Analysis of the Mechanism of Soil Cutting

(1st Report. Cutting Patterns of Soils)

By Yotaro HATAMURA** and Kenji CHIJIWA***

All equipments of earth-moving machines (e.g. bulldozer, power-shovel) cut soil. In order to analyze the mechanism of soil cutting, a study on cutting of soil is made. The main results are as follows: (1) Cutting patterns of soils consist of the following three types—shear type (sand or plastic bentonite), flow type (plastic loam) and tear type (compacted loam), (2) Failure conditions of soils are investigated. Shear type and flow type are brought about by shear failure, and tear type by tensile failure. The difference between shear type and flow type occurs only from apparent difference of shear-line. (3) Experiments to measure the distributions of internal stresses in soils are carried out. From these results, the correspondence between cutting patterns and failure conditions is explained. (4) Comparison between cutting patterns of soils and cutting patterns in other fields (e.g. metal cutting) is made.

1. Introduction

1.1 Analysis of mechanism of soil cutting

At present, in Japan, the scale of construction working has become large because of the growth of economy and progress in technique. Every work which was done by man power hitherto has changed to the work by machine. As the result the mechanization in construction field has remarkably advanced.

Machinery which is used in construction working is called "construction machinery" and especially the machinery which is used for earth-moving work is called "earth-moving machinery". Bulldozer, tractor-shovel, power shovel, scraper, earth-auger are typical of them (Fig. 1). Main problems in designing them, at present, are problems between machinery and soil (earth-moving equipment, traffic equipment) and problems of machinery itself (power source, power transmission, control) etc.

As shown in Fig. 1, any earth-moving equipment of earth-moving machines cuts soil by its cutting edge. The force which must be produced by earth-moving machines is determined mainly by the magnitude and the direction of cutting force and the point of its application.

So, in this study, a problem that occurs when the earth-moving machines cut soil is taken up from among the problems between machinery and soil. And the analysis of the mechanism of soil cutting is tried for the purpose of the improvement of traditional earth-moving methods and the establishment of foundation of developing new earth-moving methods.

Many studies have been made on this subject until now, (1)~(3) The theory on study for earth-moving, however, has not yet been established. So these studies rely upon the static soil mechanics for

---

* Received 16th October, 1973
** Associate Professor, Faculty of Engineering, University of Tokyo.
*** Professor, Faculty of Engineering, University of Tokyo, Bunkyo-ku, Tokyo.

Fig. 1 Earth-moving machines and their earth-moving equipments.
civil engineering. Comparing the soil mechanics for civil engineering with the soil mechanics for earth-moving:

In soil mechanics for civil engineering deformation is small; deformation rate is small. (strain is small) (strain rate is small)

In soil mechanics for earth-moving deformation is large; deformation rate is large. (strain is large) (strain rate is large)

and the difference between them is remarkable. Therefore, when the static soil mechanics is used for earth-moving machinery, correspondence of the theory or experiment to the actual earth-moving machine becomes poor. On the other hand, the demand for higher performance or new earth-moving method is large. So that, the actual earth-moving machine is designed by modifying the traditional machinery, adopting an idea, or relying on experience.

In this study, the soil cutting is taken up from a stand-point that soil is the material machined and moreover its deformation and deformation rate are large. And the following matters are investigated:

(1) Classification of cutting patterns (according to the kinds of soils).

(2) Deformation by cutting, cutting force, the distribution of stresses on the blade face, and the distribution of internal stresses in soil which are measured by the miniature gages developed by the authors.

(3) Friction between soil and plate

(4) Dynamic characteristics of soil.

(5) Theory of soil cutting which is induced from above experiments.

Thus, the mechanism of soil cutting is analyzed. The results of above investigations are published successively under the title of "Analysis of the Mechanism of Soil Cutting".

1.2 The purpose of the study

When the mechanism of soil cutting is analyzed or the establishment of the theory of soil cutting is sought, first of all, cutting patterns of soils must be investigated. And the investigation must clarify the kinds of cutting patterns and the correspondence of cutting patterns to the characteristics of soils.

