6, it could be noticed that vertical displacement of points is not the same. The results were found to be very comparable to a similar idealized model investigated using experimental procedure and numerical calculations published previously by Habiballah (2003).

Stress paths induced to the layered structure: It is interesting to show the stress path followed by the references points during the loading process. The deviator tress q was plotted against the mean values of stresses P applied to each element of the numerical model. Stress paths corresponding to the points A, B, H and I are presented in the Fig. 7. From this figure, it could be argued that points A, B and H undergo during loading process similar stress paths, in the first part of the loading process the value of the deviator stress increase while the value of the mean stresses remains more or less constant, then the deviator stress remains nearly constant while the mean stresses P increase until the full load was reached. This could be explained by the fact that the loading of the point A and its resulting displacement is mainly governed by the vertical component of the stresses applied to the element. However, the stress path of the point I indicate that the soil elements are to different stress paths where the horizontal component of stress applied is more pronounced (Atkinson, 2000).

Results from the investigation of the stress path variation within the structure of the model indicate that a similarity is observed in the stress paths induced to the elements of the asphalt and aggregate layers, however, the soil's elements undergoes completely different stress paths that show the start of a shearing process within the soil mass, similar observations were reported by Benedetto and Corté (2004). This kind of situation could be destabilizing for the materials and could induces relatively important and Permanente deformation's speed. This could explain the fact that rutting phenomena is not only related to the deformations of the top layers of the structure but also governed by the behaviour of the soil foundation. Up to know there are no clear indications of these effects in the literature.

Variations in the aggregate properties: Following the experimental approach used in the reference model and as far as the behaviour of the aggregate's subgrade is concerned, two analyses were considered. In the first the aggregate layer was supposed to be constituted by three

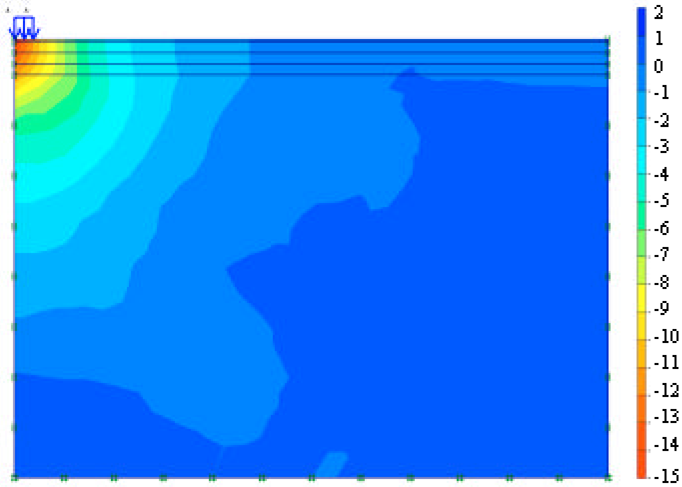

Fig. 5: Predicted vertical displacement of the asphalt surface

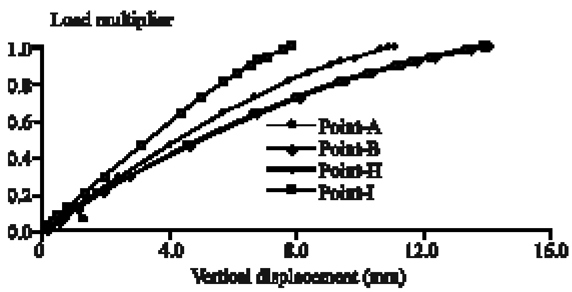

Fig. 6: Vertical displacements of the Layers (selected points)

aggregate's layers with varying elastic rigidity (GNT-Var) and noted respectively GNT 1, GNT 2 and GNT 3, in the second, the aggregate layer was supposed to has a uniform elastic rigidity (GNT-Uni) corresponding to the rigidity of the GNT 1 (Table 1). For both assumptions, the numerical model was run in a monophase calculation by considering a uniform rigidity for the aggregate and variable rigidity.

In Fig. 8, vertical displacement of the point A corresponding to the two approaches is showed. It could be noticed that the displacement of the top surface of the structure is note affected significantly by the variation of the rigidity of the subgrade. Mayorazf (2002) investigated the behaviour of the granular material and showed that its behaviour is much more affected by the layers thicknesses when subjected directly to cyclic loading.

Temperature dependent young modulus for the asphalt layer: For the bituminous (asphalt layer), the model was run many times by considering different values of the Young's modulus of the material. Three temperature dependent modulus were considered for two different thicknesses of the bituminous layers. A 4 and 10 cm. The values of the temperature-dependent Young's modulus considered are presented in Table 2.

