# SOIL PENETRATION ANALYSIS OF MOLE PENETROMETERS: REFLECTIONS ON A METHODOLOGY CONSIDERING THE PHYSICS OF SANDS

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*This paper is dedicated to the memory of Dr. Valeryi Vassilevich Gromov, who passed away on June 23 2006, and without whom neither the 'Mole' nor the 'Mole with Sampling Mechanism' could have been realized.*

**Abstract**

This paper presents some thoughts about *Mole* penetration: it is put in relation with experiments and models from the 'Modern Physics of Sands'. This reflection derives in particular from experiments demonstrating how some shocks may consolidate sand, such as 'sticking' a stick buried in sand. The current analysis of the *Mole* penetration is put in parallel with the modern physics of sands. The somewhat amazing *Stuck Stick* experiment, proposed in the literature related to this *Modern Physics of Sand*, and the *Stuck Mole Stick* experiment derived from this are reported (both were demonstrated to the IWPSS2 audience). Potential benefits of a renewed theoretical approach are identified. This paper, solely qualitative, intends to stimulate the reflection and encourage a deeper analytical approach of the *Mole* penetration — if necessary!

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# 1 Introduction

Sand is a type of granular material with a very peculiar behaviour: local interactions between grains are driving the material properties. It was shown e.g. that local arches of grains support local loads, but are easily broken by external forces or shocks. Sand analysis has challenged many scientists, but is currently progressing. Penetrometers or *Moles* are made to penetrate sandy soils or similar materials, using a shock mechanism as regular as a clock. However, many penetration analyses consider a soil model which is quasi–continuous: the penetration prediction models or analyses of test results use quasi–static parameters derived from civil engineering soil tests; then equilibrium of forces or an energy balance is established – and adequately adjusted. This paper intends to point out, mainly qualitatively, a number of topics relevant to physics of sands and related to the *Mole*. It is suggested that an approach based upon the physics of sands should be considered and included in penetrometry, in order to improve the understanding of *Moles* and penetrating bodies' performance. This paper intends to point out, mainly qualitatively, a number of topics relevant to the physics of sands.

# 2 Mole Penetrometry

Most soil sub–surface investigation techniques are performed with penetration, either carrying various sensors to depth (e.g. thermometers) or in order to bring back samples for laboratory analysis. In the field of planetary soils exploration, the main investigation and sampling methods are:

- Scooping
- Penetrometry (at low and high speed)
- Drilling

Scooping is limited to surface sampling. High speed penetrators, with ballistic entry, are expected to reach a few meters depth on the Moon or the Mars surface. Only drilling and penetrometry allow penetration to a depth of several metres, necessary for sampling into subsurface regolith. Drilling is mostly used for rocks and solid materials; it may reach several tens of metres, given sufficient thrust and energy.

A low speed 'penetrometer' or *Mole* is a cylinder with a sharp tip, inserted into a granular medium by repeated internal shocks. Penetrometry is best used for sand and other granular materials similar to regolith. In addition, sampling may be performed at a desired depth by opening a cavity behind the tip and then closing it to retrieve the sample. Penetrometry may be considered as a process causing only little destruction of the surrounding soil, as the grains are generally only slightly displaced (instead of being cut into chips and transported out of the hole). Mole penetration through operation of the inner shock mechanism needs very low power, which is of interest for planetary missions, where maximum power is limited, but often the total process duration is less severely restricted.

## 2.1 Shock mechanism principle

The *Mole* penetrometer consists essentially of a tethered, tubular body with a pointed end; this end is struck periodically by the internal shock mechanism, which slides inside to minimize the recoil. The penetration is usually more or less vertical. A cycle of the shock mechanism is depicted by the series of sketches shown in Figure 1. Note that two shocks occur: following the main shock of the hammer on the anvil, due to the release of the compressed spring, a second shock occurs when the sliding mechanism falls back.

