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THE OPTIMISATION OF TOOL SHAPES AND TRAJECTORIES IN HEAVY MACHINES

A.Jarzebowski, J.Maciejewski, D.Szyba, W.Trampczyński

Abstract

The aim of this paper is an experimental determination of the most efficient tool trajectories and tool shapes from energy consumption point of view, for heavy machines tools during the filling process. Laboratory tests were performed under plane strain conditions on a constant slope made of cohesive soil, using various model tools. The most efficient tool trajectories were searched, from energy usage point of view, to find a method of excavating an assumed amount of soil in a single tool pass. As the experiments were performed under the plain strain conditions for simplicity of assembling the photographic documentation, the influence of side walls was neglected in this study.

The experimental stand, modelling cohesive soil and the method of slope preparation are also briefly presented.

The first group of tests was carried out using various curvilinear and piece-wise linear trajectories. The two-staged piece-wise trajectory, consisting of the horizontal movement of the tool and its withdraw along the straight line was found to be the energetically most efficient. In the second group of tests this-two staged trajectory was carefully investigated and the influence of the inclination of the withdraw trajectory was studied and the optimal inclination was established. In the third set of tests various shapes of the model tools were used to investigate the influence of the rear wall position and the optimal shape was identified.

It was found, that using, in the model laboratory tests, optimal trajectories and tool shapes one can save over 50% of tool filling energy.

1. INTRODUCTION

Although it is well known, that the earth moving processes prior and during construction work, carried out by heavy machines such as loaders and excavators are energetically very ineffective and their optimisation can save a lot of energy. These processes have not been properly investigated. The earth cutting process and the tool filling process are very important for energy efficiency, but have not been properly analysed and theoretically described.

The aim of this study is to find experimentally energy efficient tool shape and the most effective trajectory which allows to excavate an assumed amount of material in a single tool pass. The material was assumed to be the cohesive, clay alike, with free boundary formed as a slope characterised by the constant inclination.

In this paper series of laboratory results are presented in order to achieve the above mentioned task, which is, to search for the energetically most effective trajectories for the loader bucket filling process and the most effective tools proportions. All experiments were carried out on a semi-laboratory scale using the special, fully automatic (computer controlled), stand and the cohesive model soil. Tests were performed under the plane strain condition (to simplify the photographic documentation) using the model of the tool, which was moved along the prescribed path. The energetically most effective trajectories and tool proportions were found on the basis of experimental results and theoretical prediction obtained using the theory of plasticity.

It was found [1, 2, 3], that in the case of earth-moving process due to heavy machine tools, the cohesive material deforms to generate rigid zones sliding along the slip lines (well visible cracks) along which the material substantially changes its parameters (the initial cohesion c decreases to the residual value close to c_r=0). In the case of the simple tool pushing process on the perpendicular wall, the force/displacement relationship (Fig. 1 [4]) shows that the horizontal force grows in unstable manner, as the process advances. The moment due to reduction of the force coincides with creation of a kinematical mechanism originating from the tool end. Such mechanisms are created periodically and are described theoretically using kinematically admissible mechanisms of the theory of plasticity [5-10]. Assuming the material to behave according to Coulomb-Mohr theory, with softening under plane strain conditions, it is possible to describe the problem of the heavy machine tool filling process using the sequence of kinematically admissible solutions. It was shown, that such a theoretical prediction describes quite well main effects observed experimentally.

