Finite element analysis of footwear and ground interaction

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FINITE ELEMENT ANALYSIS OF FOOTWEAR AND GROUND INTERACTION

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ABSTRACT

Good slip resistant tread patterns of outer-sole of military boot are vital to minimize the risk or severity of slip in combat and physical training situations. A series of non-linear, three-dimensional finite element analyses of footwear and ground interaction based upon the Drucker-Prager elastic-perfectly plastic material model was investigated. This study was aimed at how plastic failure of soil mass develops between the relative rigid boot outer-sole (cleats) and soft soil surfaces. The solid interaction models between rigid outer-sole of boot with five different typical tread patterns and soft soil surfaces have been modelled in ANSYS finite element code. The results were analysed and the suitable model was identified to reduce the failure.

1. INTRODUCTION

Military boots are designed to prevent the soft tissue and skeletal structure of the feet from damage under heavy usage. Good slip resistant tread patterns of the outer-sole are vital to minimize the risk or severity of slip under demanding conditions most likely to result in accidents. However, boot design should also offer the customer flexibility, comfort, and shock absorption, be lightweight and be able to operate regardless of the ground surface texture and various weather conditions.

The issue of footwear and ground interaction investigated in this research can be classified as a traditional stability problem. Solutions to these problems are often obtained using the theory of perfect plasticity. Therefore, elastic-perfectly plastic theory was adopted in this study and the Drucker-Prager (DP) material model was chosen to model the soil properties.

There is known that little work existing on the topic of foot ground interaction with soft surfaces, in particular using numerical modelling methods. However, there are numerous research works on some relevant domains, such as soil-tillage tools interaction, soil-wheel interaction and soil-structure interaction, etc. For instance, Araya and Gao[1] (1995) reported on their work in which three-dimensional FE analysis of a subsoiler cutting with pressurised air injection was conducted by employing DP harden material model without consideration of friction force. Saliba[2] (1989) undertook elastic-viscoplastic FE modelling for tire/soil interaction and Mouazen and Nemenyi[3, 4] (1999) published their works by adopting DP model for problem of soil-tillage tools interaction.

2. Finite Element Model

The commercially available ANSYS finite element program was used to perform analyses on five different tread patterns. The geometrical models were based upon the coordinates of real military boots. The modelling process included geometrical shape construction; mesh generation and application of boundary conditions and loading. The outer-sole of all boot models are shown in Fig. 1.

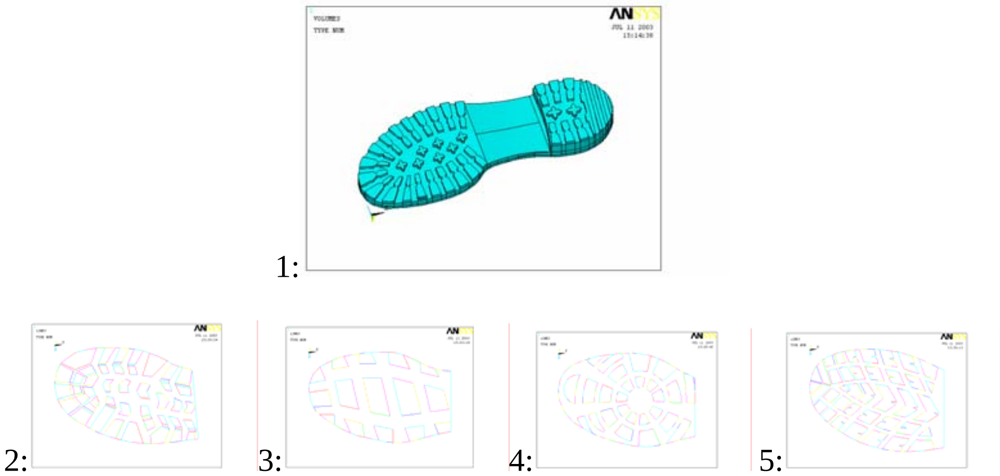

Fig. 1. The outer sole of 5 tread patterns

Two three-dimensional FEM meshes, for each model, were separately generated for the soil domain under either forepart of the outer-sole of the boot or heel of it. The soil meshes were constructed using three-dimensional eight noded solid elements. Total of 4325 nodes and 3186 elements were used to model the soil under the forepart having the first tread pattern.

