In-place determination of topsoil shear properties for off road mobility

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Abtract :

The study of the off-road mobility for a vehicle consists in the study of its drawbar pull on a given sol and can be calculated by models such the Janosi-Hanamoto's model which depend on the soils mechanic parameters like the angle of friction and the cohesion. These parameters result generally from shear tests. The annular shear test is often used to estimate the soil shearing for mobility studies. Other shear test is the translation shear test which consists in the translation at a constant speed of a loaded plate with a smooth interface or with grousers. This article aims to present the validation of the translation shear test for the study of the shearing of the granular surface soils and the methodology to apply to link this operational test to the efforts measured during full-scale tests. An experimental device was developed to perform superficial translation shear tests of a loaded plate at slow speed or fast speed to obtain the shearing forces.

Résumé :

L'étude de la mobilité de surface d'un véhicule passe par l'étude de la traficabilité d'un sol donné. Cette traficabilité peut être calculée par des modèles, comme le modèle de Janosi-Hanamoto, qui dépendent des paramètres mécaniques des sols comme l'angle de frottement et la cohésion. Ces paramètres résultent généralement d'essais de cisaillement. L'essai annulaire de cisaillement est souvent employé pour caractériser le sol dans les études de mobilité. Un autre essai est l'essai de cisaillement de traction qui consiste en une traction, à une vitesse constante, d'un plat chargé avec une interface douce ou rugueuse. Cet article vise à présenter la validation de l'essai de cisaillement de traction pour l'étude du cisaillement des sols granulaires et la méthodologie mise en œuvre pour relier les résultats de cet essai opérationnel aux efforts mesurés en vraie grandeur. Un dispositif expérimental a été développé pour réaliser les essais de traction de surface d'un plat chargé à vitesse lente ou rapide. Il permet de déterminer les forces de cisaillement à l'interface.

Key-words :

Granular topsoil ; shearing ; modelling.

1 Introduction

The movement of a vehicle on a soil induces two types of opposite forces. In off-road conditions, the running gear, composed of tracks or wheels, sinks into the surface soil and encounters obstacles which cause a resistance to the movement. At the same time, it provides a tractive effort making it possible for the vehicle to advance. This effort results from the transmission of the engine torque to the soil. The study of these resistant and driving forces is necessary to model the mobility of a vehicle.

Within an investigation of a global mechanical device for mine clearance, full-scale tests were carried out on various soils to identify the mechanisms influencing the mobility of a vehicle and to validate the models developed. In order to reproduce and to study the two principal mechanisms, a prototype experimental device was developed allowing sinkage tests and translation shear tests (Benoit, 2002) (Benoit *et al.* 2003) (Gotteland & Benoit, 2006). This can be effective to model the tractive effort of a vehicle provided that the phenomena brought into play are well understood.

This article reports the validation of the translation shear test for the study of granular top soil shearing. The experimental study is presented: the prototype device allowing the translation shear tests and the granular soil tested. The results are presented and phenomena are modelled to understand the soil's failure mechanism.

2 Experimental methods and soil tested

2.1 Experimental device

In order to reproduce the mechanisms associated with soil shearing by the running gear, a prototype experimental device was developed (Upadhyaya *et al.*, 1993; Benoit, 2002) providing a shear test by the translation of a plate (see FIG. 1).

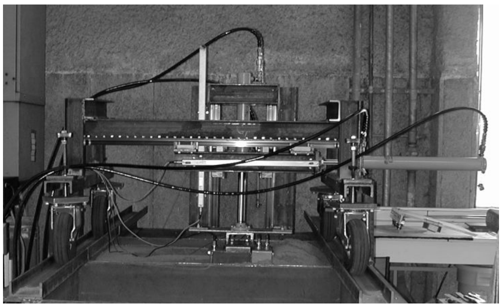

FIG. 1 – Translation shear test with the prototype experimental device

This test is carried out with the translation on approximately 400 mm, at a slow constant speed (~23 mm.min^{-1}) or fast (~840 mm.min^{-1}), with an instrumented shear head (see FIG. 2) loaded vertically. Five parameters are measured simultaneously: horizontal displacement j, vertical displacement (sinkage) z, vertical load N, total horizontal force T_{total}, bulldozing force T_{bull}. The shear force T is calculated as the difference between the total horizontal force and bulldozing force ($T = T_{total} - T_{bull}$). Horizontal and vertical displacements are measured. The shear plate (length L = 340 mm, width l = 240 mm) can have a smooth interface to represent the soil-steel friction, a bin interface to confine the soil inside and reproduce a soil-soil friction, and an interface with grousers to study their influence.

