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ON THE ENERGETICALLY MOST EFFICIENT TRAJECTORIES FOR THE HEAVY MACHINE SHOVING PROCESS (*)

A. JARZĘBOWSKI, J. MACIEJEWSKI

D. SZYBA and W. TRĄMPCZYŃSKI (WARSZAWA)

Taking into account theoretical predictions and preliminary test results, the experiments concerning the influence of tool trajectory on the specific energy of heavy machinery tool filling processes were performed. All experiments were carried out on a semi-laboratory scale using the special, fully automatic stand and the cohesive model soil. Tests were executed for both the laboratory-prepared horizontal and inclined slopes, using the model of the tool, which was first pushed into the slope and then "withdrawn" in various directions. Two different methods of driving out the tool were used: tool motion without rotation and with rotation, to simulate the filling process. It was found that the tool trajectories planned by means of the kinematically admissible solutions are energetically most effective.

1. Introduction

Although it is well known that the earth moving processes connected with construction works, performed by heavy machines such as loaders and excavators, are very important from the engineering point of view, it has not been properly investigated and theoretically described until now. In this paper series of experimental results are presented in order to search for the energetically most effective trajectory of the model of a loader bucket filling process.

Until now, several theoretical solutions of the problem of passive and active pressures exerted by a granular material on a rigid wall were found within the theory of plasticity [1–6]. Some limitations in obtaining complete solutions using the method of characteristics were reported [7]. Lately, a simplified technique, based on kinematic mechanisms for Coulomb–Mohr

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material [8] and Coulomb – Mohr material with softening [9 – 12] was developed to describe the problem of the heavy machine tool filling process. Its experimental verification is a subject of this study.

2. Experimental results

2.1. Experimental device

A fully computer-controlled stand was designed and built in the technical scale (Fig. 1) [13]. The soil sample was prepared in a fixed container (2 × 1.2 × 0.6 [m]) having one transparent wall to enable photographic recording of the material motion. The tested model of the tool (*1*) was moved within the container by means of three hydraulic jacks, whose motion was fully computer-controlled through the electric, proportional valves and a hydraulic pump. The horizontal motion was realised by the hydraulic jack (*2*), which moved the front cart (*5*), while the rear cart (*6*) was locked. The

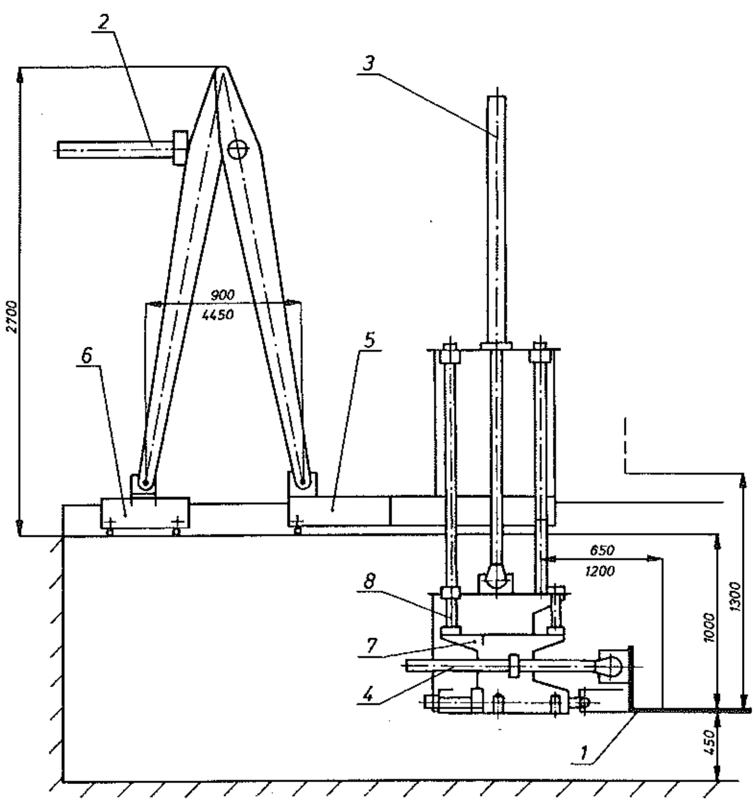

Fig. 1. Scheme of the stand.