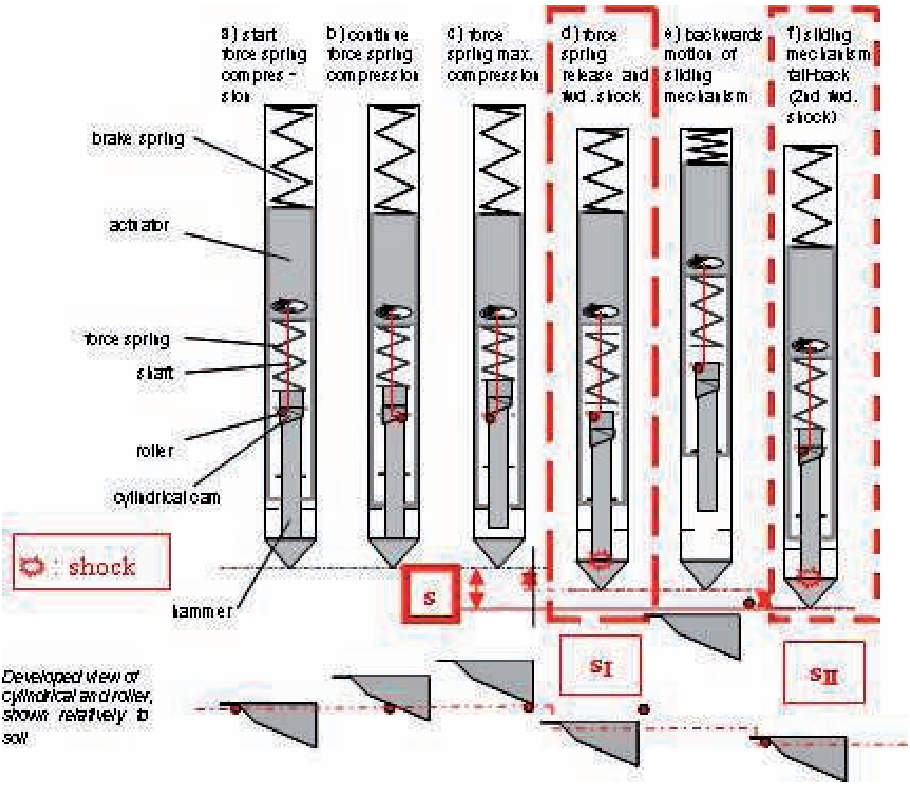


*Figure 1: Mole, sliding shock mechanism – sequences of a shock cycle (from Richter et al., 2006).*

# 3 *Mole* penetration analysis: current engineering approach and energy transfer model

In the current engineering approach, the energy transfer model combines the basic elements of the diagram (Figure 2) to predict the *Mole* intrusion into the soil.

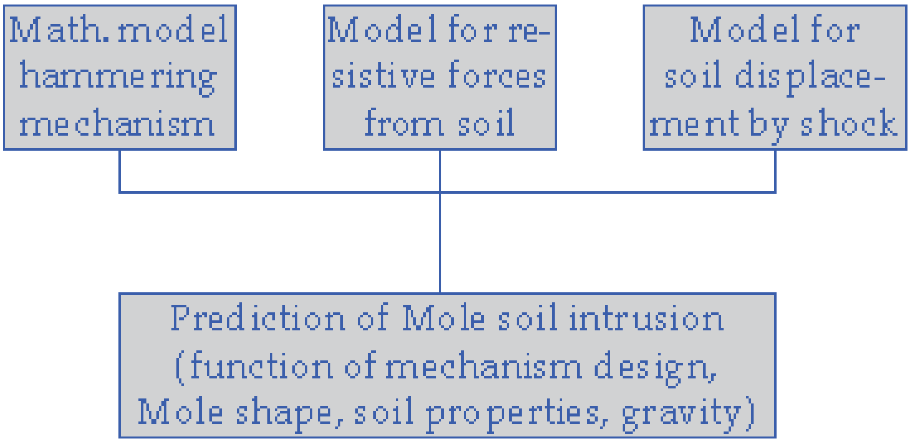


*Figure 2: Energy transfer model of Mole penetration (from Richter et al., 2006, Fig. 5–1).*

## 3.1 *Mole* shock mechanism: energy model

The mathematical model of the hammering mechanism includes the shock mechanism parameters with all masses as well as spring and internal impact losses (cf. Figure 3). It is able to compute the shock energies delivered internally in a single cycle. An energy method has been preferred to a dynamic model which would demand a direct formulation of the forces and of their equilibrium.