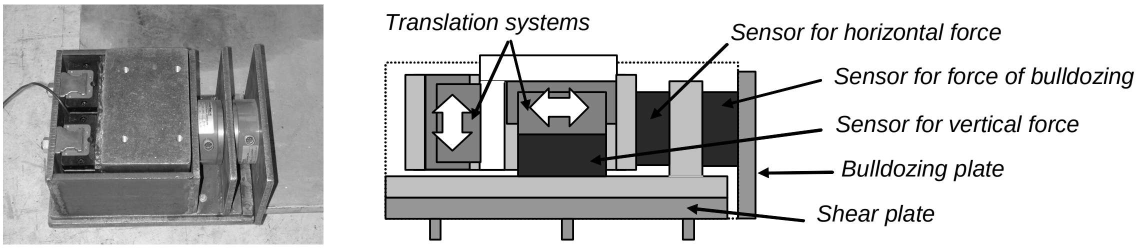

FIG. 2 – Instrumented shear head

2.2. Tested soil and experimental protocols

The translation shear tests were carried out on 0/5-mm sand. Extracted underwater, it has less than 0.3% fine particles (<80 mm) and 85% of particles smaller than 2 mm. Its low fines content makes it insensitive to water. The primarily siliceous grains are angular. The French GTR classification (GTR, 1992) of this sand is D1 with a friction angle close to 33° and a cohesion close to zero (<1 kPa). The behaviour of this sand can be considered as purely frictional. For the presented translation shear tests, the device is fixed on a 1-m^3 bin (height 0.8 m, width 1 m, length 1.3 m). The sand set-up is defined by a protocol so that the bulk density can be reproduced. The average bulk unit weight obtained is 16.3 kN.m^{-3}. The water content was also controlled by four samples per layer that were dried and weighed (see Table 1).

Table 1– Properties of D1 sand

D1 sand	**Properties**	**Mean value**	**Variability**
Mechanical characteristics (triaxial tests, direct shear tests)	Friction angle Cohesion *c*	33° <1 kPa	6% -
(translation shear tests)	Water content *w* Bulk unit weight	1.2% 16.3 kN.m^{-3}	6% 5%

2.3. Experimental results

Two phenomena were studied: the relationship between the normal load *N* and the shear force *T*, and the sinkage of the instrumented shear head induced by the shearing of the D1 sand. Twenty-four translation shear tests were carried out on sand, four per modality. The shear plate used was the alveolate plate to reproduce a soil-soil friction necessary for determining the mechanical parameters of the sand. The normal loads *N* tested were 4.1 kN, 8.2 kN and 12.3 kN (normal stress = 50, 100 and 150 kPa, respectively). The force-displacement curves and the sinkage-displacement curves showed good reproducibility, confirming the relevance of the protocol's set-up (see FIG. 3).

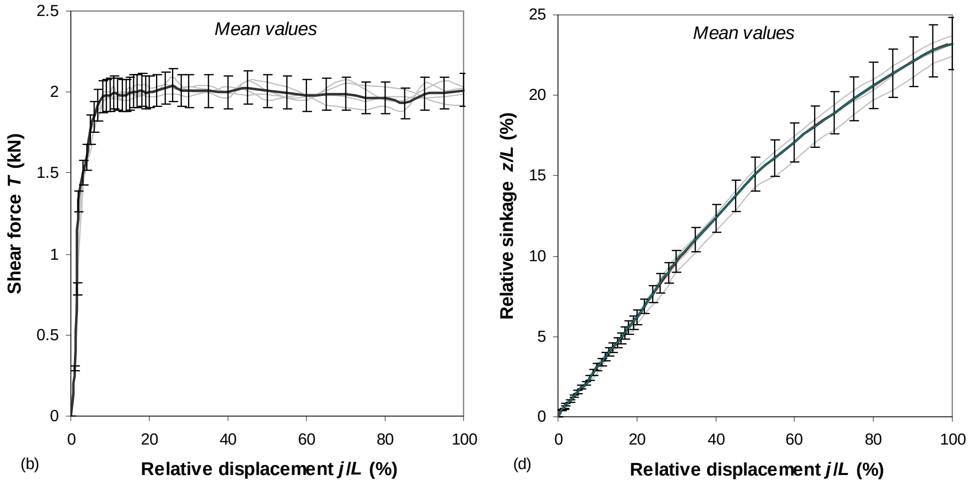

FIG. 3 – Translation shear test, (normal stress 50 kPa, slow speed = 23 mm.min^{-1}): (b) mean values (j/L, T) curve, (d) mean values (j/L, z/L) curve

