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THE INFLUENCE OF DYNAMIC SOIL PARAMETERS ON TRACTIVE PERFORMANCE OF OFF-ROAD UNDERCARRIAGES

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Abstract

Design of optimal machines and off-road vehicles requires, among others the knowledge of dynamic interaction of the traction components with soil. Due to the lack of constitutive equation of soil, in practice the research centres worldwide use the so-called process analogues, i.e. the special test devices. These devices however are used only for static tests and are burdened with the scale error. They are also often subject to the so-called wall effect and bulldozing effect.

The research conducted in The Department of Off-Road Machine and Vehicle Engineering has shown that in the dynamic interaction of traction components or working tools with soil a substantial strengthening of cohesive soils, which can cause even several times increase in their strength, which significantly changes the commonly used relationships based on static tests.

In the article, the unique on the international scale test equipment developed in the Department of Off-Road Machine and Vehicle Engineering for experimental identification of dynamic soil strength parameters is shown. In addition, the initial results of the tests obtained with this device in the laboratory and in situ are presented. The practical impact of dynamic strengthening of soil are presented as opposite to the conventional methods, at the example of traction forces generated by the tracked undercarriage estimated by virtue of an undercarriage analytical model.

Keywords: *tracked undercarriage, terramechanics, soil dynamics, off-road vehicles*

1. Introduction

Nowadays, more and more industrial branches use off-road vehicles or earth-moving machines. Primarily these are construction, agriculture, mining and military industries. The growing requirements concerning mobility of off-road vehicles and working machines force on the designers the constant search for better solutions offering higher speeds and higher traction forces at lower ground destruction and lower fuel consumption. Designing and optimising of these vehicles require knowledge of cooperation phenomena of traction components or working tools with ground. For describing of these phenomena certain test indicators are used, the so-called process analogues, coming from experimental ground tests and implemented by means of various measuring devices. Most of the standardised devices have been created for the needs of civil engineering soil mechanics, where load conditions seldom correspond to those existing under the tractive components of vehicles. The study results available in the world literature show how significant differences in the results are obtained while using standard and non-standard measurement methods [4, 6, 7, 9]. One of the most important phenomena, which influences the differences is ground strengthening as a result of dynamic deformation (Fig. 1). Familiarity with this phenomenon is particularly important against the current trend appearing in the off-road vehicles and working machines such as the increase in their mobility. Besides that, the existing methods have been burdened with errors of scale, the so-called bulldozing effect and the wall effect [3]. Moreover, none of the previous publications defines what method and what device is the best. Of course, it will depend on the needs for which the tests are performed and the requirements for the method (the costs and time of the studies, the necessity of training the operators, ease of the results processing, accuracy of measurements etc.). Based on the analysis of the available literature, the most important parameters of the devices and measurement methods have been determined which affect the values of the achieved results. They were used in designing the new measuring device presented below.

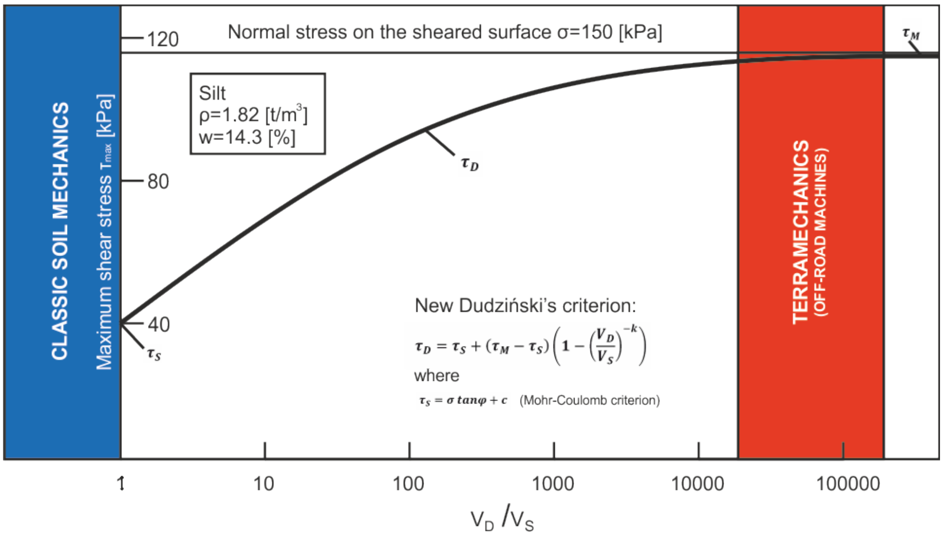

Fig. 1. The impact of the shear rate of soil on its shear strength at an example of silt [1]

