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Effects of combined cyclic vertical and horizontal loading on unsealed airstrips: model study

Les effets de chargement combiné, cyclique, vertical et horizontal sur les pistes d'aterrissage descellé : l'étude de modèle

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ABSTRACT

Unsealed airstrips get easily damaged by excessive permanent deformation due to aircraft wheel loading particularly during aircraft turning at turning nodes. This is primarily due to the effects of combined cyclic vertical and horizontal loading on the pavement at the contact areas and a simplified version of this problem was investigated using a physical model. In particular, the deformational behaviour of a model pavement under concurrent cyclic vertical and horizontal loading on a square pad was studied. Details of this model study and the results are discussed in this paper. The rut depth (RD) and horizontal deformation developed due to the loading was found to increase with the number of load cycles (N) according to the commonly used model: $\log RD = a + b \log N$. This study suggests that the inclusion of a layer of geogrid reinforcement in the pavement structure could substantially reduce the development of both vertical and horizontal permanent deformation.

RÉSUMÉ

Les pistes d'aterrissage descellé facilement se endommagé par la déformation permanente excessive en raison du chargement de roue d'avion particulièrement pendant tourner d'avion à tourner de noeuds. Ceci est principalement en raison des effets de chargement combiné, cyclique, vertical et horizontal sur le trottoir aux secteurs de contact et une version simplifiée de ce problème a été examiné avec l'utilisation d'un modèle physique. En particulier, le comportement de deformation d'un trottoir modèle sous le chargement simultané, cyclique, vertical et horizontal sur un coussin carré a été étudié. Les détails de cette étude modèle et les résultats sont discutés dans ce papier. La profondeur d'ornière (RD) et la déformation horizontale a développé en raison du chargement a été trouvé d'etre augmenter avec le nombre de cycles de chargement (N) selon le modèle ordinairement utilisé: $\log RD = a + b \log N$. Cette étude suggère que l'inclusion d'une couche de renforcement de geogrid dans la structure de trottoir réduise substantiellement le développement de déformation permanente verticale et horizontale.

1 INTRODUCTION

Unsealed airstrips form a vital part of the air transportation network in Australia and other parts of the world for both civilian and military transportation requirements. These airstrips are easily damaged due to excessive permanent deformation and therefore weight and tyre pressure restrictions are commonly imposed to minimize the risk of damage. For example, for the C130 Hercules aircraft that is commonly operated by the Australian Air Force (RAAF) on unsealed pavements, its maximum all up weight (MAUW) is usually limited to 127,800 pounds (58,000 kg) and tyre pressures restricted to 65 psi (450 kPa). Despite such restrictions, failure may still occur, particularly at turning nodes, and this has been a major concern for airfield pavement engineers.

The main cause of failure of airfield pavements from aircraft operations is due to rutting. Rutting in pavements occur due to repeated vertical loads exerted by the aircraft's MAUW in combination with the horizontal forces from braking and rolling. Moreover, the turning motions of aircraft at turning nodes and parking aprons could cause severe damage to the pavement in these areas, as the dual tandem undercarriage configuration of aircrafts such as that of C130 undergoes a skewing motion that transfers shear stresses onto the pavement. These transverse effects induce significant horizontal forces on the pavement and accelerate potential rutting failures.

As unsealed airfield pavements consist of natural soils and aggregates of different sizes and shapes in different proportions constructed by compacting them in layers under different moisture and drainage conditions, their mechanical behaviour under wheel loadings is highly nonlinear and difficult to predict. This difficulty is even further complicated by the type of loadings that is imparted on them by the aircraft operations, particularly at turning nodes, where significant horizontal loading is also imposed. Although there has been several field and laboratory studies on pavement rutting due to straight run of aircrafts or vertical stress pulse on model flexible pavements (e.g., Archilla and Madanat 2000, Gopalakrishnan and Thomson 2003), to the author's knowledge there has not been any study on aircraft turning. Moreover, there has hardly been any research on pavement behaviour under combined vertical and horizontal cyclic loading and the overall objective of this research is to study this problem in a systematic manner.