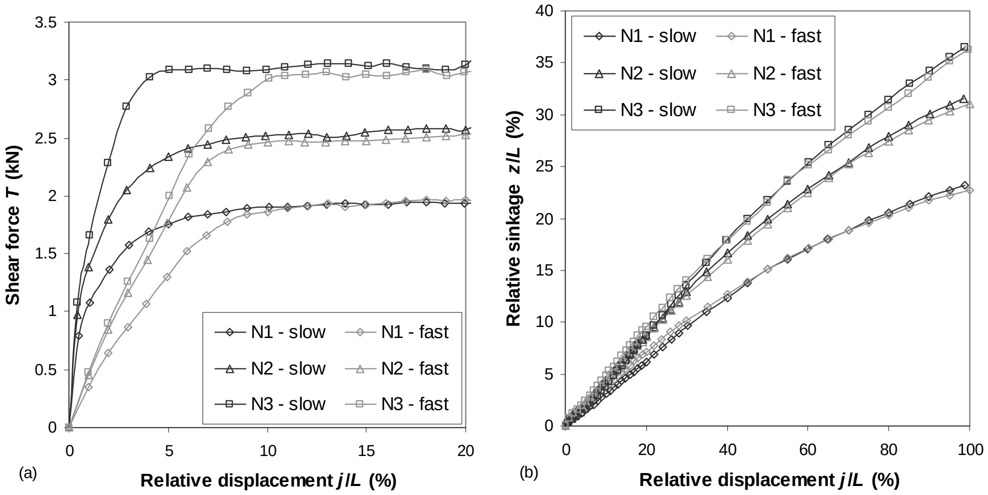

FIG. 4 – Influence of the translation speed (N1 = 50 kPa, N2 = 100 kPa, N3 = 150 kPa): (a) mean values (j/L, T) curves, (b) mean values (j/L, z/L) curves

The same shapes of the average curves were found for the other normal loads and translation speeds (see FIG. 4). Changing the translation speed influenced the initial slope of the curves (*j/L, T*) (see FIG. 4).

3. Modelling and Calculation of soil parameters

3.1. Equations of the problem

The failure mechanism can be analytically approached by geometry with two rigid blocks (see FIG. 5). This method, where blocks are widespread for stability calculations, is cinematically acceptable according to Janosi *et al.* (1961).

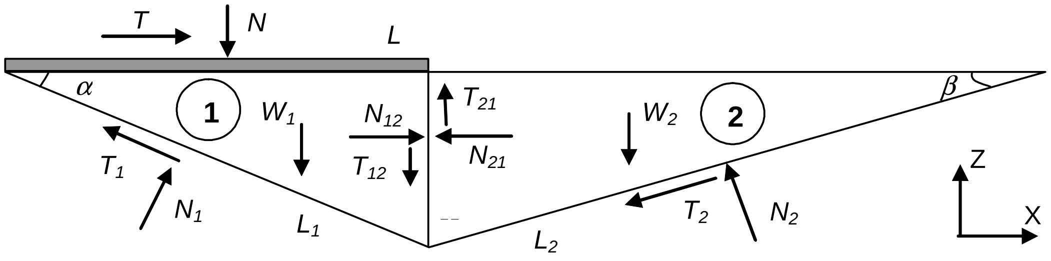

FIG. 5 – Failure mechanism with two rigid blocks

Using the identified geometry, the force balance can be put into an equation to carry out an ultimate equilibrium calculation, i.e. by assuming that the limit of soil resistance is reached along the lines. Solving the problem leads to a system of two equations with two unknown factors. The force balance provides a relation between forces *N* and *T* on the plate, the soil parameters and the geometrical parameters.

3.2. Parametric study

In order to evaluate the influence of each parameter compared to the others, a parametric study was carried out. Some parameters were fixed (friction angle = 33°, null cohesion *c*, bulk unit weight = 16.3 kN.m^{-3}). The plate length *L* was 340 mm. Then the horizontal force *T* depended only on angles α and β and on the normal load *N* equal to 4.1, 8.2 or 12.3 kN. As the experimental observations confirmed the proximity between the values of the two angles α and β, the assumption $\alpha = \beta$ was made. The calculated forces *T* were compared with the experimental data (see FIG. 6). In D1 sand and for a normal load $N = 4.1$ kN, $N = 8.2$ kN and 12.3 kN, the value of the calculated force *T* was respectively equal to 1.9 kN, 2.5 kN and 3.1 kN for an angle α = 11°, 18° and 22°. The angle α between the failure line and the horizontal line increased with normal load *N* applied to the shear plate.