2. The measurement device

Based on an extensive analysis of state-of-the-art [3], a concept was developed of creating a measurement device for determining strength properties of grounds for the needs of defining traction of vehicles. The device, due to the proper geometry and kinematics would supply information concerning strength parameters of ground in a way possibly best simulating the processes taking place under traction components of vehicles, which are essential for cross-country mobility researchers. The basic design assumptions of the device involve:

- proper size (the shear area not less than 300 cm^2),
- shear rates corresponding to those appearing between the traction components or working tools with soil (the range of measuring rates from several mm/s to several hundred cm/s),
- linear kinematics of movement (proper for a given class of the model traction component),
- constant force generating pressure for measuring the shear strength,
- avoiding the bulldozing effect,
- possibility of applying in laboratory or field tests,
- possibility of testing within wide range of normal loads.

Based on the presented concept a device has been developed in the form of a tracked undercarriage model. The surface staying in contact with the substrate is controlled within the range of 350 to 500 cm^2. The soil shearing kinematics is linear, fully corresponding to kinematics of track components movement and of some working and agricultural machine tools. The shearing appears along the plane determined by the track grousers. The solution in the form of a model of track undercarriage warrants the measurement free of the bulldozing effect appearing in case of shearing with box, grouser plate, or an instrumented wheel rolling on soil. Thanks to that it is possible to create conditions, which largely meet the objectives of the Coulomb's criterion (in case of appearance of the bulldozing effect it is harder to estimate where the shearing plane runs and what impact on the measured shear resistance has the bulldozing resistance). The model of the tracked undercarriage is linked to a frame by means of two linear guides – the vertical and the horizontal one. It can move only along the linear vertical guide. Between the frame and the model a linear displacement sensor is installed, which records depth of settlement during measurement. Movement of the model along the horizontal guide is locked by means of a force sensor, which measures the pull force (nett). The normal pressures are generated by the gravitation loads. In order to enable the tests in wide range of shear rate for driving the device the hydraulic drive was applied with an accumulator generating large flow rates. An encoder was assembled at the driving shaft used for determination of the angular speed and rotation of the driving wheel. From these values, the shear displacement and the shear speed are calculated. The track is made of aluminium. It is stretched between the driving wheel and the two carrying wheels of controlled spacing. It enables control of the surface of contact with the ground. The tension of the caterpillar is accomplished by means of a roman screw connected with a force sensor enabling recording of the track tensioning force. The design enables measurements within the range of loads corresponding to the normal unit pressures up to some 150 kPa. In addition, the device has the option of connecting additional actuator enabling the application of the variable settlement rate. In order to enable laboratory tests the device has been equipped with soil container of 45x45x70 cm size.

The device has been reported as an innovation in the patent office, and next implemented in the DORMVE. The idea of the device functioning and the measured quantities has been presented in Fig. 2. Fig. 3 presents photography of the device.

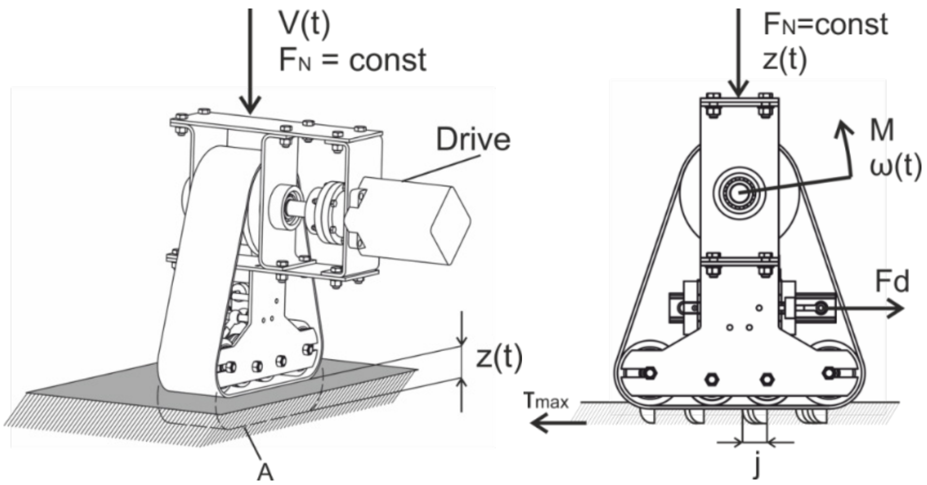

Fig. 2. Diagram of the device and the measured parameters: V(t) – variable rate of penetration (planned), F_N – the normal load, z(t) – depth of settlement, A – the surface of shearing, M – the driving torque, ω(t) – speed of the driving wheel, j – linear displacement of caterpillar, F_d – pulling force nett, τ_{max} – maximum shearing stress