## 3.2 Soil model: resistive forces

The soil model predicts the resistive forces, due to normal compression at the tip and lateral friction of the main body. A penetrometry analysis with current methods considers generally the following engineering parameters of sand:

- Density
- Compressive strength
- Lateral friction

It takes occasionally into account:

- Granulometry
- Loss angle
- Bulk modulus

It does not generally address (directly):

- Soil compressibility
- Affected volume
- Internal stresses in the surrounding soil
- Thermal aspects

Models of quasi–static penetration, based on experimental data, are used for initial estimations. Penetration resistance and maximum penetration depth are also predicted on the basis of experimental data. Soil models of penetration by shocks are derived from pile driving data and from previous *Mole* experiments.

### 3.3 *Mole* penetration model

The three previous models of the *Mole* mechanism, the soil resistance and the soil penetration by shocks are combined to predict the *Mole* penetration. Experiments of *Mole* penetration in soil are used to refine the initial predictions and to determine the permanent soil displacement achieved during a single *Mole* shock cycle.

The *Mole* displacement is particular, due to its internal shock mechanism. Figure 3 shows a typical displacement vs. time over a shock cycle; these data are coming from a *Mole* instrumented with an accelerometer. It appears that the first shock, corresponding to the impact of the launched hammer, generates a displacement with overshoot, with a recoverable elastic component and a permanent plastic displacement; the second shock, when the mechanism falls back, induces essentially a plastic displacement (usually smaller than the first one). The sum of these plastic displacements is the advance $s$ per cycle (typically about $1.5 - 2$ mm in Mars simulant). The soil reaction force $R$ is assumed constant over the advance (typically equal to $40 - 50$ N). The tether friction is included in the model, unless no hole collapse is expected. The energy transfer model, calibrated with '1 g' experiments, predicts penetration under Mars gravity as shown in Figure 4.

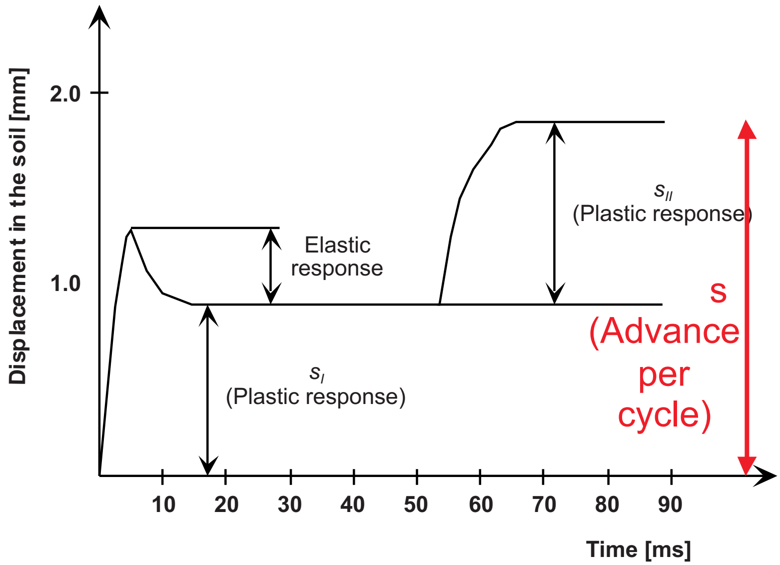


*Figure 3: Mole advance per cycle ('sgs') under Earth and Mars gravitation, in Mars soil simulant.*