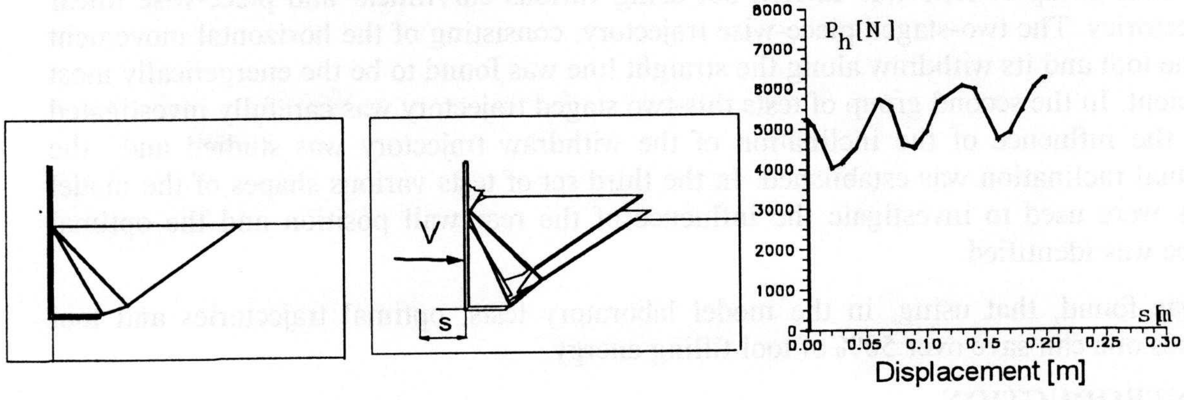


Fig. 1 Typical deformation of cohesive soil in the case of the advanced shoving process performed by the horizontal tool motion (theoretical solution)

Taking into account previously mentioned observations and theoretical solutions, it is possible to show that as soon as slip lines are created within cohesive material, the energetically most effective way of the tool filling is to follow previously created slip line by the tip of the tool [1, 11]. This observation became one of main factors for setting up an experimental program to find the energetically most effective trajectories for the loader bucket filling process and the most energy effective tools' proportions Details of that program together with the results are described in this paper.

2. EXPERIMENTAL PROCEDURE

All experiments were performed in a semi-laboratory scale using the special, fully automatic (computer controlled), stand which was described in detail in [1]. Therefore, only main features of this device will be presented in this paper (Fig. 2). The soil sample was prepared in a fixed container (2 x 1.2 x 0.6 [m]) having one transparent wall to enable taking photographic record of the material behaviour. The tested model of the tool (1) was moved within the container by means of three hydraulic jacks, which motion was fully computer controlled through the electric, proportional valves and a hydraulic pump. The horizontal motion was aided by the hydraulic jack (2), which moved the front cart (5), while the rear cart was locked. The vertical motion device was mounted on the front cart (5). It consisted of the rigid frame (6) driven by the piston (3). The hydraulic jack (4) responsible for the rotation of the tool was mounted onto the frame together with various models of the tools (1). The set of loading cells (7) allowed for the measurement of horizontal and vertical force components.

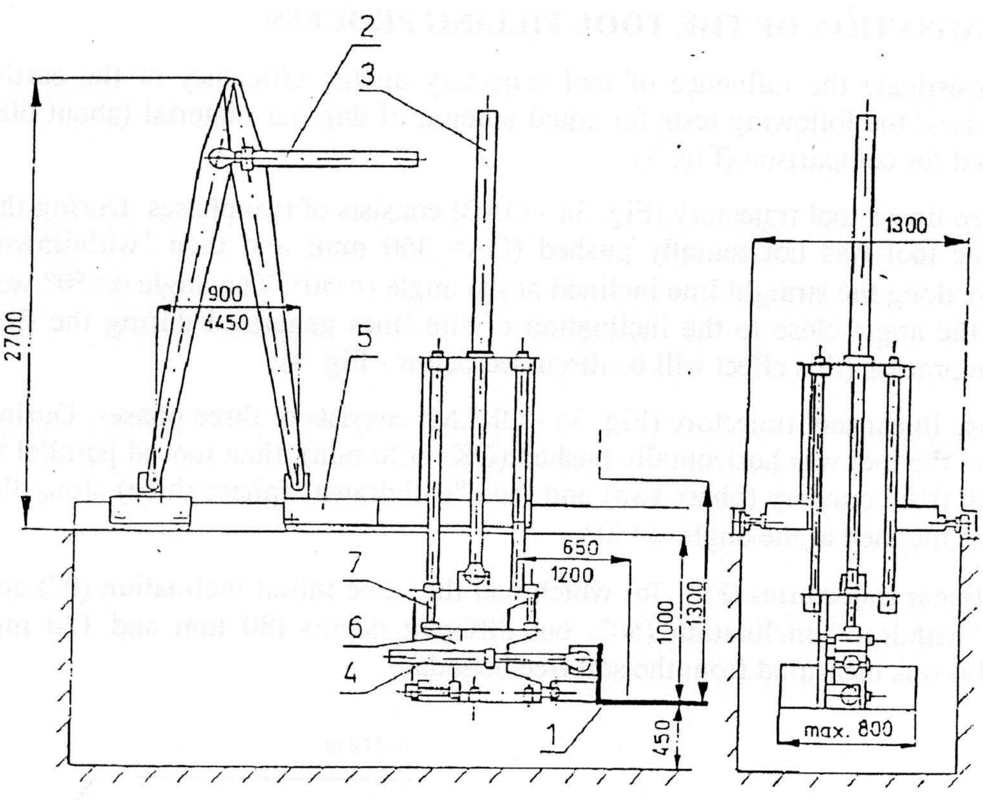


Fig. 2 The fully automated stand for testing heavy machine tools investigation: 1. Model of a tool, 2. Horizontal hydraulic jack, 3. Vertical hydraulic jack, 4. Rotation hydraulic jack, 5. Horizontal movable frame, 6. Vertical movable frame, 7. Loading cells.

Displacement of the tool was measured by two linear extensometers and one rotational. All data obtained this way was collected and stored by the computer and used for the "on line" control. Various tool trajectories were planned and realised during the test by numerical control.

The special artificial material, imitating a clay and its parameters, was prepared for this experiments. It consisted of: cement -50%, bentonite - 20%, sand - 18% and white vaseline-12%, and was characterised using the following parameters: φ =24° (internal friction angle), γ=18.4 kN/m^3. All components were heated in a furnace, mixed and cooled to room temperature.

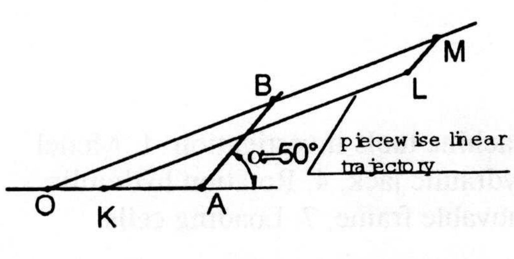
Application of white vaseline, as one of the components, resulted in obtaining a cohesive soil, which parameters were not influenced by air humidity and liquid flow. It also ensured, that those parameters were stable during all experimental program.

Before each test the model soil was mechanically pre-consolidated using a special device, based on the idea of dropping a certain mass from different heights. Special compacting procedure allowed for obtaining uniform medium cohesion c=20 kPa. Then, the slope forming process was executed in several passes, by cutting and removing thin layers of material to avoid initial cracking of the model slope inclined at the angle λ=20°.

3. THE OPTIMISATION OF THE TOOL FILLING PROCESS

In order to investigate the influence of tool trajectory on the efficiency of the earth-working processes, the following tests for equal amount of dug out material (about 600 N) were selected for comparison (Fig. 3):

1. A piece-wise linear tool trajectory (Fig. 3a - OAB) consists of two phases. During the first one the tool was horizontally pushed (OA= 360 mm) and then "withdrawn" (phase two) along the straight line inclined at the angle α=50°. The angle α=50° was chosen as the angle close to the inclination of slip lines generated during the first stage of the process (this effect will be discussed below - Fig. 4).
2. A piece-wise linear tool trajectory (Fig. 3a - OKLM) consists of three phases. During the first one the tool was horizontally pushed (OK= 120 mm), then moved parallel to the material free boundary (phase two) and then "withdrawn" (phase three) along the straight line inclined at the angle α=50°.
3. Two curvilinear trajectories (Fig. 3b) which had the same initial inclination (0°) and the same "withdraw" inclination (50°) but different depths (80 mm and 120 mm respectively) was measured from the soil free boundary.



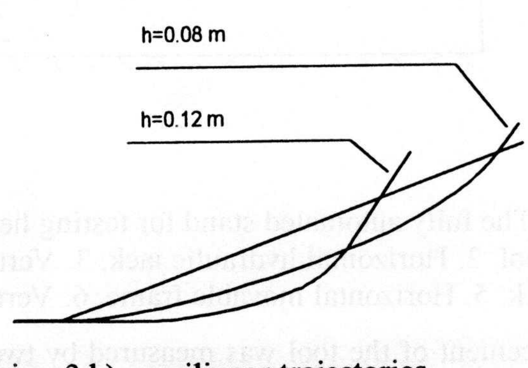


Fig. 3.a) Piece-wise linear trajectories; 3.b) curvilinear trajectories.

All experiments were realised under the plain strain condition, using the L-shaped model tool (Fig. 4c - LA=180 mm), which had the width equal to the width of the soil container. Soil samples prepared in a form of slopes at the inclination of 20 degrees were used. During the first stage of the process the tool was always pushed horizontally, but was inclined at the angle - 5 degree (Fig. 4a) to avoid friction between the bottom of the tool and the remaining layer of soil. Then, the motion of the tool was performed together with its rotation, to model the filling process. Having continuous record of the force acting on the tool and its displacement during the process, the amount of specific energy W_f was calculated for the unit weight of the soil dug out by the tool.

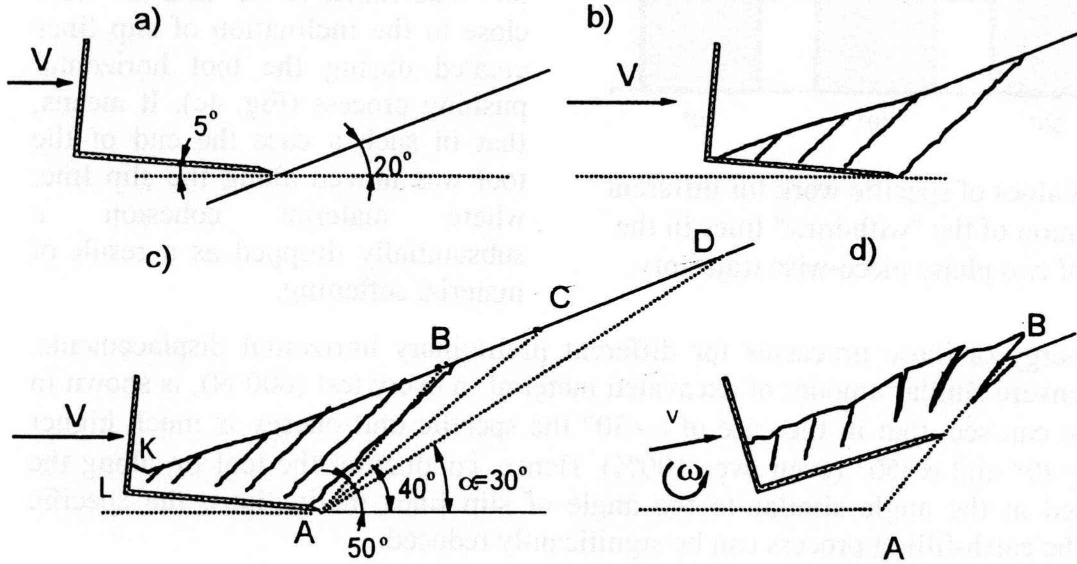


Fig. 4 Experimental program for slope sample: a) model of the tool and slope; b) initial stage of the process - horizontal movement; c) advanced stage of horizontal movement and various trajectories; d) the final stage of the process.

In Fig. 5 values of specific energy W_f for various trajectories are presented. One can notice, that two-stages piece-wise linear trajectory is the most energy efficient and over 50% of filling energy can be saved.