Fig. 3. The device in the laboratory of DORMVE and in course of the field tests [5]

3. The results of the initial tests

Within the tests of the presented device the initial research on two cohesive granular media were performed. These were the agricultural clayey soils collected in the vicinity of Wrocław. The tests were performed in the laboratory on disturbed soil samples. The procedure of preparation and conducting the research has been presented in work [5]. The strength parameters were determined in the apparatus of direct shearing. Humidity and density were determined as well. Next, the strength parameters were determined in the new device during quasi-static shearing with the same shearing rate as in the box apparatus. The achieved results have been presented in Tab. 1.

Tab. 1. Summary of the basic parameters of the tested grounds determined in accordance with the standard [5] and with the new device

Ground	Humidity [%]	Density [kg/dm^3]	Cohesion [kPa]	Angle of the internal friction [°]	Cohesion [kPa]	Angle of the internal friction [°]
			Box apparatus		New device	
Clay soil 1	17.0	1.95	30.5	12.1	11.0	14.8
Clay soil 2	19.6	1.88	34.0	8.0	11.9	16.6

The further step was studies of the impact of shearing rate on the shear strength of the media under tests. The tests have been conducted within the rate range from about 1 mm/min to about 5000 mm/min. The test results have been presented in Fig. 4.

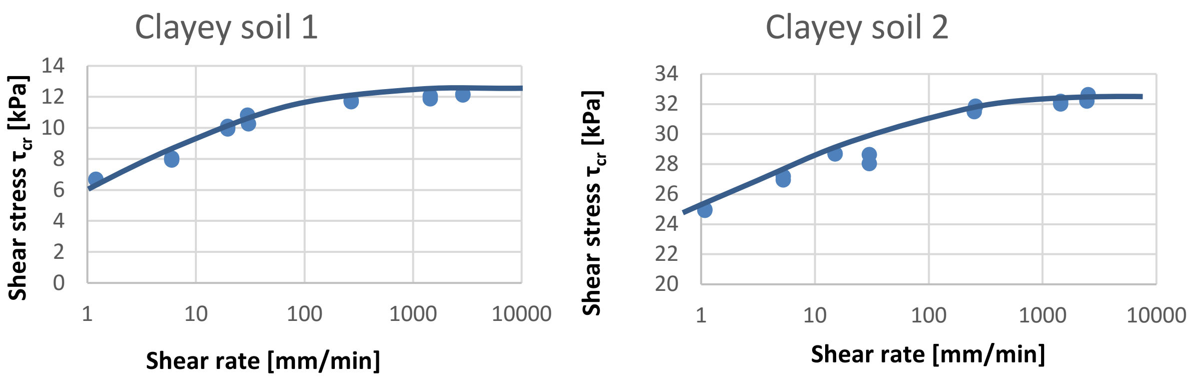

Fig. 4. Dependence of the shear strength on the shearing rate of the clay soil 1 and 2

For the results obtained that way, the trend line was determined through the non-linear regression. For approximation, the dynamic model of the limit shear stress proposed by Prof. P. Dudziński [1, 2] for the cohesive media was applied:

$$\tau_D = \tau_C^{max} + [\tau_M - \tau_C^{max}]\left[1 - \left(\frac{V_a}{V_s}\right)^{-k}\right], \tag{1}$$

where:

$$\tau_C^{max} = \sigma \cdot tan\varphi + c, \tag{2}$$

τ_M – the limit shear stress at the shear time close to 0,
τ_C^{max} – the limit shear stress at the minimum shear rate in a given device determined according the Coulomb's criterion,
V_a – shear rate,
V_s – the maximum shear rate in the standard box device.

As Vs the minimum rate with which it was possible to perform measurement using the new device (1 mm/min) was assumed. Estimated values of parameters for the applied model were collected in the Tab. 2. The table presents also the determined values of the dynamic strengthening factor, defined as the ratio of shear strength at shear time approaching zero, to the strength for minimum rate applied in the tests:

$$\delta_d = \frac{\tau_m}{\tau_s}. \tag{3}$$

The indicator δ_d gives the pictorial information on how susceptible a given ground is to dynamic strengthening.