As a first step in investigating this difficult problem, a physical model testing program was initiated. In particular, the load-deformation behaviour of a model pavement under cyclic vertical and horizontal loading was studied and the results obtained from this ongoing research are reported in this paper. The potential benefits of using a layer of geosynthetic reinforcement within the pavement structure were also briefly examined and the results compared with the unreinforced case.

2 MODEL TESTING

Model tests were carried out in a 1.1 m x 1 m x 0.41 m steel tank available at the Civil Engineering lab of UNSW @ ADFA with the unsealed airfield pavement thickness scaled down to 0.34 m and the contact area of aircraft wheel tire on the pavement was scaled down to 0.13 x 0.13 m square (see Fig. 1).

2.1 Pavement structure

A bulk sample of pavement materials, obtained from an unsealed airstrip at Wagga Wagga, NSW, was used in the model

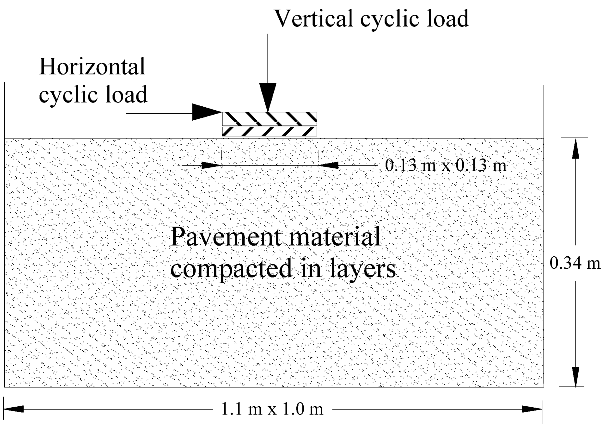

Fig. 1 Schematic of the test arrangement

testing, which was compacted in layers similar to the field, but its overall moisture level was maintained constant at approximately 12.5%. The pavement material was a silty clay with some sand, classified as a CL according to Unified Soil Classification System.

The liquid limit and the plasticity index were determined as 33% and 19% respectively from Atterberg limit tests performed in accordance to Australian Standard (AS 1289.3.2.1 1995) and Australian Standard (AS 1289.3.1.1 1995).The Standard proctor compaction test was performed in accordance to Australian Standard (AS 1289.5.1.1 – 1995) indicated that its maximum dry density (MDD) was 1910 kg/m^3 with a corresponding optimum moisture content of (OMC) of 12.5%.

The pavement material was compacted in 4 layers (i.e. 4 x 85 mm compacted thickness) and its overall density was maintained the same at 2150 kg/m^3 for all the tests reported in this paper. This was achieved by controlling the moisture content at approximately 12.5% and using the same weight of material for each layer and maintaining the thickness of each compacted layer at 85 mm.

2.2 Pavement loading

The magnitude of the horizontal loading on the pavement due to the rolling wheel load could vary depending on factors such as tyre-pavement interface friction and tyre-imprint. Furthermore, significant transverse horizontal forces are likely to be imparted during the turning motion of an aircraft as mentioned previously. This study examines the effects of concurrent vertical and horizontal cyclic loading on the deformational behaviour of the pavement with the horizontal loading nominally set at 20% of the vertical loading.

It is worth noting that the vertical stress pulse is generally the one that is considered for characterizing a pavement material and often with its resilient modulus obtained from triaxial tests on cylindrical samples under cyclic or repeated vertical loading (e.g. Hicks and Monismith 1971, Lekarp et al. 2000). Moreover, while vertical loads applied in a cyclic manner have been extensively researched previously (e.g. Monismith et al. 1975, Chen 1999, Chai and Miura 2002, Kim et al. 2003), there has not been any study reported in the literature on the combined effects of cyclic vertical and horizontal loading as mentioned previously.

The duration between aircraft cycling over a particular area will obviously vary depending on the number of movements on the airfield. Even at the busiest airfield, aircraft may traverse over the same area only every 60 seconds. For simplicity, a loading frequency of 1 cycle per min. was used in this study.

Wheel loading was applied through a 130 mm x 130 mm x 30 mm steel loading plate, but to simulate the tire-pavement interaction that takes place in the field as closely as possible, a 6 mm thick rubber (hardness 62 Shore A, similar to that of a C130 aircraft tyre material) was glued to its base. In pavement design, the tyre-pavement contact stress is usually assumed to be the tyre pressure. The maximum tyre pressure of 450 kPa allowed for a C130 aircraft on unsealed pavements was used in this model study.