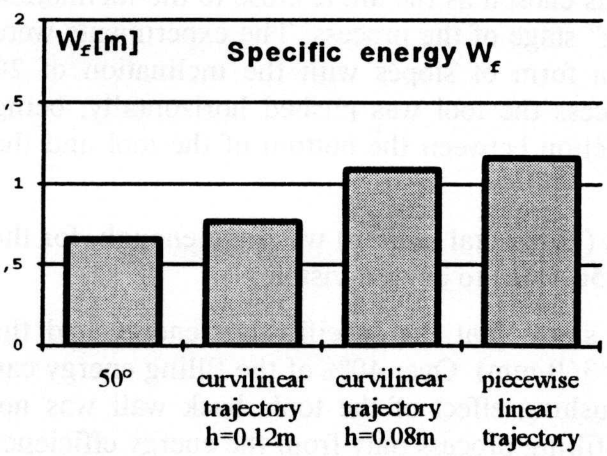


Fig. 5 Values of specific energy for different trajectories.

Because it was found, that the two-stages piece-wise linear trajectory is energetically most efficient, a set of additional tests for such tool paths was then performed.

The typical scheme for such tests is shown in Fig. 4. The L-shaped tool, inclined at an angle-5° simulating the real process, (LA=180 mm) was first pushed into slope to a certain position (Fig. 4b). When the tool was advancing, the slip lines were created

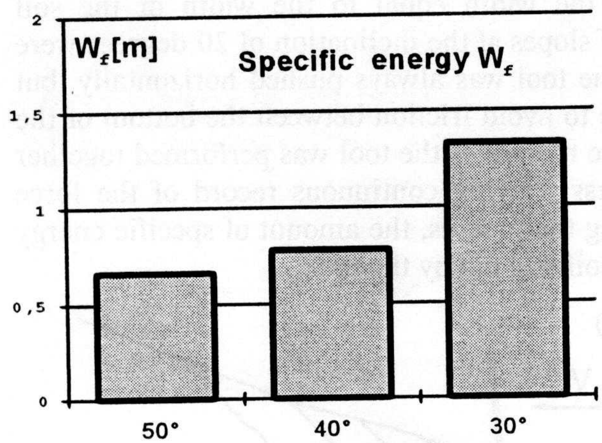


Fig. 6 Values of specific work for different inclination of the "withdraw" lines in the case of two phase piece-wise trajectory.

periodically from the tool tip to the material free boundary, at the angle α=45°. In the next phase, the tool tip was moved along three different straight lines (Fig. 4c), with simultaneous rotation of the tool (Fig. 4d) to have it filled with the material. Those straight lines were inclined at angles α=30°, 40° and 50°. The values α=40° and 50° were close to the inclination of slip lines created during the tool horizontal pushing process (Fig. 4c). It means, that in such a case the end of the tool was moved along the slip line, where material cohesion *c* substantially dropped as a result of material softening.

Specific energy of those processes for different preliminary horizontal displacements, chosen to ensure similar amount of excavated material in every test (600 N), is shown in Fig. 6. One can see, that in the case of α=30° the specific unit energy is much higher than for α=40° and α=50° (even over 100%). Hence, conducting the tool tip along the line inclined at the angle similar to the angle of slip lines inclinations, the specific energy of the earth-filling process can be significantly reduced.

4. THE OPTIMISATION OF THE TOOL SHAPE

In order to investigate the influence of tool shapes on the efficiency of the earth-working processes, a series of piece-wise linear two-stages tool trajectory tests, for equal amount of excavated material was performed (Fig. 3a - OAB). The model tools, which shapes are schematically presented in Fig. 7, were horizontally pushed to a certain position and then "withdrawn" (phase two) along the straight line inclined at the angle α=50°. As for the previous series of tests, the angle α=50° was chosen as the angle close to the inclination of slip lines generated during the "pushing" stage of the process. The experiments were carried out on soil samples prepared in a form of slopes with the inclination of 20 degrees. During the first stage of the process the tool was pushed horizontally, being inclined at the angle-5 degree to avoid friction between the bottom of the tool and the remaining layer of soil.

The length of the first phase of the process (horizontal motion) was long enough, for the pushing effect of the tools back walls (Fig. 5c - KL) to be well visible.