The outer-sole of boot was assumed to be a rigid object even though it actually has some deformation under loading. Therefore, its Young's modulus is much greater than that of the soil. The soil was selected as sandy loam[3].

Vertical compressive and transverse shear forces are applied to the ground via the footwear during the process of gait. For transient analysis, the vertical compressive force is mainly a result of the weight of the soldier's body and ammunition in his backpack.

Although the weight of the human body is not linearly distributed over the inner sole in a particular time instant and position of gait[5] the vertical compressive force distribution applied to the soft ground via the outer-sole of boot is more even than the distribution of body weight over the inner sole, owing to rigidity of outer-sole. For this study, the particular time and position of gait was based upon two modes:

a) Forepart of boot slips backward due to plastic failure of soil with whole forepart in contact with the soil surface and full sinkage with compressed soil.

b) The heel of boot slips forward due to plastic failure of soil with whole heel in contact with the soil surface and full sinkage with compressed soil.

The most promising tests applied a vertical force equivalent to at least 50% of bodyweight, that is, 400 to 830 N[6]. For this study, mode a) vertical force is 50%* (800N+200N) considering 200N ammunition weight, and b) vertical force is 80%* (800N+200N) considering 200N ammunition weight and more of the bodyweight distributed on heel of the fore foot during the process of gait.

The transverse force consists of a shear force due to the vertical areas of cleats and friction forces due to contact between the cleats and the soil surfaces in horizontal direction. For this stage of study, the interface friction between the cleats and the soil surface is assumed to be zero, so the transverse force is only composed of a shear force. For this analysis, mode a) the shear force is 0.35 of the vertical force, and b) shear force is 0.5 of the vertical force.

3. MODELLING RESULTS

Non-linear finite element analyses for total five different tread patterns were carried out and traction forces effect, displacements of the soil are evaluated and validated by experimental results.

3.1 Traction forces

The effects of traction forces are an important factor in judging how good one kind of tread patterns resists slip. After obtaining the numerical solutions of the five tread patterns, the effects of the traction forces can be evaluated by means of reaction forces. From Fig. 2, it is obvious that the reaction force of the first tread patterns is greater than the others. Therefore, the first tread pattern demonstrates the best traction forces effects among these five tread patterns, under the same loading conditions. The second tread patterns show the poorest traction force effects than the others.

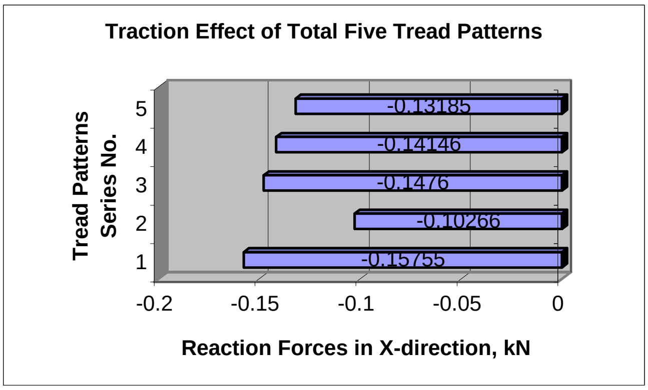

Fig. 2. Traction effect evaluated by reaction forces in X direction

3.2 Soil deformation

The soil deformation is complex in nature because of the complex tread patterns geometry and transverse loading conditions. From Fig. 3, it can be seen that the greatest soil displacement occurs within soil mass contacted by the tread patterns or nearby and larger deformation regions are concentrated on the areas contacted by cleats. These cleats are located at rear part of forepart of outer-sole.