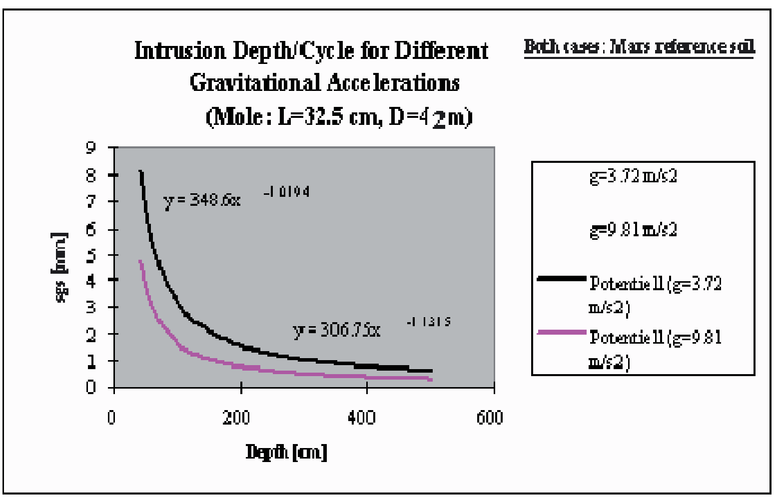


*Figure 4: Typical displacement vs. time over a shock cycle.*

### 3.4 Note on penetration data

Experimental data are used to identify numerically the *Mole* performance as a function of these parameters. A large dispersion of test data is usual, and interpolation of test data by a function should always be presented with its uncertainty. This is even more important in the case of extrapolation. Prediction is mainly based on extrapolation, when considering higher or smaller values of parameters, e.g. soil compressive strength, depth, or gravity. For more details, please refer to Richter et al. (2006) and Nadalini (2006).

## 4 *Mole* penetrometry and the *Modern Physics of Sands*

During informal discussions about *Mole* penetrometry with a young colleague, a few books about the physics of sand, both from Duran (1999, 2003) were recommended: Duran (2002) is qualitative, proposing some 15 experiments and no equation, intended for general public; Duran (1997) is a more conventional introduction to the physics of granular materials.

### 4.1 The *Stuck Stick* experiment

This experiment, which demonstrates sand consolidation by applied shocks, is proposed in the book of Duran (2002). It needs only simple material:

- A cylindrical container.
- Two sticks – one buried in sand, the second used as hammer.
- Sand or granular material to fill the container.

Reference sizes and data below are given indicatively, with values close to the demonstrated ones:

- The container should be ca. 1 dm$^3$, preferably lightweight (e.g. plastic; ca. 10 cm diameter, 17 cm height and 100 g mass).
- The sticks are made of wood ca. 2 cm in diameter, slightly longer than the container and not too smooth; they are e.g. cut off from a broom stick.
- A very convenient type of sand is sepiolite (in German: Meerschaum', in French: écume de mer'), a clay mineral and complex magnesium silicate; it is commonly used as pet litter and therefore easy to procure. Grain size is ca. 5 mm, and density is relatively low.

Note that this experiment is rather 'robust': it allows large variations of these dimensions and materials.

