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Pile driving models for the evaluation of soil penetration resistance measurements from planetary subsurface probes

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ABSTRACT

Several planetary lander missions conducted in the past and planned for the near future have instruments on board, which are dedicated to the determination of various material properties, among them mechanical properties of the surface like material strength and penetration resistance. In this paper two instruments are considered in more detail: (i) the MUPUS penetrator, a device aboard the Lander *Philae* of ESA's Rosetta mission, and (ii) the *Mole* HP^3, which is part of the payload of NASA's next Discovery mission *InSight*, due for landing on Mars in 2016. Both devices are driven by hammering mechanisms designed to work under low or micro-gravity conditions and blaze themselves a trail into the subsurface of their respective target bodies. Naturally the speed with which this process takes place and if penetration is possible at all depends on the mechanical properties of the soil. However, a quantitative evaluation of soil mechanical parameters from measured depth-versus-time data is not a straightforward task. In this paper we apply an old technique, originally developed for modelling the driving of a pile into the ground, to describe the performance of penetrators and Moles developed for planetary applications. The numerical pile driving model of Smith (1962) is scaled and adapted for this purpose and used to predict the penetration behaviour of these instruments in dependence of their internal construction and the properties of the soil they are driven in. The model computes the permanent set of the surrounding soil in response to one hammer blow cycle as well as the oscillations and waves excited inside the devices and in the surrounding soil. Both the penetration resistance of the tip and the resistance caused by friction of the penetrator along the cylindrical side wall are calculated. By comparing the modelling results with previous laboratory measurements it is demonstrated that the models produce realistic results and can be used both as tools for proper design of future penetration devices and for the evaluation of soil-mechanical properties from measured penetration data. The most sensitive soil parameter controlling penetration progress per stroke is the *ultimate static bearing capacity* of the ground. Although the method used for our calculations is essentially the same as that applied by Smith (1962) for describing the behaviour of long and heavy piles in geotechnical engineering, it is found that the penetration process for such small and light weight systems takes place in a quite different way. While for the former secondary oscillations are irrelevant for the determination of the permanent set caused by one stroke, in the latter the penetration in response to one hammer stroke takes place in many small increments, until a stable depth is reached. Our model describes the full dynamic behaviour of the system over an arbitrary time span and has the potential to be adapted to systems with other geometrical dimensions and masses, as long as the diameter/length ratio of the probe remains reasonably small.

1. Introduction

Several planetary lander missions conducted in the past and planned for the near future have instruments on board, which are dedicated to the determination of various material properties, among them thermal properties (e.g. thermal conductivity) and mechanical properties like material strength and penetration resistance. The first experiments of this type were performed in the frame of the lunar missions in the 1960s and 1970s. For most of these tests cone penetrometers were used to determine the penetration resistance of the lunar soil at various places. An overview of these historical experiments can be found in Ball and Lorenz (1999).

These first penetrometers mostly performed *quasi-static* measurements, i.e. the cone was pushed into the ground with a low velocity and the resistance force against this action was measured and used to determine the relevant geotechnical parameters like

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cohesion and angle of internal friction (Jones, 1971) or the ultimate bearing capacity of the ground. Another possibility to determine these parameters are *dynamical* methods, using an internal or external hammering device, which drives a slender cylindrical body into the ground. Two probes of this type have been developed for use in currently active planetary missions:

- The Rosetta Lander *Philae*, which landed on comet 67P/Churyumov-Gerasimenko on 12 November 2014 [IS1], had the experiment MUPUS (MUlti-PUrpose Sensor for surface and subsurface science) on board. This device is a penetrator driven into the ground by a recoilless hammering mechanism mounted atop of a 30 cm long hollow glass fibre tube of 10 mm outer diameter with a tip made of titanium (Spohn et al., 2007). After Philae's landing on the comet the attempt was made to drive this tube into the cometary soil. Although the procedure failed due to the unexpectedly high penetration resistance it encountered, the instrument operated nominally on the cometary surface, and using similar devices on future lander missions to the Moon, Mars, asteroids or other comets is still an option to be studied.
- A somewhat different type of ground-penetrating instrument will be flown on NASA's next Discovery Mission *InSight*, due for launch in spring 2016. This is a so-called *Mole*, again a cylindrical rod with a tip, but using an internal hammering mechanism integrated inside the tube, which drives the instrument into the ground by internal spring action. Various versions of such Moles have been developed in the past for planetary missions in the frame of project studies (Kochan et al., 2001; Grzesik, 2004; Richter et al., 2006). More recently another Mole prototype (denoted hereafter as KRET) was built and tested at the Space Research Centre of the Polish Academy of Sciences, Warsaw (Grygorczuk et al., 2009a). The Mole version selected as payload for the NASA Discovery Mission *InSight* (hereafter denoted as HP^3) is based on these previous studies, but adapted to operate properly in Martian environmental conditions (Lichtenheldt, 2013).