Typical soils which are encountered in the construction in Japan and the typical soils from the view point of soil mechanics are picked up to investigate the cutting patterns. Experiment of two-dimensional cutting is carried out in a miniature soil bin. Under a constant condition of cutting the classification of cutting patterns is made. On the other hand, a routine test of soil mechanics (statical tri-axial compression test) and a tensile test are carried out. Thus the statical rupture characteristics of soils are clarified. Moreover, it is tried to explain the correspondence of the cutting patterns to the statical rupture characteristics from the distribution of internal stresses in soil obtained by experiment. And the cutting phenomena of soils are compared with cutting of other fields.

2. Deformation of soils by cutting

An experiment of soil cutting in a miniature soil bin is carried out to clarify the deformations of various soils.

The kinds of soils which are investigated are quartz sand, river sand, "Masado" soil, alluvial silt, "Kanto" loam, "Kibushi" clay and bentonite (Table 1). The reason why these soils are chosen is that these soils are posing a problem in civil engineering of Japan or are expected to have interesting characteristics from a view point of engineering.

The apparatus of the experiment is a miniature soil bin shown in Fig. 2. The cutting depth d = 2.5 cm and the cutting speed v = 0.1 ~ 0.3 cm/s. The cutting blade is made of steel, and the roughness of the blade face is about 9μ which is felt smooth by hand.

Deformation of soil is photographed by a grid which is marked on the side of soil at the pitch of 0.5 cm. When a photograph is taken, the movement of cutting blade is once stopped. Main results are shown in Fig. 3.

The result of experiment of deformation by cutting shows that the following three cutting patterns appear in soil cutting.

(1) Shear type: As the cutting blade proceeds, a clear shear line appears intermittently from the cutting edge aslant up to the free surface, then the shape of the shear line changes. After some proceeding of the cutting blade, the first shear line vanishes and a new shear line appears far ahead of the old one. Therefore, the chips which are accumulated at a certain pitch move along the blade face (Fig. 4).

(2) Flow type: A clear shear line of shear type does not appear, but appears a zone in which the

<table>
<thead>
<tr>
<th>Table 1. Soils used in the experiment for cutting patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinds of soils</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>(a) Soils mainly consisting of sand-size grain</td>
</tr>
<tr>
<td>Dry quartz sand</td>
</tr>
<tr>
<td>Wet quartz sand</td>
</tr>
<tr>
<td>Wet &quot;Masado&quot; soil</td>
</tr>
<tr>
<td>Dry river-sand</td>
</tr>
<tr>
<td>(b) Soils mainly consisting of silt-size grain</td>
</tr>
<tr>
<td>Wet alluvial silt</td>
</tr>
<tr>
<td>(c) Soils mainly consisting of clay-size grain</td>
</tr>
<tr>
<td>Dry powdery loam</td>
</tr>
<tr>
<td>Compacted loam (compacted by pressure about 100Kg/cm²)</td>
</tr>
<tr>
<td>Plastic loam</td>
</tr>
<tr>
<td>Extremely plastic loam</td>
</tr>
<tr>
<td>Plastic &quot;Kibushi&quot; clay</td>
</tr>
<tr>
<td>Plastic bentonite (for construction)</td>
</tr>
<tr>
<td>Plastic bentonite (for casting)</td>
</tr>
</tbody>
</table>

Fig. 2 Apparatus for investigating the deformation of soil by cutting.
shear deformation occurs continuously when the cutting blade proceeds. A line which is obtained by connecting the points where the deformation is most remarkable, may be called "shear line". This shear line stays in a constant position relative to the cutting blade irrespective of its proceeding. So the chip becomes continuous and moves along the blade face in the same flow of water interrupted by a weir (Fig. 5).

(3) Tear type: As the cutting blade proceeds, a primary crack appears in the direction of cutting.

As the cutting blade goes on, a secondary crack appears perpendicular to the primary one. So the shape of the chip is just like a block which is torn off from the original soil (Fig. 6).

In order to investigate the detailed deformation of soils (dry quartz sand and plastic loam), an experiment of soil cutting was carried out in a large soil bin which is similar to the miniature one (details are published in the second report.). In both cases of dry quartz sand and plastic loam, the soil particle is compressed in the direction of cutting on both sides of
the shear line. And the soil particle which is located under the cutting blade does not present a remarkable deformation on both sides (forward and backward) of the cutting blade, but is compressed downward slightly just under the cutting edge. Minutely observed, the shear line is curved in the downward concave in the neighborhood of the cutting edge and linear beyond there. (This shape is also explained in usual soil mechanics.) From this shape of the shear line, it is expected that the directions of principal stresses in soil are distributed radially in the neighborhood of the cutting edge, and are parallel beyond there. By the way, the soils which belong to each type are as follows.