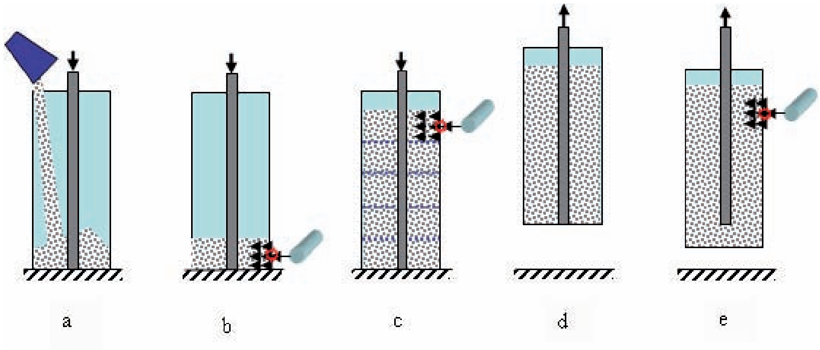


*Figure 5: The 'stuck stick' experiment: (a) a stick is held in the centre of a container, while it is filled with a first sand layer; (b) small external shocks (taps) are applied around the container to compact the sand; (c) layer addition and shocks are repeated until the container is full; (d) pulling the rod may also lift the container (within some limits)!; (e) small taps at the top of the suspended container will make it fall down. The vertical arrow symbolizes a hand pushing or pulling the rod.*

To proceed perform the following steps (cf. Figure 5a–e):

- The empty container is put on a table; one stick is firmly held and pushed in the centre of the container's bottom; a first sand layer, up to a height of 2–3 cm, is poured around the stick (sketch a).
- Using the second stick as a hammer, small, gentle tapping shocks (ca. a dozen) are applied all around the container wall, to equalize the sand surface (sketch b).
- Always holding firmly the stick in the centre, more sand layers are poured and tapped, until the container is full (sketch c).
- Grasping now the end of the stick, one tries to pull it out of the container: in most cases (!), the container is lifted with the stick as if it was stuck (sketch d)!
- Keeping the container slightly above a table, more outside tapping may be used to free the stick; one may note that shocks applied near the top are more efficient than shocks applied at a lower level (sketch e).

This experiment is quite amazing at first sight! It remains so when repeated with different materials or sizes, as its success includes actually some 'suspense'! It has been later repeated successfully with the same stick and container and various types of sand, the finest one showing that equilibrium was just reached but obviously with a small margin.

When using beads of quasi–spherical glass instead of sand, of higher density, the weight of the full 1 $dm^3$ container was obviously exceeding the sticking force; subsequently a smaller, 0.3 $dm^3$ plastic container (diameter 5 cm $\times$ height 16 cm; 10 g) was tried. Despite

*Figure 6: The* Stuck Stick *experiment: preparation and four 'sticking' proofs (with sepiolite sand and various glass beads).*

a majority of pessimistic forecasts, the stick got stuck in beads of ca. 4 mm diameter (Figure 6). It was further as well stuck with very fine beads of 1.5 mm diameter. This is quite remarkable, as such fine beads behaviour is close to the one of the poppy seeds 'flowing as easily as water' as Lucretius noted (quoted in Duran (1999), p. 16).

### 4.2 Arches formation in sand

The interpretation of the *Stuck Stick* experiment in the *Modern Physics of Sands* (Duran, 1999; Duran et al., 1998) is based on the formation of 'arches'; these arches are a stable shape chains of compressed grains. The following paragraphs clarify the chain's concept.

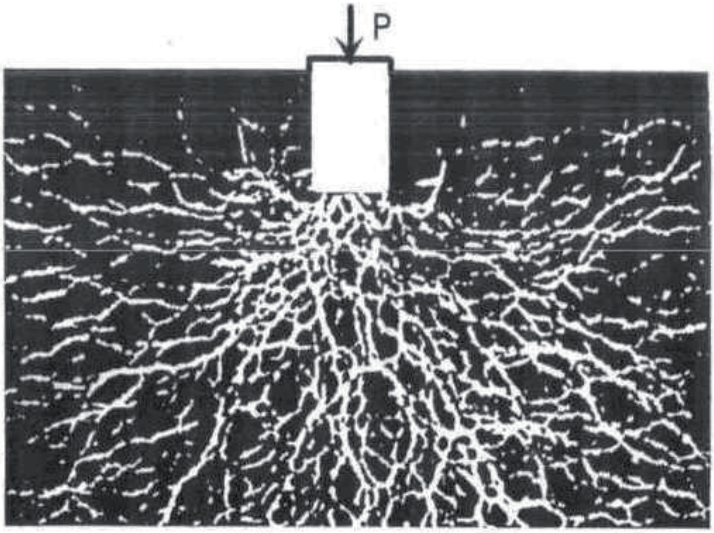


*Figure 7: Dantu's experiment: Stress pattern observed in a two–dimensional granular material under compression (reproduced from Duran, 1999).*