Tab. 2. Summary of the estimated parameters of the model obtained at the base of the determined trend lines

Soil	τ_s	τ_m	k	δ_d	The share of variance explained by the model
Clayey soil 1	6.15	13.3	0.246	2.16	0.972
Clayey soil 2	24.79	37.35	0.123	1.51	0.968

4. The impact of dynamic shearing on tractive parameters of tracked vehicle

Based on the obtained test results, simulations with the use of mathematical model of the tracked undercarriage moving over the deformable ground with use of the achieved coefficients of dynamic ground strengthening were performed. The model has been described in the work [8]. The most significant goal of the simulations performed was determining the impact of ground shear rate under the tracks on the generated drawbar pull. The drawbar pull is defined as the ratio of pull force to the vehicle weight:

$$\mu_u = \frac{F_u}{G}. \tag{4}$$

The ground shearing speed under the track depends first of all on track slip and vehicle speed. At the first stage of the simulation the slip was assumed as $i = 0.1$, as this is the approximate value at which the tracked vehicles operate most frequently and achieve at it the highest traction efficiency at cohesive soils. Fig. 5 presents the predicted dependence of the drawbar pull from the vehicle speed at slip $i = 0.1$. The diagrams present the predicted values for cohesive grounds with the strengthening factor $\delta_d = 2.8$ and $\delta_d = 1.7$. For comparison, the straight line designates the predicted drawbar pull in case of not taking into account the dynamic soil strengthening (which corresponds to the previous models). It can be noticed that within the practical speed ranges of 10 km/h row the predicted value is by some 20-60% higher. It means that not taking into account of the shear dynamics causes significant underestimation of the generated traction forces. It has to be noted, however that with the increase in speed also the soil-tool working resistance grows (e.g. during ploughing), which, on the other hand increases the external resistance of a vehicle.

5. Conclusions

In the work, the new device and new method of determining strength parameters of soil have been presented. The parameters are determined by means of the device being a model of the real object in the scale, thanks to which it exactly reproduces the movement of the modelled object. The process of determining the parameters is performed within the speed range close to the real ones appearing during interaction of a track with ground. Moreover, the developed method minimises the influence of the scale effect and the bulldozing effect, as well as the wall effect.

At the base of the tests performed, it has been confirmed that soils react to the rate of the shear process. Along with the increase in the shear rate, the increase in the shear resistance is observed, which may be expressed with the equation (1).

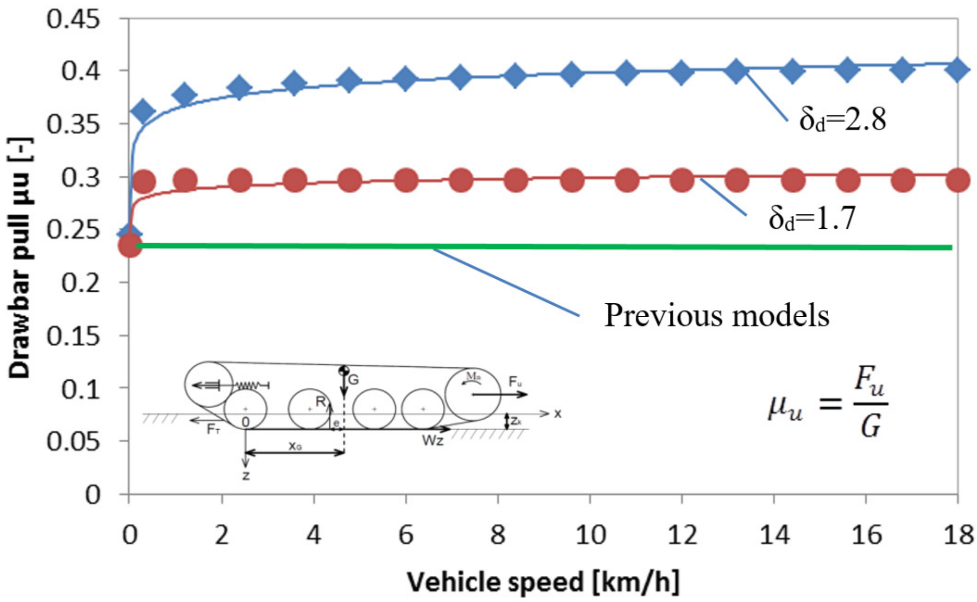

Fig. 5. Dependence of the vehicle speed on drawbar pull for slip i = 0.1

As a result of the conducted simulations, it has been found that the rate of ground deformation under a track has significant impact on the generated tractive forces. The predicted drawbar pull, while taking into account slip i = 0.1, at vehicle speed of about 8 km/h may amount even up to 60% more than in case when the shear dynamics in the model is not taken into account. Consideration of the impact of ground shear rate on its shear strength may constitute the essential factor in the process of optimising the tracked undercarriages, especially among the modern vehicles that develop considerable driving speeds.

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