vertical motion device was mounted on the front cart (*5*). It consisted of the rigid frame (*7*) driven by the piston (*3*). The hydraulic jack (*4*) responsible for the rotation of the tool was mounted on that frame together with various models of the tools (*1*). The set of load measuring cells (*8*) allowed for the measurement of horizontal and vertical force components. Displacement of the tool was measured by two linear extensometers and a rotational one. All the data obtained in this way were recalculated (and stored) by the computer and used for the "on line" movement control. Various tool trajectories were planned and realised during the test by numerical control.

2.2. Sample preparation

The special modelling material was developed and prepared for this study, as a mixture of: white cement (50%), bentonit (20%), fine grain sand (10%), coarse grain sand (8%) and white vaseline (12%).

All components were heated in a furnace, mixed and cooled to room temperature. Material parameters of this model soil, such as internal friction angle φ and material cohesion c, were measured during a direct shear test, and the following values were found: $\varphi = 23.4°$, $c = 19.6\,\text{kPa}$, for unit weight of $\gamma = 18.4\,\text{kN/m}$, what corresponded to initial condition after a sample preparation at the beginning of each test.

Application of white vaseline as one of the components resulted in obtaining cohesive soil, what usually is correlated with moisture content. Here, water was not used and, successfully, soil parameters were not influenced by air humidity and liquid flow or liquid distribution within the sample. Thus, one of the serious troubles with experimental cohesive soil tests dependence on atmospheric conditions were avoided. However, it was observed, that the soil model used was sensitive to seasonal changes of temperature in the laboratory. Because of this phenomenon, series of tests were performed during the same period and only the tests results obtained within the same season were compared.

In every test the container was filled subsequently layer by layer (60 mm each) and compacted to ensure the repeatability of the weight density. A special plate was used for the compacting process, which was executed in several steps. The plate was dropped from a certain height for each step and this height was increasing during the process. Finally, an upper thin layer of material (20 mm thick) was cut off and removed to ensure material homogeneity. As a result, a flat soil sample of thickness 300 mm, uniform density and homogeneous distribution of material parameters was obtained.

In the case of tests performed on slopes, the initial slope was formed with the assumed inclination of 20 degrees. At the beginning the sample was prepared similarly to the horizontal ones described above. Then, the slope forming process was executed in several steps by cutting and removing thin layers of material, to avoid initial cracking of the model slope.

2.3. Laboratory tests

Using the described above stand it was possible to simulate a wide program of soil shoving processes with different working paths. In that series of experiments the L-shaped model tool was applied. Since the tool had the width equal to the width of the soil container, all tests were approximately performed under plane strain conditions.

A photograph showing a typical shoving process is presented in Fig. 2a. During this initial test the tool was subjected to horizontal motion and, consequently, it pushed the soil sample. As a result, the characteristic soil deformation pattern was observed, consisting of several rigid zones sliding along the slip lines (well visible cracks, denoted by arrows in Fig. 2a) within which the material changed its strength parameters. This phenomenon resulted in an unstable relation between the horizontal component of the earth working force and the tool displacement as the process advanced (Fig. 2b). The instant of the force drop coincided with the creation of a new slip line originating from the tip of the tool. Creation of the slip lines repeated periodically. Such a material behaviour can be theoretically predicted using kinematically admissible solutions of the theory of plasticity [12, 14].

2.3.1. Tests made on samples with horizontal boundary. The described phenomenon of slip line generation was later applied in the process of searching for the most efficient soil cutting and tool filling trajectory. The simplest idea was to follow the tip of the tool along the slip line generated in the first phase of the process – the horizontal pushing phase. To check this idea, two sets of tests were performed on the model soil samples with horizontal boundaries. In both groups of experiments two-stage tests were performed. During the first stage the model tool (inclined at an angle of 5° to avoid friction between the bottom of the tool and the remaining layer of soil) was pushed horizontally through the soil sample. In the second stage, the tool was "withdrawn" from the sample along the straight lines with various inclinations (Fig. 3a). In the first group of tests, the second stage was executed by parallel translation of the tool, whereas in the second group of tests the tool