### *4.2.1 Dantu's experiment*

A compressive force in a granular medium is balanced by the forces from this medium; the civil engineer Dantu could visualize them in a famous experiment. In his test set–up, practically planar, a block compresses a transparent granular material between two transparent plates; photo–elastic techniques make them visible (Figure 7): they form a dendritic configuration, oriented mainly downwards, but as well laterally and even partly upwards, and with many voids. The force distribution is fully discontinuous, and one gets the impression that several chains of adjacent grains, highly compressed, are present. A model of such a chain is the 'inverted chain' (Figure 8).

### *4.2.2 The 'Inverted Chain' experiment*

The arch formation is an example of a single chain of grains in equilibrium under their own weight. It is illustrated by another experiment proposed by Duran (2003), the 'Inverted Chain': a necklace of spherical beads has its ends pinned on a smooth plate, initially horizontal, on which it rests; when the plate is inclined (e.g. 600 from horizontal), one should build a stable 'bridge' or 'arch' upwards. This experiment may also be repeated with a bicycle chain. One readily notes that the stable form is (quasi) identical to the one of the hanging chain. It is easy to achieve it by letting first the chain hang freely, and then tilting slowly the plate with the chain upwards (Figure 8). Dantu's experiment reveals a large number of similar arcs or chains, indeed subject to more complex forces; these arcs are in an equilibrium state, which may, however, be disturbed easily (e.g. by shocks) to reconfigure itself in an overall similar configuration, although very different on a local scale.

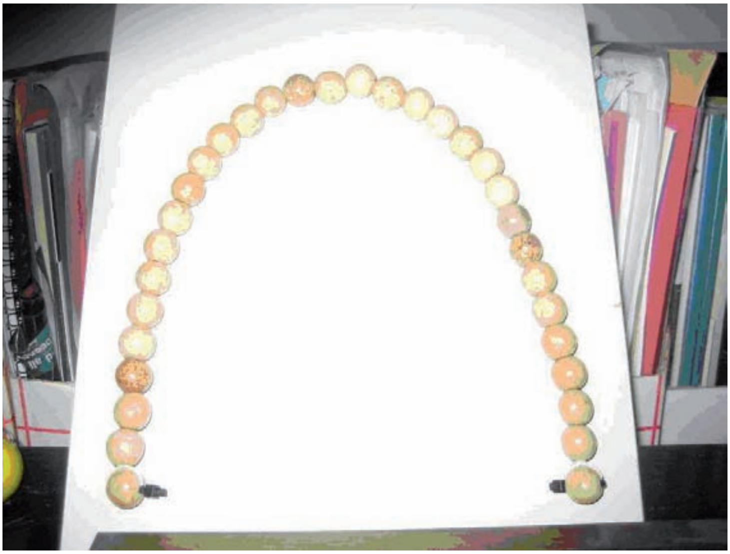

*Figure 8: The 'Inverted Chain' experiment: a quasi–vertical arch similar to contact chains (from Duran, 1997).*

#### *4.2.3 Interpretation of the 'Stuck Stick' experiment*

Duran (1999) proposed a mechanical model of chain formation, presented here qualitatively (let us mention that Duran (1998) developed a more quantitative mathematical model). Figure 9 shows a segment of the *Stuck Stick* in its container. On the left half, the circles model some grains, which are considered as elastic balls with a rough surface (such that some inter–granular friction exists in the grain packing). The arches formation is imagined to work as follows:

- It is assumed that first a loose, quasi–complete linear chain of grains (white balls) exists; this chain is supported by the grey balls (also shown there).
- Under some shock action, a ball (in black) is inserted, with the consequence that then all the white balls of the chain are in direct contact.
- After more shocks, the black ball is totally inserted and the chain is fully blocked: a stable arch is formed between 2 walls.
- A large number of similar arches are eventually created between several hard 'pin points' (formed by grain clusters, other chains and the container walls).