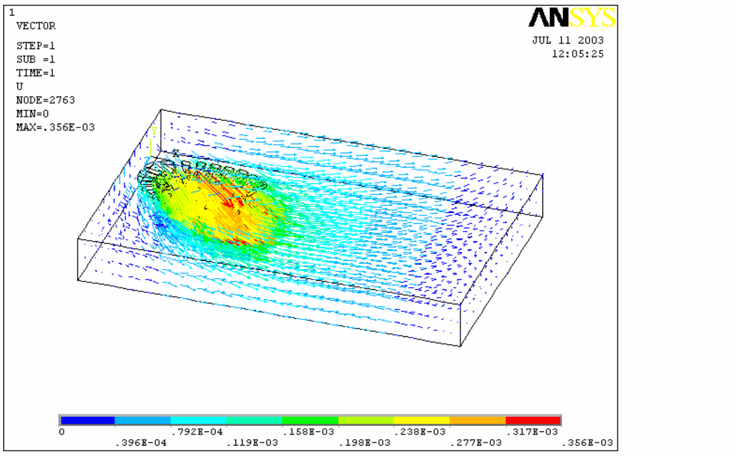

Fig. 3. Soil displacement vectors for the first tread patterns

3.3 Experimental validation

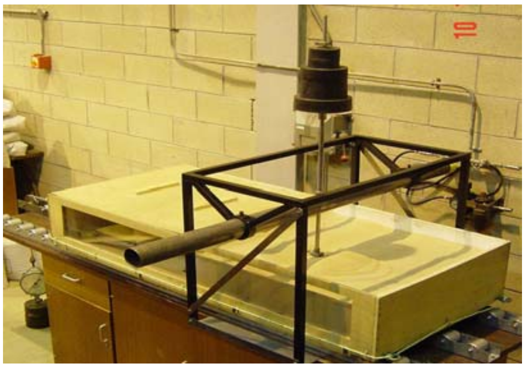

Fig. 4. Experimental validation carried out in the soil tray test

An experimental rig was used to measure the soil failure distance as well as the upward soil movements for the first tread pattern. A comparison of the measured dimensions of soil failure in the experiment and predicated results by the FE modelling is summarized in Table 2.

Table 2 Comparison between FEM and soil tray test

Failure distances / Items	Forward soil failure distance (f), mm	Lateral soil failure distance (l), mm	Max. upward soil movement(v), mm
Experiment	360	350	30
FE modelling	365	390	32

4. CONCLUSIONS

The Finite Element Method was used to establish a methodology to judge how performance is for a particular tread patterns design.

A series of non-linear, three-dimensional FE modellings have been successfully conducted to evaluate the traction forces, soil deformation and failure distance for total five typical tread patterns.

From FE analyses, the first tread patterns shows the best traction force effects to resist slip in the gaiting direction. In general, the significant soil displacements occur in the regions contacted by cleats at rear part of the tread patterns and zones under central part of the tread patterns.

The FE numerical modelling provided a good agreement with the experimental results for soil failure pattern and the forward soil failure distance as well as the maximum upward soil movements.

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REFERENCES

1. Araya K., Gao R., A Non-linear Three-Dimensional Finite Element Analysis of Subsoiler Cutting with Pressurized Air Injection, *J. Agric. Engng. Res.* (1995) **61**, 115-128.
2. Saliba J. E., Elastic-Viscoplastic Finite-Element Program for Modelling Tire/Soil Interaction, J. AIRCRAFT, Vol. 27, No. 4. Copyright © 1989 American Institute of Aeronautical and Astronautics, Inc.
3. Mouazen A. M.; Nemenyi M., Tillage Tool Design by the Finite Element Method: Part 1. Finite Element Modelling of Soil Plastic Behaviour, *J. Agric. Engng Res.* (1999) **72**, 37-51.
4. Mouazen A. M.; Nemenyi M., etc., Tillage Tool Design by the Finite Element Method: Part 2. Experimental Validation of the Finite Element Results with Soil Bin Test, *J. Agric. Engng. Res.* (1999) **72**, 53-58.
5. Zhu H., Maalej N., etc., An Umbilical Data-Acquisition System for Measuring Pressures Between the Foot and Shoe, *IEEE Transactions on Biomedical Engineering*, Vol. **37**, No. **9**, September 1990, Page 908-911.
6. Wilson, M. P., “Development of SATRA Slip Test and Tread Design Guideliones,” *Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, ASTM STP 1103,* B. E. Gray, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 113-123.