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ScienceDirect
Journal of Terramechanics 48 (2011) 360–371
Journal of Terramechanics
www.elsevier.com/locate/jterra

A systematic approach to reliably characterize soils based on Bevameter testing ☆

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Available online 29 April 2011

Abstract

Although a lot of information about soil parameter identification exists in literature, there is currently no algorithm who makes use both of state of the art identification methodologies and incorporating statistical analysis. In this paper a state of the art soil parameter identification method is presented including the calculation of its standard deviations and a proper weighting of the objective function. With this algorithm and a Bevameter with advanced sensor and actuator technology a test campaign is started to find a reliable soil preparation, which is applicable to a large planetary rover performance testbed. Furthermore, the preparation method has to be valid and stable for various types of dry, granular and frictional soils, typically used for planetary rover testing in space robotics, since the result of pre-tests show that the soil parameters are highly depending on the preparation. Besides preparation, the soil parameters are also influenced by different Bevameter test setup variables. Thus, the effect of the penetration velocity as well as the penetration tool geometry for pressure–sinkage tests on soil parameters is investigated. For shear tests the influence of the dimension of the shear ring is analysed as well as the variation of the grouser height, the number of the grousers and the increase of the rotational shear velocity. The results of the extensive test campaign are evaluated by the proposed identification algorithms.

Keywords: Bevameter; Soil parameter; Testbed; Identification; Planetary rover; Statistical analysis

1. Introduction

Although the rover performance and mobility testing plays an important role in the ExoMars programme of the European Space Agency (ESA), simulation of the rover performance is an additional part for a successful mission. With a verified and validated simulation tool, special mobility cases occurring during the mission can be examined leading to the best trajectory of the vehicle. Furthermore, in an early stage of a project, simulation has the capability to provide information about the performance of different mobility concepts. An example for such a simulation tool is given in [1]. Therein, a soft soil contact model is used to describe the interaction between a wheel and a soft deformable soil [2]. To verify and validate the simulation software, testing and simulation have to go hand in hand. Therefore, the test facility described in [3] is used with the current ExoMars BB2 breadboard (see Fig. 1). An essential input for the simulations are the soil parameters identified from Bevameter measurements (see Fig. 2). However, a reliable mechanical characterization of soft soil by Bevameter testing is a very delicate issue to accomplish, since the soil parameter determination often depends to a large extent on several testing impacts, like the soil preparation method. Moreover, the identified parameters are influenced by several test setup parameters. Using soil parameters identified with improper test setup variables on a soil prepared with an unreliable preparation method as inputs for validation simulations leads to incorrect simulation results and consequently to incorrect validation and correlation results. Therefore, an applicable and stable soil preparation method is indispensable as well

☆ This paper was awarded as one of the best papers at The Joint 9th Asia–Pacific Conference of ISTVS and 31st Annual Meeting of Japanese Society for Terramechanics, Sapporo, 2010.

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0022-4898/$36.00 © 2011 ISTVS. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.jterra.2011.04.001

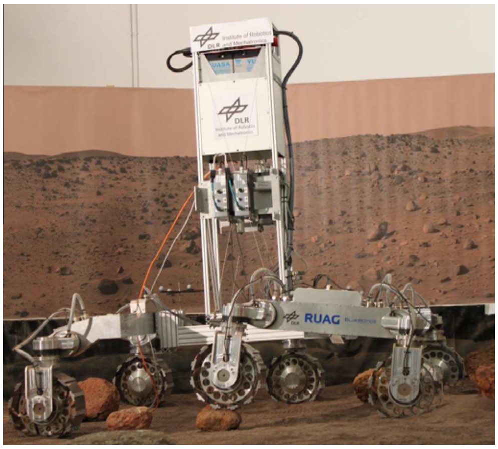

Fig. 1. ExoMars BB2 breadboard.

