

# EVOLUTION OF DEFORMATION FIELDS IN PLOUGHING OF SAND

## EVOLUTION DES CHAMPS DE DEFORMATION LORS DE LA DECOUPE OTHOGONALE DE SABLES

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**ABSTRACT** – This paper reports on an experimental study on the ploughing or orthogonal cutting in sand. Plane strain cutting or ploughing experiments were carried out on model Ottawa sand while being imaged at high resolution. The images obtained were further processed using image analysis and the evolution of the velocity and deformation fields were obtained from these analysis. The deformation fields show the presence of a clear shear zone in which the sand accrues deformation. A net change in the direction of the velocity of the sand is also clearly visible. The effective depth of cut of the sand also increases with continuous cutting as the sand reposes on itself. This deformation mechanics at the incipient stages of cutting is similar to that observed in metal cutting.

### 1. Introduction

Ploughing, dredging and trawling in granular materials is often encountered in many civil engineering and infrastructural applications. The fundamental boundary condition in these classes of problems is that of orthogonal cutting.

Orthogonal cutting involves a plough (or a wedge shaped tool) removing a certain preset depth of soil as the tool moves in a direction normal to the depth of embedment of the tool. If, the deformation in such a set up is confined to 2 directions (i.e. plane strain), a narrow zone at the intersection of the tool and the material is formed which propagates through the cutting. The ratio of the thickness of the removed material to the depth of the cut is a measure of the strain in shear zone. The ploughing problem offers a unique perspective into the behaviour of sands subjected to severe plastic deformation (as has been very well understood in metal cutting - Johnson and Mellor). The velocity of traverse of the box, allows a control of the strain rate in the sand. Hence a combination of strains and strain rates can be achieved in this ploughing problem.

The effect of the development of pore pressure on the force applied on a tool (or plough) has been examined by Palmer (1999) using dimensional analysis. This analysis was also verified using model experiments under 1-g conditions, utilising Terzaghi's consolidation theory, a prediction of the pore water pressure developed during this severe plastic deformation of the soil is also presented in this paper. The effect of cavitation due to negative pore water pressures as a consequence of dilatancy is also addressed by correcting for the increased effective stresses in the soil. Van Os and Van Leussen (1987) present a full scale test on cutting forces in sand; the effect of dilatancy and the consequent increase in the cutting forces are

discussed in this paper. The authors also use a simple "single plane" cutting model to analyse their experimental data. Miedema (1985) summarises a series of experimental, and analytical papers on dredging in sand with an elegant mathematical model akin to the metal cutting models (Johnson and Mellor), effects of hydrostatic stress on the sand deformation is also considered in this model. Using contact dynamics simulations Nougier et al 2000 study the force fluctuations in ploughing of sand in a 2-d set up. The force exerted on the plough is close to the predictions made using Coulomb's failure in 2-d and 3-d using passive earth pressure theory. Additionally, their simulations show large fluctuations in the force exerted on the plough. Additional calculations on the strain tensor are also presented in the paper. In a recent study on the locomotion of organisms in sand, an experimental study in estimating the forces during the ploughing of granular media has also been reported by Gravish et al 2010. In the context of moving rovers in space applications, a series of controlled cutting experiments on a lunar regolith (model material) have also been reported by Skonieczny et al 2010, Wettergreen et al 2010. A recent study on the deformation fields in orthogonal cutting of sand with different plough angles (rake angles) has been presented by Murthy et al 2013. This paper presents additional results to this previous study (Murthy et al 2013), especially focussing on the evolution of deformation fields during ploughing of clean rounded sand.

### 2. Experimental

In order to study the evolving deformation parameters, the model sand was confined in a plexiglas box and a series of plane strain ploughing

tests were performed. This plexiglas box was mounted on a screw driven linear slide (Parker, USA) and the plough was fixed while the sand box was moved at a constant velocity. The dimension of the box used in this program was 2.5cm x 25 cm x 15 cm. A plough (or henceforth referred to as a tool) made of high speed tool steel (of the same thickness of the box) was fixed to a stationary frame and was adjustable only in the "z" or vertical direction, such that the depth of ploughing was controlled. The tool was placed at desired 'depths' in the box and the ploughing experiments were carried out at a constant speed.

Images were captured during the traverse of the box. The field of view of the images was kept constant in and around a region of the fixed tool. A Hasselblad medium format single lens reflex camera was used to capture images at very high resolution. A sample image obtained from the experiment is also shown in the fig. 1. Images were captured at a frame rate of 0.25 fps.

The model sand used in these experiments was rounded, medium fine, standard quartzitic sand (Ottawa sand C 778) of mean grain size 0.45 mm. This sand has been used extensively as a model material in many studies, including a comprehensive mechanical characterisation presented in Murthy et al 2007.

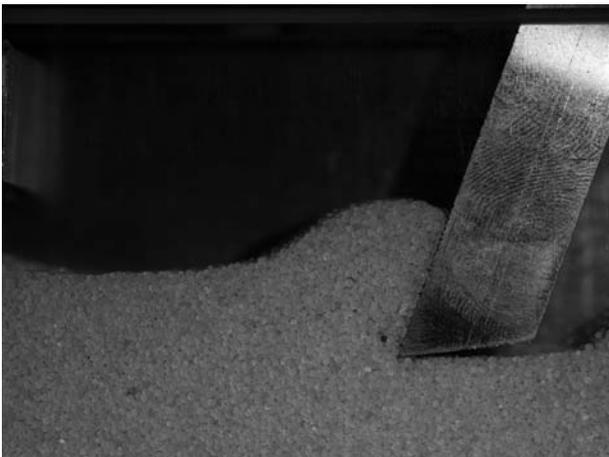


Figure 1. Sample image obtained during the experiment. The tool is kept stationary while the sand box is moved at a constant velocity

A PIV (particle image velocimetry) algorithm was used to analyse the images captured through the ploughing process, such an analysis has extensively been used to study the deformation field in soils (White et al 2003, 2004). The basic premise of a PIV algorithm is to assess a degree of match between images captured temporally, using a statistical cross correlation algorithm. Details of the PIV algorithm are provided by White et al 2003 and Adrian and Westerweel 2010. The deformation fields obtained from the PIV algorithm can be used to deduce velocity fields, strain rate fields and strains (mathematical description of the velocity,

strain rate and effective strain rate are presented in Murthy et al 2012).

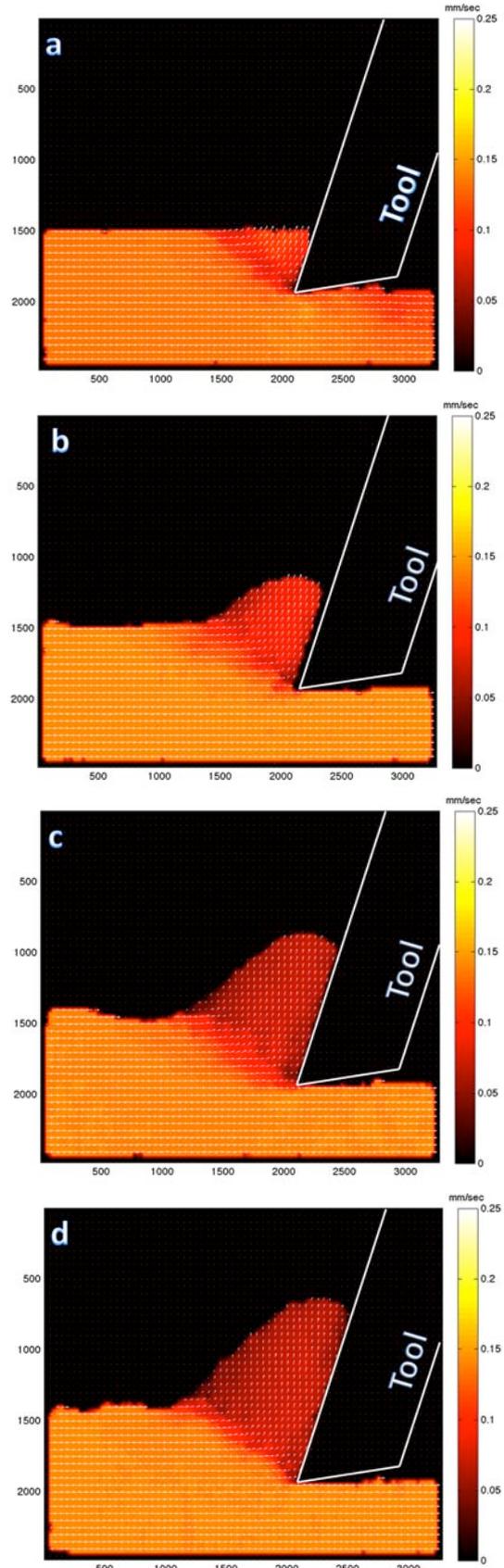


Figure 2 (a-d). A Series of velocity of contour maps on which a quiver plot is overlaid obtained at various time elapses indicating the evolving velocity of the sand during cutting.

### 3. Results

A series of ploughing experiments were conducted in this research programme. A preset depth of cut (of about 10 grain diameters ~ 4.5 mm) was used for all the cutting experiments. The yellow colour in the bulk of the sand represents the velocity of cutting while the chip also shows predominantly a uniform velocity.

The angle of the plough was fixed at 20 degrees measured with respect to the vertical. The Figure 2 presents a series of velocity fields with continued movement of the box.

The velocity field evolution shows the growth of the region of the sand removed or "chip" as indicated in the figure 2. The direction of traverse of the sand particles subjected to orthogonal cutting is clearly visible in the quiver plot overlaid on the velocity contour map in figure 2. This change in the direction of traverse of the sand being cut, and the formation of a shear zone at the corner of the plough or initiation of the chip is clearly visible in the contour of the velocity map. The bulk velocity of the sand is predominantly horizontal and is about 0.1mm/s (the cutting velocity), while the velocity direction in the chip is tangential to the plough rake face and drops to about 50% of the cutting velocity. The velocity field shown in figure 2 has a bulk region, wherein the velocity of sand is predominantly horizontal and a zone adjoining the plough is the shear zone, wherein the deformation changes direction. This shear zone extends from the tip of the plough through the thickness of the chip region. The chip region shows velocities which are tangential to the rake face of the plough shows a strong component in the vertical direction for the velocity vectors. A small region of zero velocity is also found at the corner of the tool tip and this is seen through the progress of the chip. This non-homogeneous deformation field also shows the presence of a small dead zone very close to the plough tip. In addition the presence of a zone at the far end of the shear zone also shows a "vortex" formation.

With continued progress in ploughing, the sand moves along the rake face of the plough (increase in the overall height of the chip), the sand grains begin to repose down the chip. The effective depth of ploughing increases as the sand reposes in front of the chip. Such an increase in the effective depth has been reported by the simulations of Noguier et al 2000 The shear zone wherein the sand accumulates the deformation continues to increase in size allowing a large amount of material to undergo plastic straining. As the sand grains continue to repose the height of the chip reaches an asymptotic value, however, this was length of cut was not reached in this set of experiments. A formation of a small vortex or particle rotation, as the sand grains repose with progress of cutting is also seen during this process. Fluctuations in the force signature on the plough has been observed in

both simulations and model experiments (Noguier et al 2000 and Palmer 1999), an analysis of the force signatures will be presented in forthcoming publications.

### 4. Summary

The force exerted during the traverse of a plough is well documented; however, this study presents the evolving velocity fields during the ploughing of dry sand. The velocity field shows an evolution towards the establishment of a steady state. The sand is subjected to large deformations as it is ploughed. A shear zone is established at an initial stage of the cutting process, and this shear zone increases in size corresponding to the increase in the size of the chip. The velocity in the chip is predominantly uniform with very little variation seen in the magnitude, however the direction of the sand changes as the chip progresses upward. The effective depth of cut during the ploughing also is seen to vary with continued ploughing, as the sand reposes in front of the plough. Further studies relating the velocity, strain rate, strain magnitude in addition to force fluctuations are presented in forthcoming publications.

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