(1) Shear type: Dry quartz sand, wet quartz sand, wet “Masado” soil, wet river sand, wet alluvial silt, dry powdery loam, plastic bentonite (for construction and casting).

(2) Flow type: Plastic loam, extremely plastic loam, plastic “Kibushi” clay.

(3) Tear type: Compacted loam.

About these soils, it is peculiar that bentonite (either for construction or for casting) presents the shear type although it has the similar failure condition and smooth touch with plastic loam or plastic “Kibushi” soil which presents the flow type. And also it is peculiar that the compacted loam presents the tear type.

3. Failure conditions of soils

From the above experiment, it has become clear that the soils present different cutting patterns and there are three kinds of them. Then the conventional triaxial compression test (Fig. 7) and a tensile test (Fig. 8) which is not made usually are made in order to clarify the correspondence of cutting patterns with the failure conditions. In these tests, the tensile test of soil is not made in the conventional soil mechanics but is considered to have special importance for the mechanics of earth-moving.

The tensile test of soil is made as follows. The soil is put into a mold for the tensile test piece, and is compressed by the top and bottom plungers almost with the same pressure as the soil is put into the miniature soil bin. Then a bucket is hung at the bottom of the test piece, and lead grains are poured. The tensile strength is estimated from the weight of lead grains and the cross-sectional area of test piece when the test piece breaks.

Several examples of the deformation by tri-axial compression test are shown in Fig. 9. And several examples of the deformation by tensile test are shown in Fig. 10.

Main examples of the failure conditions of soils which are obtained in these tests are shown in Fig. 11. According to the above results, three kinds of cutting patterns of soils have correspondence to their failure conditions as shown in Fig. 12. And their characteristics are as follows.

(1) Two kinds of failure conditions are related to the shear type. The one is represented by dry quartz sand. Its shear failure condition is \( \tau = \sigma \tan \phi \) (\( \tau \): shearing stress, \( \sigma \): normal stress, \( \phi \): coefficient of internal friction and \( \phi \) is large), and its tensile strength is zero. The other is represented by plastic bentonite. Its failure condition is \( \tau = c + \sigma \tan \phi \) (\( c \): cohesive stress, \( \phi \) is small), its tensile strength
Fig. 10  Deformation of soil by tension

(1) Plastic bentonite  (2) Plastic loam  (3) Compacted loam

Fig. 11  Failure conditions of soils

(1) Dry quartz sand  (2) Plastic bentonite  (3) Plastic loam  (4) Plastic clay  (5) Compacted loam

\[ \tau = 0.10 + 0.03 \sigma \]

\[ \tau = 0.15 + 0.1 \sigma \]

\[ \tau = 0.14 + 0.08 \sigma \]

\[ \tau = 0.16 + 0.18 \sigma \]

\[ \sigma = -0.6 \]

\[ \sigma = -0.43 \]

\[ \sigma = -0.2 \]

\[ \sigma = 0.1 \]

**Fig. 12**  Relationship between cutting types and failure conditions of soils

\( \tau \): shearing stress  
\( \sigma \): tensile strength  
\( \sigma_t \): tensile strength

(1) Shear type  
(2) Flow type  
(3) Tear type
|σ₁| is large and |σ₂| is larger than c.

(2) The failure condition of flow type is represented by plastic "Kibushi" clay. Its shear failure condition is \( \tau = c + \sigma \tan \phi \) (\( \phi \) is small), tensile strength |σ₄| is large and |σ₁| is larger than c. By the way, this condition is the same as the condition of plastic bentonite which presents shear type.

(c) The failure condition of tear type is represented by compacted loam. Its shear failure condition is \( \tau = c + \sigma \tan \phi \) (\( \phi \) is small), which is the same as shear type or flow type. But the tensile strength |σ₁| is small and |σ₄| is smaller than c.