A sinusoidal type vertical and horizontal cyclic loadings in-phase was applied using actuators and the load-deformation-time response was monitored for over 1000 cycles. Two LVDTs were installed to measure the vertical displacements and another two LVDTs were installed to measure the horizontal displacements (see Fig. 2). Dynamically rated load cells were installed in the loading assembly to measure the applied vertical and horizontal loads. Load application and the collection of load - displacement data were carried out using a computer control / data acquisition system. The measured vertical and horizontal stress applications with time is plotted in Fig. 3.

Fig. 2: View of the loading arrangement with the LVDTs in place

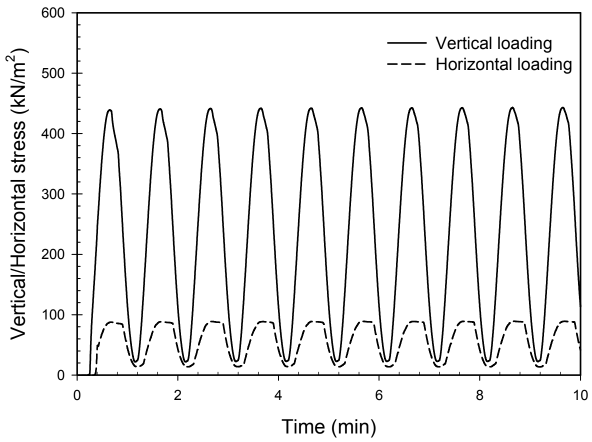

Fig. 3 Applied vertical and horizontal loadings

3 RESULTS AND DISCUSSION

Rutting in a flexible pavement is a load-induced permanent deformation caused by a combination of densification and shear-related deformation (White et al. 2002). Rutting in pavement materials develops gradually with increasing number of load applications (Sousa et al. 1991, Gopalakrishnan and Thomson, 2003 among others). To examine the accumulation of permanent deformation with load repetitions, the variation of rut depth (i.e. vertical displacement at the surface of the pavement at the loading pad) with the number of loading cycles obtained from multiple tests carried out in this model study is plotted in Fig. 4. Although there is some scatter in the data, this study also shows

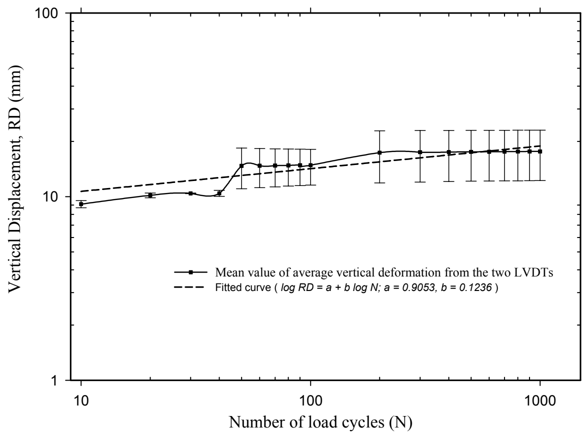

Fig. 4 Variation of vertical displacement with number of load cycles

the general trend of increasing permanent vertical displacement with the number of loading cycles.

There are a number of analytically and statistically-based, mechanistic or mechanistic-empirical, and phenomenological models proposed in the literature to predict the permanent deformation in asphaltic concrete, granular materials and soils (Gopalakrishnan and Thomson 2003). A relatively simple model (e.g. NCHRP 1-26 1990, Thomson and Nauman 1993, Gopalakrishnan and Thomson 2003) that is commonly used for flexible pavement materials is of the form:

$$\log RD = a + b \log N \qquad (1)$$

or $RD = A N^{b}$

where, RD = rut depth, N = number of load cycles and a and b are experimentally determined factors and A = *antilog of a*.

The response of vertical displacement with the number of cycles obtained from this model study also agrees well with the above model and, from regression analysis of the data, the constants were determined as $a = 0.9053$ and $b = 0.1236$.