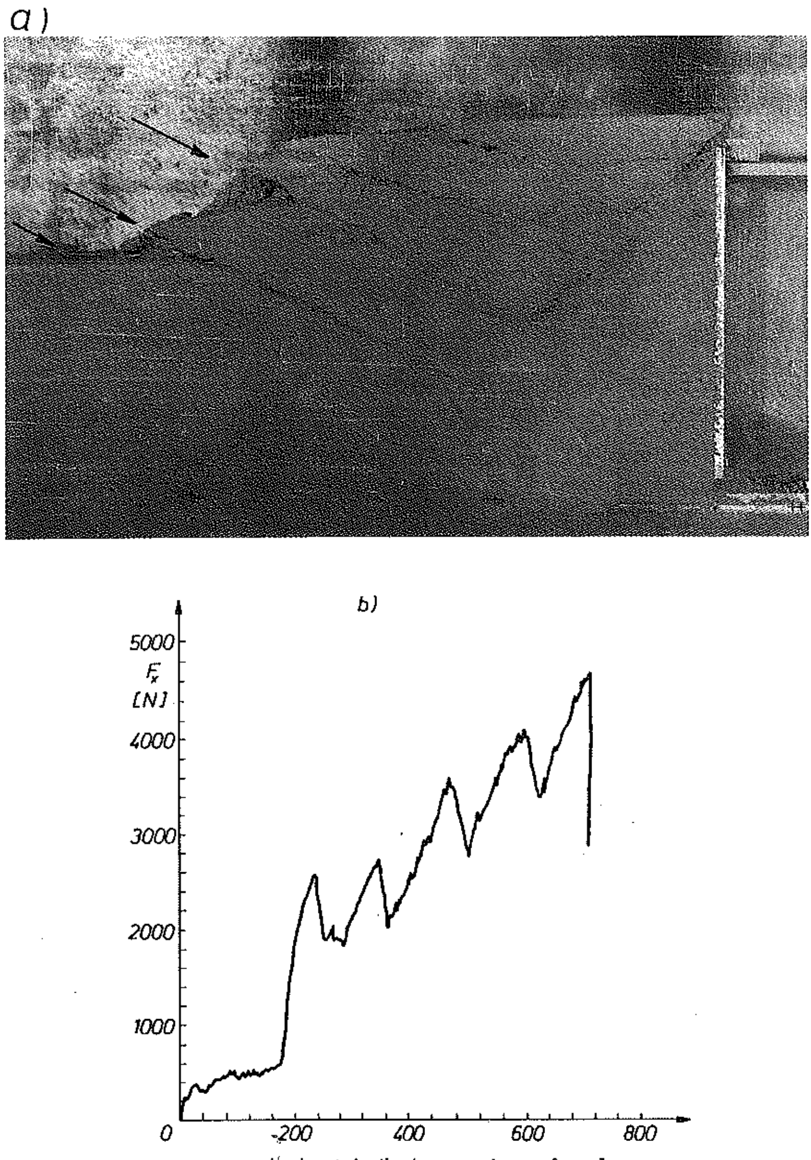

FIG. 2. Typical deformation of cohesive soil in the case of the advanced shoving process by horizontal tool motion: a) a photo showing subsequent slip lines; b) horizontal force versus horizontal displacement.

was "withdrawn" together with its rotation, to model the real tool filling process.

In the first group of experiments the same first phase of the process was executed, and in the second phase the path inclinations of 22°, 31° and 42°

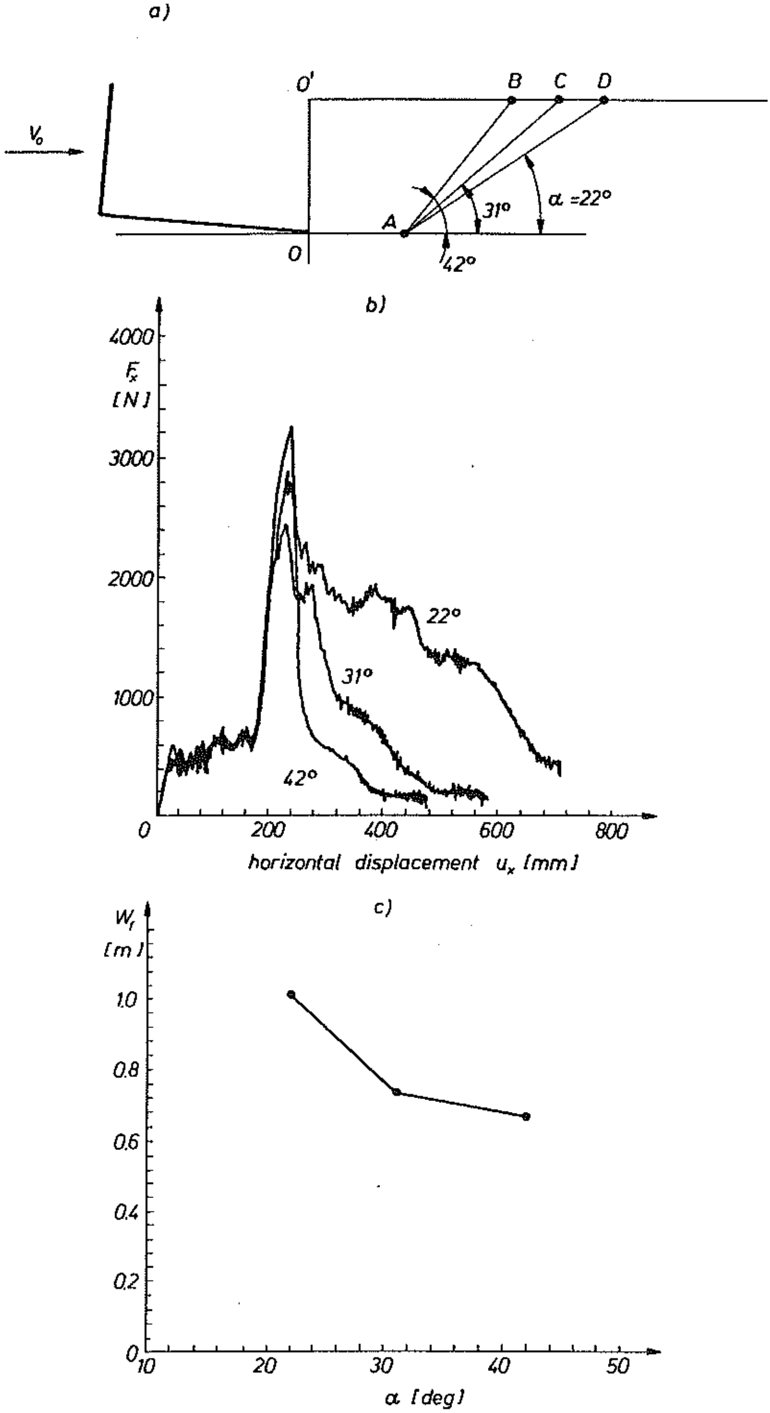

FIG. 3. Experimental program for flat soil sample: a) various trajectories; b) horizontal force versus horizontal displacement for three different trajectory inclinations.

were used. The value of 31° was equal to the inclination of the slip lines generated during the first stage of the process.

The amount of specific energy W_f, calculated for the unit weight of the soil excavated was computed for every test to allow direct comparison. For example, for the tool trajectory OAB (Fig. 3a), the area of the cross-section $OABO'$ multiplied by the width of the soil bin was used to define the amount of excavated soil.

In Fig. 3b the relation between horizontal force and the displacement of the tool is presented for the three trajectories mentioned above, whereas in Fig. 3c the relation between specific energy W_f and trajectory inclination is plotted. Although the amount of the soil excavated increased with decreasing trajectory inclinations, the efficiency of the process was also decreasing (notice high value of energy for the inclination of 22°). It was caused by generation of new slip lines even during the "withdrawing" phase (see Fig. 4, where the initial slip line is denoted by AD and subsequent slip line by $A'D'$). The efficiency of trajectories with inclination similar or higher than the inclination of the naturally generated slip line was comparable (the difference in specific energy was equal to 10%).

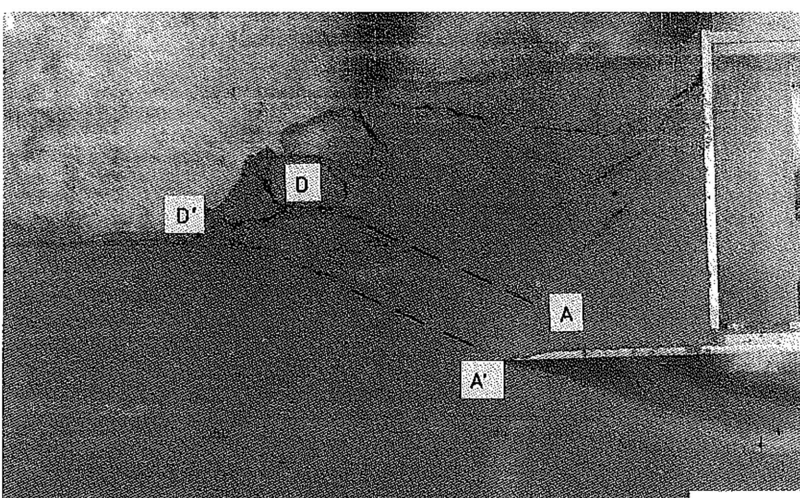

FIG. 4. An advanced stage of the shoving process for trajectory inclination 22 (AD – initial slip line, $A'D'$ – new slip line, generated during the "withdraw" phase).

In the second group of tests (with tool rotation during the "withdraw" phase), again three different trajectory inclinations were executed (20°, 31° and 50°). In addition, three different points for the transition from the first to the second phase of the tool trajectory were used in order to investigate more precisely the instant when the slip line begin to generate. The trajectory switch points (Fig. 3a – point A) were chosen slightly before, shortly after and during the generation of the slip line during the initial (pushing) phase. Results of those tests are given in Table 1 and plotted in Fig. 5a and 5b. The influence of trajectory inclination on values of specific energies are similar for both groups of tests (without and with tool rotation).

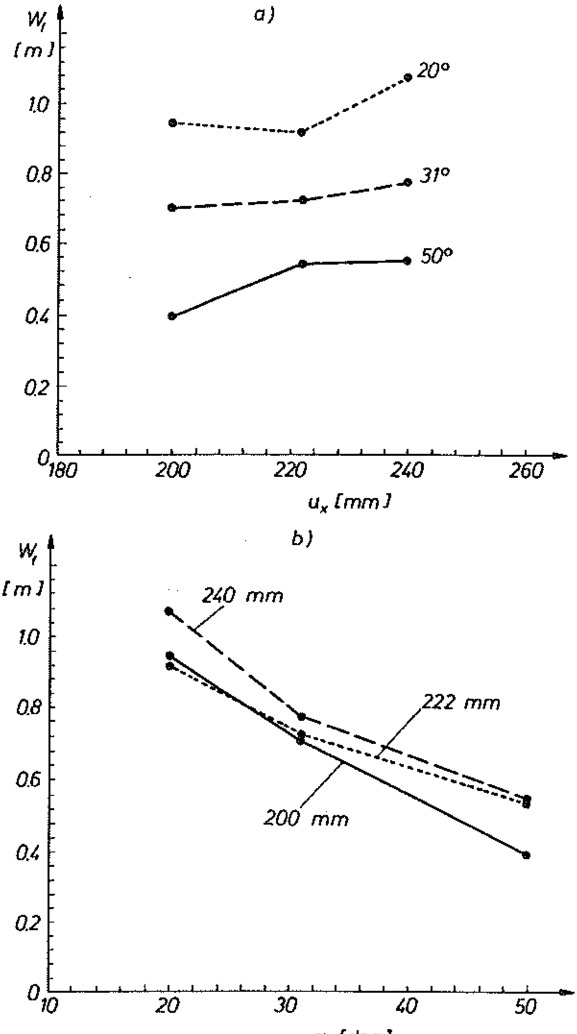

FIG. 5. a) Values of specific work W_f versus range of the initial phase of trajectory for different trajectory inclinations; b) values of specific work W_f versus trajectory inclination for different ranges of the initial phase of trajectory.

The influence of the instant of slip line generation combined with the moment of passing from one trajectory phase to another is much more im-

Table 1. Results of experimental program for flat soil samples.

1	2	3	4	5
Test No	Trajectory switch point A u [mm]	Trajectory inclination α [deg]	Weight of excavated soil [N]	Specific energy W_f [Nm/N]
1	200	31	739	0.70
2	222	31	763	0.72
3	240	31	794	0.77
4	200	20	918	0.94
5	222	20	950	0.91
6	240	20	972	1.06
7	200	50	584	0.39
8	222	50	635	0.54
9	240	50	667	0.55

portant for less inclined trajectories. In the case of displacement of the tool equal to 210 mm, the slip line was generated as a result of trajectory change and turned out to be less efficient than the trajectory with a natural slip line (222 mm) – for 20° of trajectory inclination. For steeper trajectories (in the second phase), the influence of the position of the trajectory switch point on the energy of the process was not observed, although the influence on the resulting force during the process was clear (see Fig. 6).

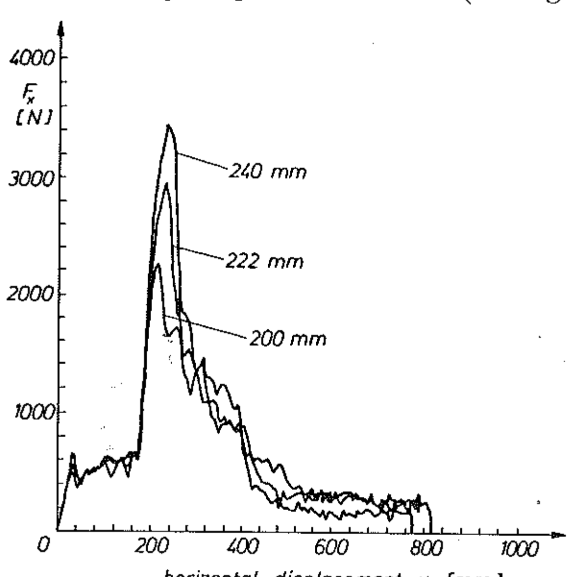

FIG. 6. Horizontal force versus horizontal displacement for three different ranges of the initial phase of trajectory.

Comparing the results for tests with translating and rotational "withdraw" phases (Figs. 3c and 5b) one can observe, that there was no significant influence of the tool rotation on the specific energy of the process. However, the tool rotation leads to its better filling by the material.

2.3.2. Tests on slope-shaped samples. All tests in this group of experiments were performed on soil samples prepared in the form of slopes with the inclination of 20°. During all tests the same L-shaped model of the tool was used and the tool was rotating during the "withdraw" phase of the trajectory. Tests with various trajectory inclinations and various trajectory switch points (Fig. 7c – point A) from the initial pushing phase to the "withdraw" phase were performed. The typical scheme of the test in that group of experiments is presented in Fig. 7. The straight line trajectories were inclined at the angles of 30°, 40° and 50°. The values 40° and 50° were close to the inclination of slip lines created during the horizontal pushing process (Fig. 7c).

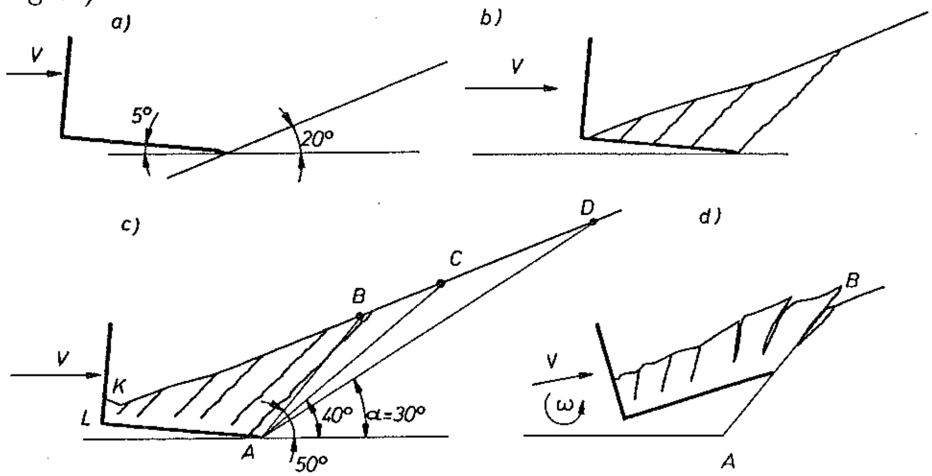

FIG. 7. Experimental program for slope sample: a) model of the tool and slope; b) initial stage of the process – horizontal movement; c) advanced stage of horizontal motion and various trajectories; d) the final stage of the process.