Fig. 2. Bevameter for soil characterization.

as information about the effect of the variation of the test setup parameters on the soil parameters. These issues are investigated in an extensive test campaign presented in this paper. The test campaign is performed on various types of dry, granular and frictional soil, typically used for planetary rover testing in space robotics. Besides the preparation and the test setup, the identification algorithm is another important part to receive stable and reliable soil parameters. The currently known soil identification methods [4,5] do neither incorporate a statistical analysis of the identified parameters nor consider the nonlinear behaviour of the soil equations directly. Both issues are included in the soil identification algorithm presented in this paper.

In Section 2 the soil parameter identification methods are described. The test results are shown in Section 3, the identification results in Section 4. Section 5 finally gives a conclusion of this paper.

2. Soil parameter identification

In the following section a general approach for an identification problem is given. This approach is adopted to the identification of soil parameters using a pressure–sinkage test or a shear test (see Sections 2.1 and 2.2). For parameter identification a general minimization problem is used

$$\min_{\hat{\theta}} E(\hat{\theta}) = \min_{\hat{\theta}} \frac{1}{2}\left\|\mathbf{w_r}\cdot\mathbf{e}(\mathbf{X},\hat{\theta})\right\|^2 = \min_{\hat{\theta}} \frac{1}{2}\left\|\mathbf{w_r}\cdot[\mathbf{y}-\mathbf{f}(\mathbf{X},\hat{\theta})]\right\|^2. \quad (1)$$

The objective function is given by $E(\hat{\theta})$, and the error function by $\mathbf{e}(\mathbf{X}, \hat{\theta})$. The vector $\mathbf{y}$ consists of the measured values. The model function of the identified parameters, $\hat{\theta}$, and controlled inputs, $\mathbf{X}$, is denoted by $\mathbf{f}(\mathbf{X}, \hat{\theta})$. The controlled inputs are variables or values on which the result of the model function depends. Furthermore, a weighting factor $\mathbf{w_r}$ is included in Eq. 1. The solver for the optimization problem depends on the chosen model function, i.e. a nonlinear solver (e.g. Levenberg–Marquardt) for a nonlinear objective function or a linear solver for a linear objective function. An overview of solvers for minimization problems is given in [6]. The quality of the fit is calculated by the root mean square of the identification error over the measured values:

$$\epsilon = 1 - \frac{\sqrt{\frac{\sum \mathbf{e}(\mathbf{X},\hat{\theta})^2}{N-2}}}{\frac{\sum |\mathbf{y}|}{N}}. \quad (2)$$

Here N is the number of data points used for the identification which is equal to the length of vector $\mathbf{y}$. If the identification is perfect, ϵ is equal to one, otherwise less than one. This equation is adopted from [7] and kept more general in order to be applicable for problems with negative measurement values. However, such an evaluation concerning the identification quality allows no statement about existing deviations of the identified parameters. Therefore, for a nonlinear problem, the calculation of the standard deviation σ, according to [8], of the identified parameters is included in the identification

$$\sigma = \sqrt{diag(\mathbf{Cov}(\hat{\theta}))}, \quad (3)$$

with the covariance matrix

$$\mathbf{Cov}(\hat{\theta}) = \frac{1}{N-N_p}\cdot\mathbf{e}(\mathbf{X},\hat{\theta})^T\cdot\mathbf{e}(\mathbf{X},\hat{\theta})\cdot(\mathbf{J}^T\mathbf{J})^{-1}. \quad (4)$$

The number of identified parameters is denoted by N_p; $\mathbf{J}$ is the Jacobian given by

$$\mathbf{J} = \frac{\partial[\mathbf{w_r}\cdot\mathbf{e}(\mathbf{X},\hat{\theta})]}{\partial\hat{\theta}}. \quad (5)$$

For a linear problem the standard deviations of the identified parameters are calculated according to [9].

2.1. Pressure–sinkage test

The quantity describing the relationship between the penetration depth of a plate into soil and its reaction is pressure. Therefore, the measured force has to be transformed into the required quantity, since the Bevameter is equipped with a force/torque-sensor: