ANALYSIS OF PLOUGHING IN SAND

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INTRODUCTION

Numerous applications in geomechanics involve large displacement of soil by lateral movement of an object, a process here referred to as 'ploughing'. In applications such as earthmoving (Fig. 1) and trenching (Fig. 2), the ploughing effect is plainly visible, although this phenomenon can also play an indirect role. For example, significant volumes of soil can be displaced when pipelines buckle laterally (Fig. 3), and tractive devices for off-road equipment often rely on grousers or cleats that plough the soil as a result of slippage.

While some level of understanding of ploughing in saturated clay can be derived from the literature on machining of metals, studies concerned with ploughing in sands are limited. Also, there is a basic lack of understanding of the unsteady regime in which the object first begins to slide across the surface with prescribed force or penetration. In this transient regime, the shape and location of material boundaries, as well as the stress and displacement fields, evolve in time. As a consequence, basic quantities of interest such as horizontal (drag) force and penetration also change in time.

The overall goal of this research is to build a basic understanding of ploughing processes in dry sand, beginning with fundamental aspects for simple object geometries and progressing to applications. A major objective is to develop efficient computational approaches for modelling the complete ploughing process. In contrast to finite element methods, which lack the robustness required to solve such evolutionary plasticity problems, and discrete element methods, which are highly inefficient, the proposed techniques are tailored specifically to the ploughing process to achieve a high level of efficiency, accuracy, robustness.

Figure 1: Excavation of soil by earthmoving equipment.

Figure 2: Skid plough used to create trenches for pipelines and cables.

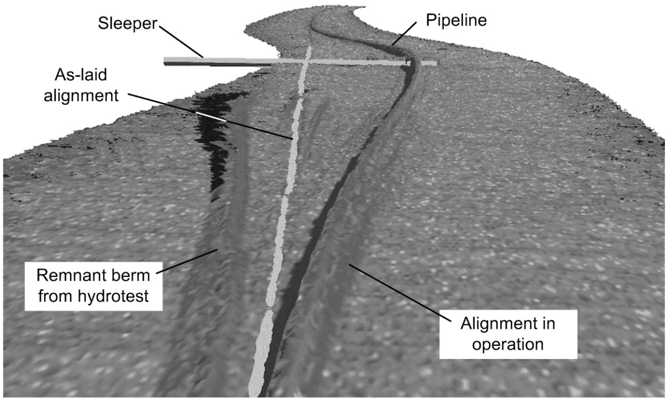

Figure 3: Ploughing effect caused by lateral buckling of a pipeline.

INCREMENTAL PLASTIC ANALYSIS

One proposed computational approach draws on concepts from the kinematic method of limit analysis to obtain a realistic pattern of deformation within each increment of displacement. By appropriately updating material boundaries within each increment, the full process is simulated.

A preliminary analysis for the fundamental cutting problem involving a flat, vertical blade translating through sand at constant depth is shown in Fig. 4 (Hambleton and Kashizadeh 2013a,b). The sequence of images in Fig. 4 shows both the theoretical prediction and the results of a preliminary laboratory test for various values of u/d, the ratio of the wall displacement to the depth of cut. Markers are placed in both the computational results and the experiments to show the accumulated deformation. The red line in the theoretical predictions shows the current position of the single slip surface (shear band) assumed in the computational model. It can be seen that the method predicts the deformed shape and succession of slip surfaces well, although the slip surfaces transition at a higher frequency than predicted.

Current research activities are focused on refining the constitutive law assumed in the computational model and extending the method to more complex geometries and loading conditions. A long-term goal is to extend the methodology to three dimensions, where the incremental analysis will hold even greater advantages over alterative numerical methods, especially with respect to efficiency.

PHYSICAL MODELLING

Having completed the preliminary tests shown in Fig. 4 as a proof of concept, a full suite of laboratory testing is currently underway at the Centre for Offshore Foundation Systems (COFS). These experiments focus on recording the force-displacement history as well as the evolving pattern of deformation within the soil. The test setup makes it possible to take high resolution images, which can be subsequently analysed with a high precision using Particle Image Velocimetry (PIV). The first phase of the project focuses on testing at 1g.