Experimental results presented in Fig. 8 show, that the specific unit energy had the lowest value for the "long" tool (Fig. 7, L=360 mm). Over 40% of the filling energy can be saved this way. In such a case, the pushing effect of the tools back wall was not observed. It means, that analysing the tool filling process only from the energy efficiency point of view, the most favourable tool shapes are such, that the energy due to the tool back wall pushing process is minimised.

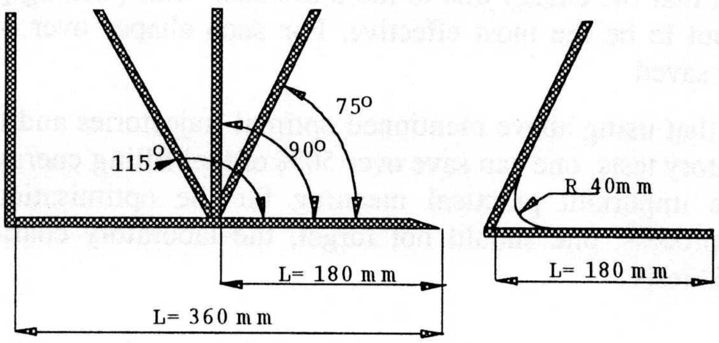


Fig. 7 The model tools shapes

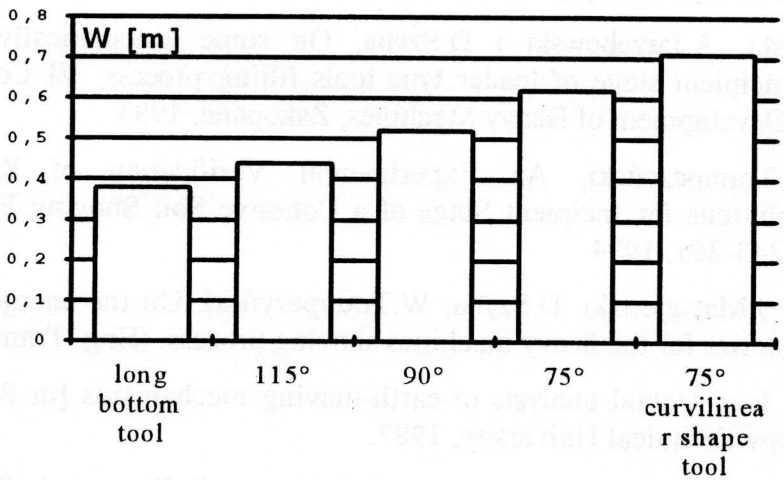


Fig. 8 Values of specific tasks for different tool shapes in the case of two phase piece-wise trajectories.

5. CONCLUSIONS

Presented experimental results show that in the case of cohesive soil earth-moving process the following conclusions can be drawn:

1. Material deforms as rigid zones sliding along the slip lines where material substantially changes its parameters (cohesion).
2. Moving the machine tools along previously created slip lines, one can substantially save energy used during earth-moving processes (tool filling). This observation was the basis for the optimisation of the filling process.
3. For different trajectories, the two-stages piece-wise linear trajectory with the withdraw path inclined at the angle equal to the inclination of slip lines, turned out to be the most effective from the energy efficiency point of view. 50% of filling energy can be saved this way.
4. In the case of two-stages piece-wise linear trajectories, consisting of horizontal pushing followed by straight line "withdraw", the influence of the withdraw trajectory inclination was most important. For inclinations equal to the inclination of the slip lines created during the first phase, the process was energetically most effective.

5. The tool shapes, such that the energy due to the tool's back wall pushing process was minimised, turned out to be the most effective. For such shapes over 40% of tool filling energy can be saved.

Presented results show, that using above mentioned optimal trajectories and tool shapes, during the model laboratory tests, one can save over 50% of tool filling energy. Although these results may have important practical meaning for the optimisation of heavy machines tools filling process, one should not forget, the laboratory character of the model and the performed tests.

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