The NCHRP 1-26 (1990) study indicated that, for reasonable stress states, the b term in the model is in the range of 0.1 and 0.2 and the value of $b = 0.1236$ obtained in this model study also supports this general behaviour.

The variation of the horizontal displacement with the number of cycles obtained from multiple tests in this investigation is plotted in Fig. 5. The scatter of the horizontal displacement data was significantly more than that of the vertical displacement but it also showed the general trend of increasing permanent horizontal displacement with number of load cycles. This response was fitted with a similar equation as that for the rut depth, again of the form:

$$\log HD = c + d \log N \qquad (2)$$

or $HD = C N^{d}$

where, HD = horizontal displacement, N = number of load cycles, c and d are experimentally determined factors and C = *antilog of c*. Again, by regression analysis, the constants c and d were determined as *0.8517* and *0.0915,* respectively.

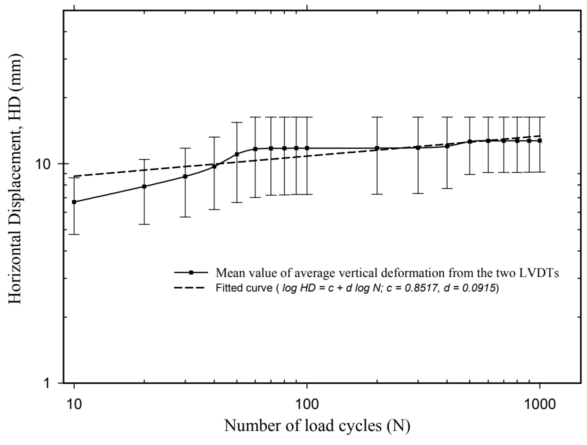

Fig. 5 Variation of horizontal displacement with number of load cycles

To study the effects of using this type geosynthetic reinforcement, tests were carried out with a layer of Tensar SS2 geogrid included in the pavement structure at a depth of 85 mm from the surface. The depth of 85 mm (i.e., *D/B* ratio of 0.65, where D = depth of geogrid reinforcement, B = width of loading pad) was chosen on the basis of bearing capacity of footings on geogrid reinforced sloped fills reported by Selvadurai and Gnanendran (1989), who found that the maximum increase in bearing capacity occurs when the reinforcement layer is included at a depth ranging between 0.5 and 0.9 times the width of foundation.

The variation of permanent vertical deformation with the number of loading cycles obtained from multiple tests carried out in this model study, with a layer of Tensar SS2 geogrid reinforcement included in the pavement structure, is plotted in Fig. 6. It can be seen that the scatter in the data observed previously for the unreinforced case, has nearly vanished and this study also shows the general trend of increasing permanent vertical displacement with the number of loading cycles. The model described by Eqn. (1) used earlier for the unreinforced case, was also fitted for this response and the constants were determined as $a = 0.9715$ and $b = 0.0523$.

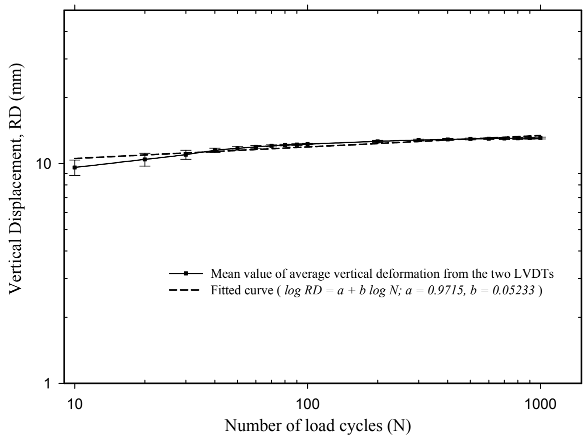

Fig. 6 Vertical displacement vs. number of load cycles – reinforced case

It is interesting to note that the slope of the fitted line has decreased indicating that the geogrid reinforcement has suppressed the accumulation of permanent deformation (or pavement rutting) quite substantially. The value of b has decreased from 0.1236 to 0.0523 indicating a decrease of about 58% suggesting that the inclusion of a layer of geogrid reinforcement has the beneficial effect of decreasing the permanent deformation (or rutting) of the pavement by approximately that amount.