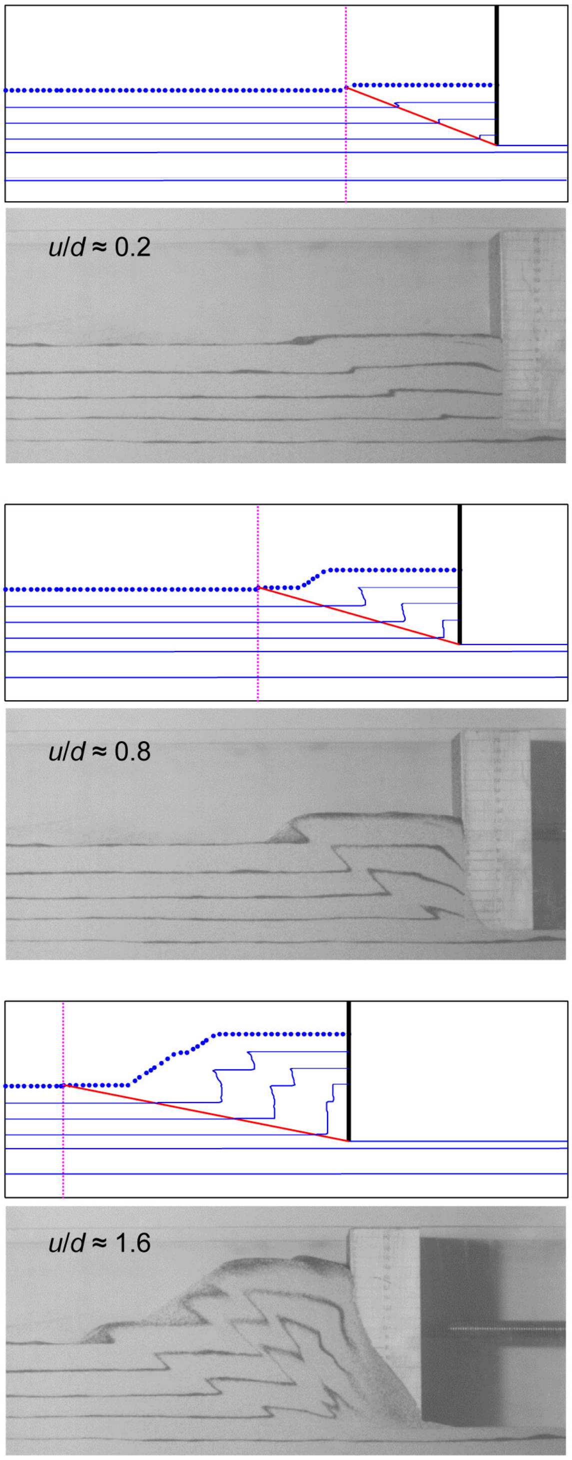

Figure 4: Sequence of predicted and observed deformation for vertical blade translating through dry sand at constant depth.

However, the apparatus developed for the 1g tests can be placed directly in the beam centrifuge located at COFS, thereby replicating the conditions for large-scale ploughing processes.

EXPECTED OUTCOMES

Ploughing processes are ubiquitous in the natural world and industrial applications, and this study represents one of the first attempts to develop a systematic framework for understanding and predicting these processes in their entirety. This will not only shed light on a phenomenon that is poorly understood but also facilitate technological breakthroughs.

In applications such as excavation and trenching, it is desirable to minimize the lateral forces developing during the ploughing process, thereby minimizing power expenditure and fuel consumption. Most carbon dioxide emission from earthworks is the result of fuel consumed by machinery (Hughes *et al*. 2011), and a major component of this is attributed to excavation of soil. A small improvement in efficiency therefore has a potentially large effect in reducing costs and mitigating environmental impacts. In other applications, such as the design of tractive devices and foundations to resist lateral loads, the objective may be to maximize the lateral force (resistance) generated by the soil. Ultimately, this study will provide valuable information for assessing optimal configurations and operating conditions.

REFERENCES

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