The values considered were taken from the Algerian guide for design of new pavement, determined experimentally at frequency of 10 Hz (0.02 s). In Table 3 the names of the numerical models corresponding to each temperature and a thickness of the bituminous layer are presented. For example T20-BB4 stands for a layer a bitumen having thickness of 4 cm with an elastic Young's modulus corresponding to a temperature of 20°C. The results of the analysis are presented in terms of variation of the displacement of the point A versus the loading's multipliers. It could be seen from the Fig. 9 and 10 that the temperature related Young's modulus affects the behaviour mainly in terms of displacement.

Table 2: Young's Modulus variation with temperature

Temperature	Young's modulus	Poisson's ratio
20°C	4000	0.35
25°C	3500	0.35
30°C	2500	0.35

Table 3: Simulations program

Layer thickness (cm)	Temperature	Model name
4	20°C	T20-BB4
	25°C	T25-BB4
	30°C	T30-BB4
10	20°C	T20-BB10
	25°C	T25-BB10
	30°C	T30-BB10

Cyclic loading of the structure: The numerical model developed was then used in a study where the loading

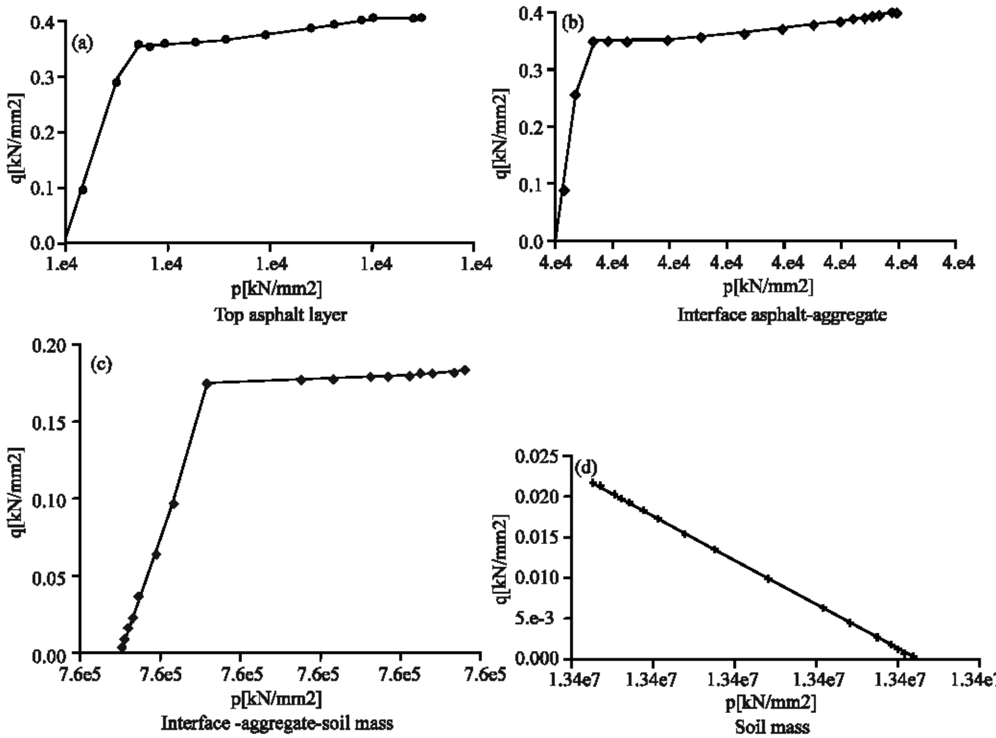

Fig. 7: Stress paths of the points

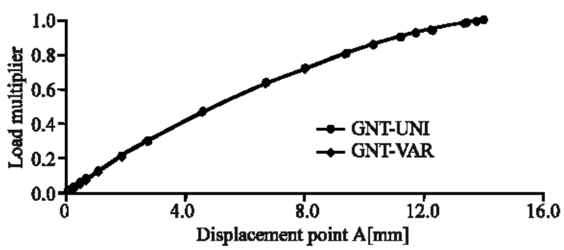

Fig. 8: Effects of the aggregate rigidity

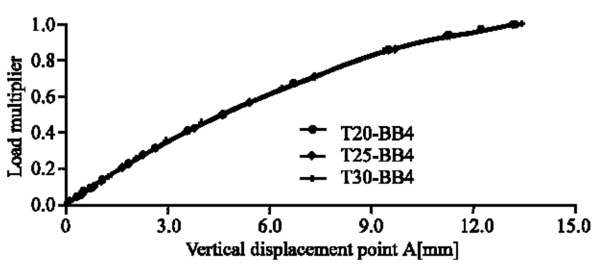

Fig. 9: Temperatures variation effect for the layer BB4

was applied in cyclic form following the procedure explained in this study. The interest of the present simulation was to find out the effect of cyclic loadings