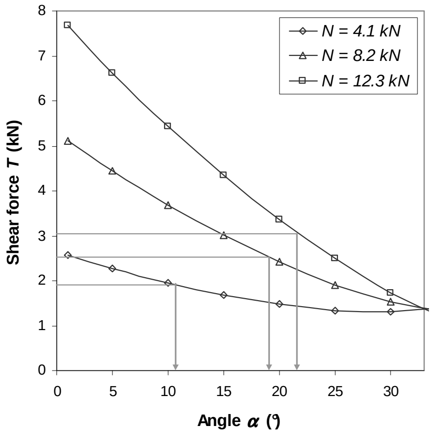

FIG. 6 – Determination of angle α for different normal loads N

The sinkage induced by soil shearing was observed in all the experimental tests. Two combined mechanisms caused this phenomenon. The first is a variation of the stress distribution below the plate involving a modification of the bulk unit weight of the soil. The second mechanism is the sinkage of the plate depending on the failure line induced by its load. In the shear tests carried out on D1 sand, the sinkage induced by the horizontal displacement was quasi linear. In experiments, the shear plate followed a slip surface with an angle that can be evaluated with the measured sinkage ($\tan\alpha = z/L$). The results of the calculations of the angle α for various normal loads *N* highlight the similarity with the experimental data of the sinkage induced by shearing. The experimental values of the relative sinkage z/L for a normal load *N* of 4.1 kN, 8.2 kN and 12.3 kN were equal to 23%, 31% and 36%, respectively (see FIG. 7).

3.3. Calculation of the soil parameters

One of the advantages of shear tests is that they provide soil mechanics parameters and in particular the friction angle and the cohesion *c* used by the Mohr-Coulomb yield criterion. Calculating these parameters requires that the maximum shear stress on the failure surface be determined. In this type of test, the shear force *T* divided by the plate surface *S* does not correspond to the maximum shear stress. The T_m/S values show a linear behaviour but are not superimposed with the Coulomb straight line corresponding to the values of the D1 sand, ϕ = 33° and $c = 0$ (see FIG. 7). The analysis of the failure mechanism provides a Mohr-Coulomb behaviour by locating the failure lines and therefore specifying the value of the maximum shear stress. With angle α and parameters *T*, *N*, bulk unit weight, β, *L*, and *c* described previously, the friction angle of granular topsoil can be calculated using equilibrium calculation.

4. Conclusion

A prototype experimental device allows laboratory (and in-situ shear tests) by translation of a plate at slow or fast speed, representative of traditional soil mechanics tests and the real kinetics of the slip under a vehicle's running gear, respectively. The tests presented were performed in the laboratory on clean sand. The protocol to set up the soil allows a good reproducibility of the tests. The main results are: 1) the shear-displacement curves had no peak state so that the Janosi-Hanamoto (1961) approach could be used, 2) the tests showed a significant sinkage, 3) the increase in the translation speed induced a decrease in the initial slope of the curve, 4) the critical state force was not modified by the speed (i.e cohesion and friction angle were not affected by the translation speed). In a first approximation, an analytical approach of this mechanism related the geometry of the slip line to the mechanical parameters of the granular soil, is used. This approach is based on the method of calculation to the ultimate equilibrium for two rigid blocks.

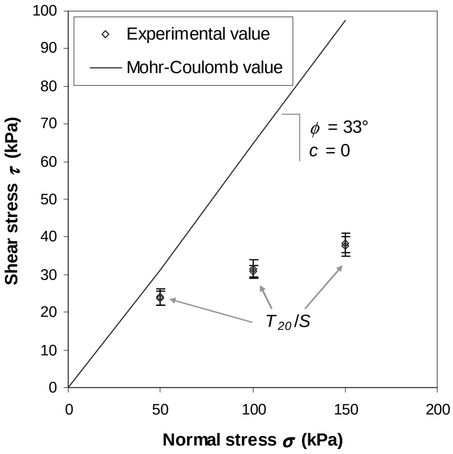

FIG. 7 – Experimental results and Coulomb straight line in the Mohr plan

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