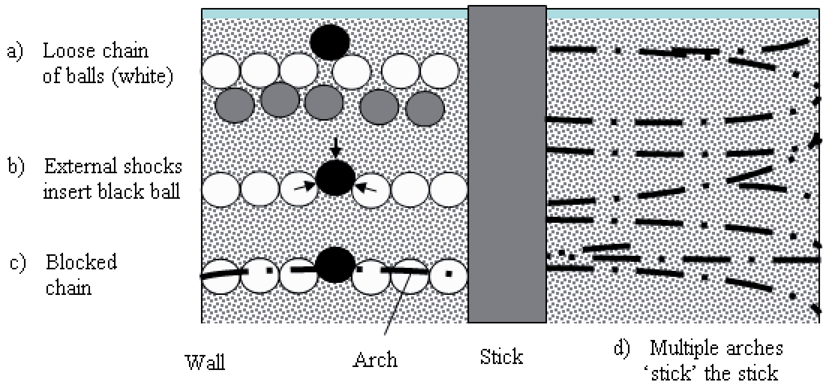


*Figure 9: Arches blocking a stick in a container; model of formation: left, (a) to (c): model of balls under shocks, the black ball completes and blocks the white chain, forming an arch. Right, (d): multiple arches in the container block the stick (Figs. from Duran (1999) and adapted from Duran (1998)).*

Multiple arches, which may resemble the tree shown in Dantu's experiment (Figure 7), may eventually block the walls' displacement, as demonstrated in the above *Stuck Stick* experiment. For a given sand layer subjected to a series of shocks, a shock may break some of the previous arches, but will create some other ones. However, the following layer is expected to build more arches, so that creating eventually a sticking effect sufficient to lift the container.

### 4.3 The *Shock–Driven Stick* experiment

This experiment examines the effect of shocks applied directly on the buried stick, instead of the container walls as previously described.

The material for this experiment is very close to the one used for the *Stuck Stick* experiments: only one stick (previously stuck) needs to have a pointed end (e.g. a 30° half–cone) – similar to a *Mole*, therefore it is called called a *Mole Stick* (Figure 10). The container is full of sand, and the *Mole stick* held above its centre; even shocks are applied on the upper end of the *Mole Stick*, using the second stick as a hammer, until it has reached the bottom of the container. Then, pull (gently) the *Mole Stick* upwards! One should note that the *Mole stick* is stuck, as previously. As remarks, one should note that the sticking effect is somewhat smaller than the previous one — this experiment may therefore be less successful. However, thanks to its similarity with the *Stuck Stick* experiment, it is probable that similar sticking mechanisms also act during *Mole* penetration.

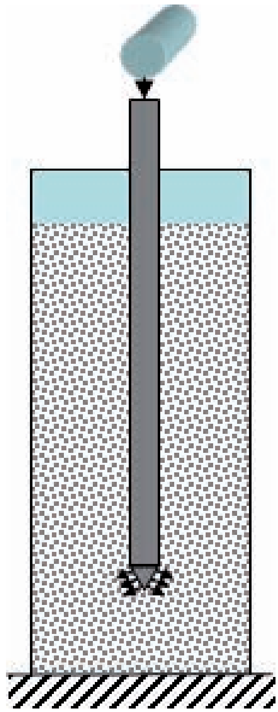

Figure 10: The 'Shock–Driven Mole Stick' experiment.

### 4.4 The *Screw Stick* experiment

A similar and quite strong sticking effect may be obtained without shocks, when driving down the *Mole* stick by hand with a screw effect, as described by Pousaz–Shepherd (2006). For this experiment the setup is the same as for the *Shock–Driven Mole Stick* experiment, but without the hammer. The cause of arches formation is obviously the quasi–static torque applied to the stick; the study of this physical mechanism would deserve separately special attention. This experiment is mentioned because of its close relation with the previous ones, but it is not discussed further here.