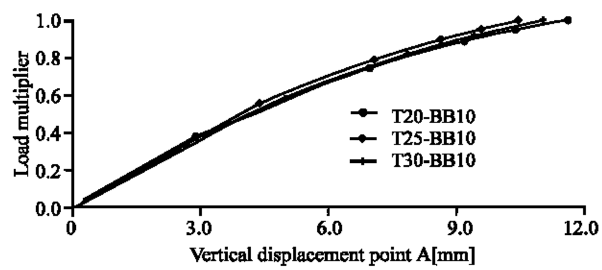

Fig. 10: Temperatures variation effect for the layer BB10

upon the development of irreversible deformation, especially on the top surface of the road (referred herein by the displacement of point A), According to work of Larsen and Ullidtz (1997) irreversible deformations are the major cause of the apparition of rutting. Ten loading-unloading cycles were simulated, the displacement of the point A was computed for different values of load multipliers. The results are presented in Fig. 11, where the displacement was plotted in a logarithmic scale. Following this figure, it could be argued that the repeated loading-unloading of the road in a very small time laps, which simulate the tire's passage effect, induces irreversible deformations to the bituminous layer represented by the vertical displacement of the point A.

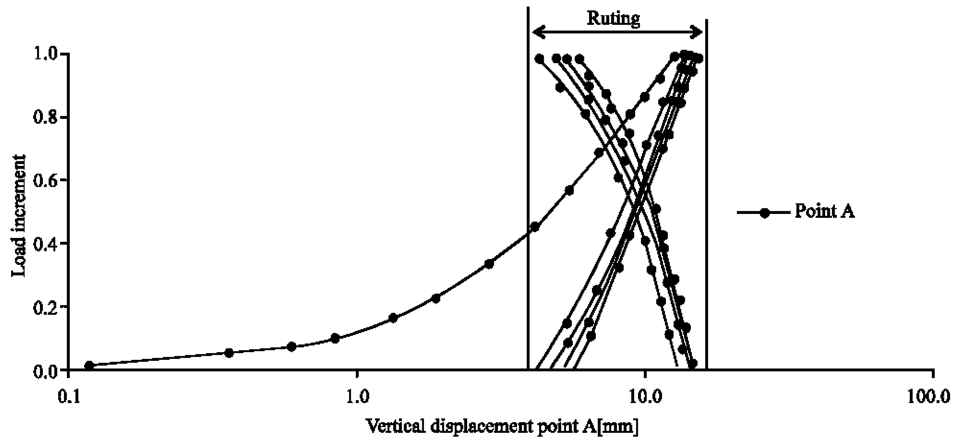

Fig. 11: Irreversible deformations due to cyclic loading

CONCLUSION

This study deals with the behaviour of an idealized road structure observed using a numerical simulation. The investigated layered structure is constituted by the asphalt layer, a layer of aggregate material as sub grade and foundation of soil mass. The numerical model was developed using the Plaxis program, with respect to the geometry, dimensions and boundary and loading conditions of a physical model investigated by a previous researcher.

The stress paths were found to progress in different manners following the position of the elements. The stress path variation within the structure of the model indicate that a similarity is observed in the stress paths induced to the elements of the asphalt and aggregate layers, however, the soil's elements undergoes completely different stress paths that show the start of a shearing process within the soil mass.

The numerical model developed was used in a simulation were some parameters as the Young's modulus of the materials, the temperature effect and the type of loading. Emphasis was put upon the behaviour of the structures when subjected to static and cyclic loadings induced by the normalized stress of a wheel. The irreversible deformation of the road surface, usually called rutting was investigated. Following the results obtained from this simulation, it could be concluded that rutting starts appearing whenever the road is subjected to a cyclic (repeated loading-unloading) which simulate the tire's effect, the deformation remains in an elastic band as long as the load is applied, but after load relief the numerical results highlight the fact that plastic deformations representing the rutting of road surface which characterise a sort of irreversible strains or a start of a localised degradation process.

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