In Fig. 8b the influence of trajectory inclination on the specific energy W_f is shown for two different trajectory switch points. The observed tendency is similar to that described for flat soil samples (cf. Fig. 3c). Hence, conducting the tool tip along the line inclined at the angle equal or larger than the angle of slip line inclinations, the specific energy of the earth-filling process can be significantly reduced.

Figure 8a shows the relation between the specific energy W_f and the range of the pushing stage of the trajectory (the influence of the trajectory

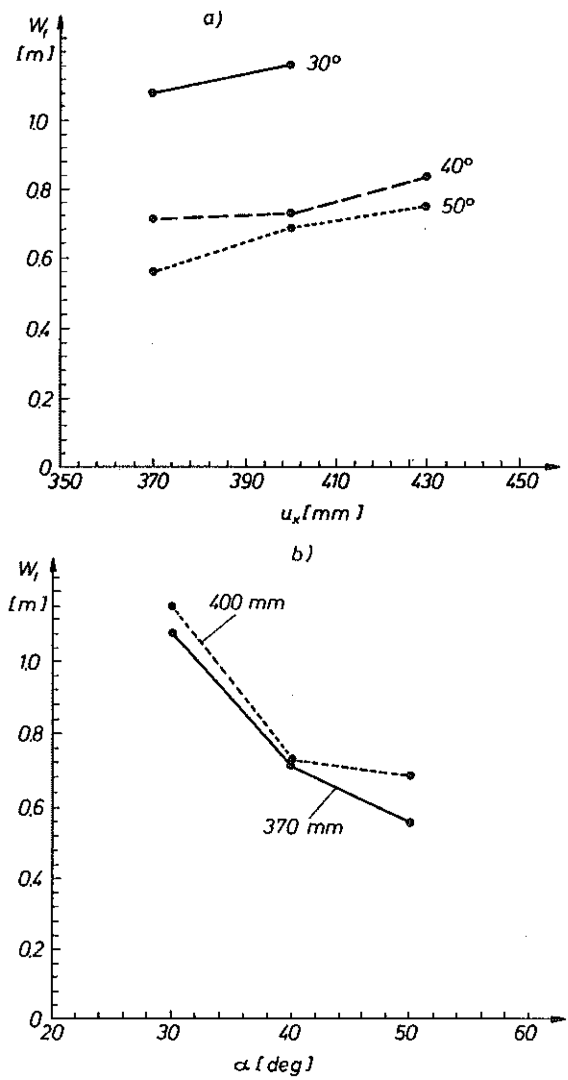

FIG. 8. a) Specific work versus trajectory inclination for two different ranges of the initial trajectory phase; b) specific work versus range of the initial phase of trajectory for different trajectory inclinations.

switch point) for three different inclinations of the tool paths. In this group of tests the difference in trajectory switch points was more significant than for tests performed on samples with horizontal boundary. Thus, the influence of the range of the pushing phase was more visible. It was shown, that extension of the pushing phase is ineffective from the energetic point of view and should be avoided during the earth working processes. However, it results in better filling of the tool.

In order to investigate more precisely the influence of trajectory on the efficiency of the earth-working process, several tests for equal amount of the excavated material were selected for comparison and some additional experiments for curvilinear trajectories were performed. From all the piece-wise linear tool paths were selected such trajectories, for which the weight of the excavated material was close to 600 N (Fig. 9a). Additional curvilinear trajectories had the same initial inclination (0°) and the same "withdraw" inclination (50°) and two different depths h of 80 and 120 mm (Fig. 9b) measured from the free boundary of the soil.