In this paper the existing prototypes mentioned above (MUPUS penetrator, Mole HP^3 and Mole KRET) are used as examples to study the penetration process of such systems, which are driven by hammering action, into granular cohesionless soil, for example dry loose sand or gravel. The mathematical method to be applied is basically the theory of *Pile Driving*, a discipline of high importance in civil engineering in general and in geotechnical engineering in particular. The pioneer of this theory, which is based on the one-dimensional wave equation, is the US civil engineer E.A.L. Smith, who was the first to implement the process of pile driving into a quantitative numerical model (Smith, 1962).

While most of the applications in civil and geotechnical engineering refer to constructions of considerable size and weight (typically in the dozens of metres length range and with diameters in the order of decimetres and with masses of several tons), the instruments developed for space experiments are of much smaller scale, both in length and in diameter, and they are much lighter in weight. Nevertheless, the basic physics is the same, so the concepts developed by Smith can be scaled and adapted in a rather straightforward way to interpret the soil penetration behaviour of a slender cylindrical probe driven by applying regular hammer strokes. This will be demonstrated in this paper by adapting Smith's algorithm to the case of the MUPUS penetrator on the one hand and to the case of the Moles HP^3 and KRET on the other hand.

In Section 2 we describe the theory of pile driving and present the relevant numerical equations for these two cases with the appropriate geometries, while in Section 3 we consider a benchmark example for pile driving, which demonstrates the principal suitability of the code based on previous work by Smith (1962). In Sections 4 and 5 the adaption of the model to the case of the MUPUS penetrator and the case of the Mole HP^3 (as well as Mole KRET), respectively, is described and the results obtained from the model calculations are presented. Finally, in the discussion given in Section 6 a comparison of the performance of the two existing Mole prototypes (HP^3 and KRET) is shown and the modelling result for the Mole KRET is compared with the measured penetration of the Mole in a sand sample in response to one stroke. Section 7 contains our conclusions and an outlook on future work.

2. Theory of pile driving

The penetration model is constructed in analogy to dynamic pile driving models as developed by E.A.L. Smith and his co-workers in the 1950s and 1960s (Smith, 1954, 1962; Lowery et al., 1969). These methods can be applied to slender rods or tubes driven into the soil by hammering action. Essentially they are based on a numerical solution of the one-dimensional wave equation. The equations describe the forward motion of the body under the action of a single hammer stroke and the stresses and accelerations occurring in the body as well as in the surrounding soil in response to a single hammer stroke.

Starting point for the method is the one-dimensional wave equation for a solid body,

$$\frac{\partial^2 D}{\partial t^2} = c^2 \frac{\partial^2 D}{\partial s^2} \tag{1}$$

where D is the longitudinal displacement of a mass element of the pile along its vertical coordinate s and t is time. The velocity of the

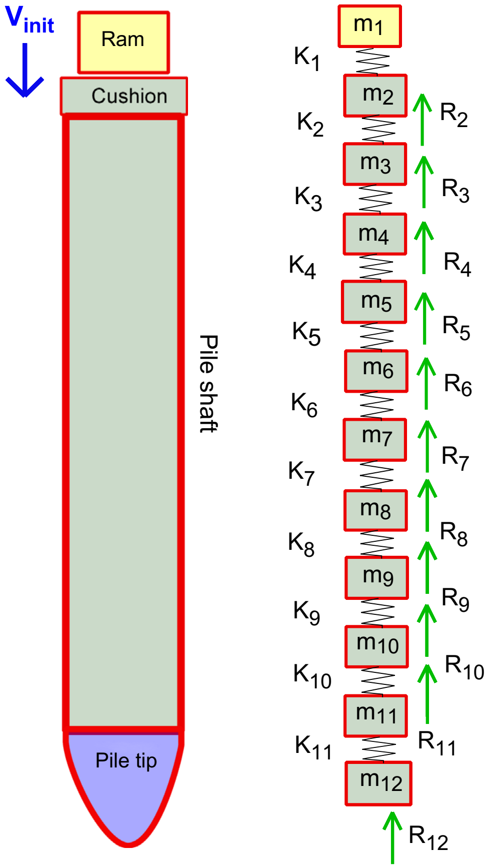

Fig. 1. Numerical modelling scheme for the pile driving model after Smith (1962). Mass element m_1 corresponds to the ram (hammer), while mass element m_2 represents a cushion block, which is used in typical geotechnical applications to avoid damage of the pile. Its material parameters can be different from those of the pile. Mass element m_{12} corresponds to the pile tip, which pushes the soil aside in response to a hammer stroke.