### 4.5 Modern analytical models

The *Modern Physics of Sands* uses simple mechanical models to illustrate some basic principles of the medium behaviour. More complex models can be developed by applying sophisticated numerical methods. Such models describe elasto–plastic grains, which are considered separately, not as a comtinuum. When such a very complex model is built, the limit for solving it is usually the available computer power.

# 5 Some assumptions on *Mole* penetration

The experiments described above help us to propose a tentative interpretation of the *Mole* penetration, purely qualitative. Let us consider a *Mole* penetrating a soil vertically, either driven by its internal shock mechanism or, as in the case of '*Mole stick* experiment, because of externally applied shocks. It appears that:

- When penetrating the soil, the *Mole* exerts a downwards force during each shock.
- The *Mole's* weight is added to the downwards force (a marginal effect).
- The total force is reacted by soil friction (dynamic during the advance, then static); this reaction depends on: (i) The soil properties: compressive strength, etc. – including its boundaries (container walls), and (ii) The *Mole's* shape and main parameters (diameter, roughness, tip shape, etc).
- Each shock creates (towards it ends) arches between the *Mole* and the soil.
- The next shock will break the existing arches, and create other ones.

In addition:

- The penetration displaces the soil (which is assumed to move mainly laterally).
- A penetration beyond one *Mole* length allows the soil to re–close the hole and recover its shape (which depends further upon soil properties: tests described in Richter et. al. (2006) showed that in some soils the hole behind the *Mole* remains open).

# 6 Expected improvements

## 6.1 Areas of improvement

The areas of improvements can be illustrated with the help of the previous Figure 2. A dynamic mathematical model of the hammering mechanism would be required to express directly the contact forces; a better soil model should improve noticeably both the models for resistive forces from soil and for the soil displacement by shocks, and eventually the model of the penetration performance of the *Mole*.

## 6.2 Expected benefits from a *Modern Physics of Sand* approach

Presently, no analysis of a stick penetration, furthermore of a *Mole*, has been treated with a *Modern Physics of Sands* approach (this needs to be confirmed by extensive literature search). With the present knowledge, it is assumed that a *Modern Physics of Sands* approach may provide a better understanding of *Mole* penetration:

(a) The *Mole* performance and reliability might be increased, at given power, following an optimal re–design.

(b) The penetration performance, in a different soil and under a different gravity, could be more confidently extrapolated from available experimental data on Earth.

(c) Inversely, experimental measurements from a planetary mission could be more accurately analysed to derive the soil properties from mission data.

(d) A mathematical model of the *Mole with hammering mechanism* could allow a better assessment of the mechanism parameters.

### 6.3 Proposed future approach

Two main steps are proposed — both supported by *Mole* penetration experiments for validation:

1. A first step should link a dynamical model of the *Mole* and its shock mechanism to a continuous soil finite elements model (FEM); such soil models already exist.
2. The second step shoud link the *Mole* to a model of finite grains: as mentioned earlier, this implies a very large computing effort.

Therefore, the *Mole* behaviour could be better understood and predicted, following a modelling and computing effort initially moderate, then more sophisticated.

## 7 Conclusion

The behaviour of the *Mole* or 'Mobile Penetrometer' with its shock mechanism has been presented with a current analytical method, based on experiments, civil engineering data and conventional analysis with energy methods. Some modern methods of the *Physics of Sands* have been presented quantitatively and some phenomena were illustrated by experiments. *Stuck Stick* and the *Shock–driven Stick* experiments show clearly that shocks may have some unforeseen effects, usually unpredicted. It is assumed that these modern methods (like continuous soil FEM or even grain FEM) could improve the *Mole* modelling, at the expense of high computing efforts. A future mission with a *Mole*, pursuing efforts of the ill–fated PLUTO *Mole* on Beagle2/Mars Express, would benefit from better predictions and data interpretation.

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