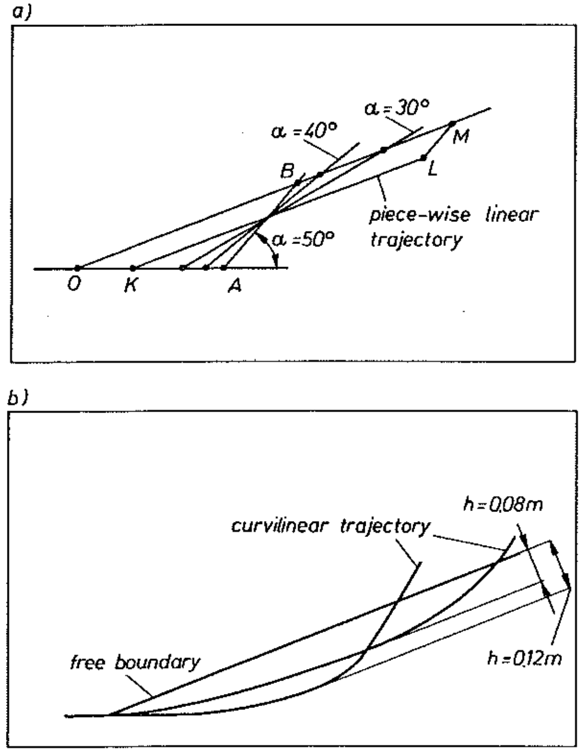

FIG. 9. a) Piece-wise linear trajectories; b) curvilinear trajectories.

In Fig. 10 values of specific energy W_f for various trajectories are presented. One can notice that the piece-wise linear trajectory inclined at the angle of 50° (more than slip line inclination) is energetically most efficient. Similar results were obtained for piece-wise linear trajectory with the inclination of 40° (close to the inclination of the slip lines), and curvilinear trajectory with the shape similar to the piece-wise linear of 50° (depth – 120 mm). In the case of piece-wise linear trajectory with the inclination of 30°, the specific energy was almost by 100% higher.

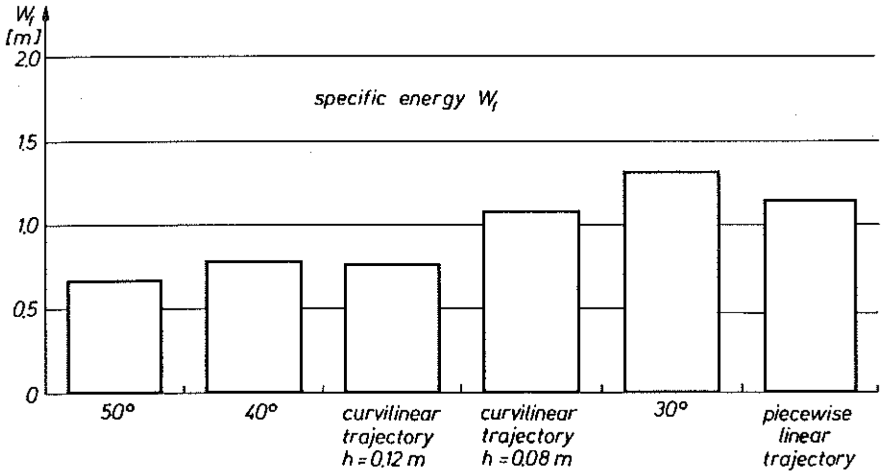

FIG. 10. Values of specific work for different trajectories.

3. Conclusions

1. Cohesive materials with softening deform during the shoving process and assume the form of several rigid blocks sliding along discontinuity lines; a corresponding oscillation of force is observed. This behaviour can be described theoretically using kinematically admissible solutions of the theory of plasticity.

2. Specific energy of the earth-moving shoving process increases with the increasing range of the pushing phase of this process.

3. For similar pushing phase ranges the influence of the withdraw trajectory inclination was most important. For inclinations greater than the inclination of the slip lines formed during the pushing phase, the energetic efficiency of the process was similar. For smaller inclinations, the specific energy substantially increases.

4. The piece-wise linear trajectory with the withdraw path inclined at the angle greater than the inclination of the slip lines formed during the pushing phase appears to be the most effective from the energetic point of view.

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