The variation of the horizontal displacement with number of load cycles, for the case of Tensar SS2 geogrid reinforcement layer included in the pavement structure, is plotted in Fig. 7. The scatter of the horizontal displacement data was significantly greater than that for the vertical displacement, but considerably less than that of the unreinforced case discussed earlier. The horizontal displacement again shows the general trend of increasing permanent horizontal displacement with the number of load cycles. This response was fitted with Eqn. (2), as before, and the constants were determined as $c = 0.8509$ and $d = 0.0634$.

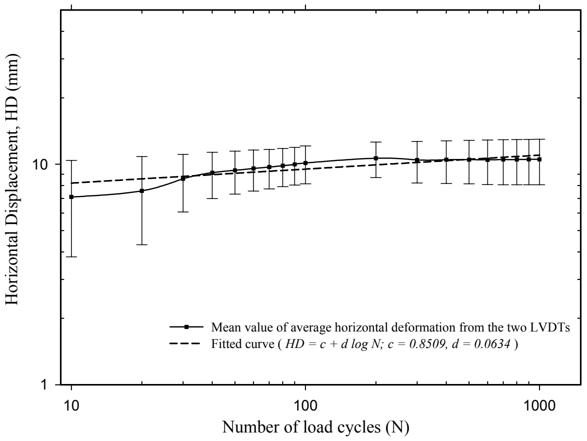

Fig. 7 Horizontal displacement vs. number of load cycles – reinforced case

Similar to the earlier observation concerning pavement rutting, it is noted that the slope of the fitted line has decreased, indicating that the geogrid reinforcement has significantly suppressed the accumulation of permanent horizontal deformation. The value of the slope *d* has decreased from 0.0915 to 0.0634 indicating a decrease of about 31% suggesting that the inclusion of a layer of geogrid reinforcement has the potential benefit of decreasing the permanent horizontal deformation by approximately that amount.

4 SUMMARY AND CONCLUSIONS

As unsealed airfield pavements are often constructed with natural soils and aggregates by compacting them in layers under different field conditions, their deformational behaviour under wheel loading is highly nonlinear and difficult to predict. These airstrips are easily damaged due to excessive permanent deformation, particularly during aircraft turning at turning nodes. This is primarily due to the effects of combined cyclic vertical and horizontal loading on the pavement at the contact areas and this problem was investigated using a physical model and the results are discussed in this paper.

Model tests were carried out with the unsealed airfield pavement thickness scaled down to 0.34 m and the wheel loading was applied through 130 x 130 mm square metal plate with tyre-type rubber base. A bulk sample from a typical airstrip was used as the pavement material with its density and moisture maintained constant and concurrent in-phase vertical (450 kPa) and horizontal (20% of vertical) sinusoidal-type cyclic loadings (1 cycle/min) were applied to examine the gradual development of vertical and horizontal deformations.

The rut depth (RD) that was developed due to the loading was found to increase with the number of cycles (N) and satisfied the commonly used model: $\log RD = a + b \log N$ with $a = 0.9053$ and $b = 0.1236$. The horizontal displacement (HD) also increased with number of load cycles and satisfied a similar equation: $\log HD = c + d \log N$ with $c = 0.8517$ and $d = 0.0915$.

The potential benefits of using a layer of Tensar SS2 geogrid reinforcement within the pavement structure at $D/B = 0.65$, where D = depth of geogrid reinforcement and B = width of loading pad, were also briefly examined and the results compared with the unreinforced case.

Equations similar to those used for the unreinforced case were fitted for the geogrid reinforced case also and the constants were determined as $a = 0.9715$ and $b = 0.0523$ for the rut depth variation and $c = 0.8509$ and $d = 0.0634$ for the horizontal displacement variation with number of load cycles. The decreases in the magnitudes of *b* and *d* indicated that there were considerable benefits to be derived from using geogrid reinforcement in the pavement structure for reducing the permanent deformation with load repetitions. This study suggests that the inclusion of a layer of geogrid reinforcement could decrease the pavement rutting by about 58%. Moreover, the geogrid reinforcement has the potential benefit of decreasing the permanent horizontal deformation also by about 31%.

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