4. Distribution of internal principal stresses in soils

From the above experiment, the relationship between cutting types and failure conditions of soils is clarified. In order to explain the reason for these correspondences, the distribution of internal principal stresses in soils must be clarified.

So, experiments of soil cutting in a large soil bin are carried out, and the distributions of internal principal stresses are measured by "internal stress cells" which have been developed by authors (details are published in the 2nd Report). The soils which are used in these experiments are dry quartz sand as a representative of the shear type, and plastic loam as a representative of the flow type. The main results of these experiments are shown in Fig. 13. The cutting conditions are: the cutting angle \( \alpha = 60^\circ \), the depth of cut \( d = 1.0 \) cm and the cutting speed \( v = 5 \) cm/s.

In both cases of dry quartz sand plastic loam, the distributions of principal stresses are very similar. And their schematic distributions are shown in Fig. 14. In the zone before and above the cutting blade, both the maximum and minimum principal stresses are compressive and the directions of maximum principal stresses are horizontal or slightly inclined almost in parallel. Only the trajectories of maximum principal stresses which originate from the cutting edge diverge abruptly. In the zone under the cutting edge, both in front and back of it, the maximum principal stresses are compressive, but the minimum principal stresses are zero or tensile.

5. Investigations

5.1 Investigation of the experiments

From the above three experiments, the following things became clear: (1) There are three cutting patterns such as shear type, flow type and tear type. (2) And their main causes are the differences in their failure conditions (shear and tensile failure conditions). (3) Distributions of internal principal stresses in soils. Then we consider the relationship between cutting patterns and failure conditions of soils based on the distribution of principal stresses.

The results of above three experiments are summarized as in Fig. 15. In this figure, (1) shows the distribution of principal stresses occurring in soil cutting, (2) shows the stress states at each point in soil by Mohr's stress circle, (3) shows the failure conditions and (4) shows the cutting patterns.

Using these figures, relations among (1) ~ (4) are investigated. The schematic distribution of internal stresses is shown in the shape of (1), irrespective of the kinds of soils or the cutting conditions. The most important zone which decides the cutting pattern are the zone A which may induce the shear failure and the zone B which may induce the tensile failure. A is located at the zone in the front part of the cutting blade and B is located at the zone in the front and rear part of the cutting blade. The stress states are two kinds as shown in figure (2). The one is the soil whose failure condition is affected by self weight, and the other is the soil whose failure condition is not affected by self weight. Sand belongs to the former, plastic loam, plastic bentonite (for construction and casting) and compacted loam all belong to the latter. On the other hand, every failure condition is expressed as one of figure (3). And any one of Mohr's circles in figure (2) touches any one line of failure conditions in figure (3) inevitably. Then the soils break. When the shear rupture line is touched, soil
breaks in shear and its cutting pattern becomes shear type or flow type as shown in figure (4). When the tensile rupture line (or point) is touched, soil breaks in tension and its cutting pattern becomes tear type.

Then we consider in detail the relationship between the stress states (2) and the failure conditions (3).

(1) Shear type: Sand and plastic bentonite are cut in this type. Their Mohr’s stress circles are shown in Fig. 16.

In case of sand [Fig. 16(a)], either circle (a) and (b) touches the shear rupture line, and the sand breaks in shear failure. By the way, the circle (c) does not appear.

In case of plastic bentonite [Fig. 16(b)], all circles (a) ~ (c) touch the shear rupture line, and the bentonite is cut in shear failure. By the way, even the circle (c) which is located in the left extreme side does not touch the tensile rupture line because the value of $\sigma_1$ is very large.

When the soil cut by shear failure, and moreover the part in which the shear failure once occurred is more slippery than the surroundings, the shear line appears intermittently. Therefore the cutting pattern becomes shear type.

(2) Flow type: Plastic “Kibushi” clay and plastic loam are cut in this type. Their Mohr’s stress circle is shown in Fig. 17. All circles (a) ~ (c) touch the shear rupture line, and everywhere the soil breaks in shear failure. By the way, the circle (c) does not touch the tensile rupture line (or point).

From the view-point of failure of soil, this type is similar to the shear type presented by plastic bentonite. But the apparent chip formation is different. The shear line appears intermittently in shear type and continuously in flow type.

The apparent difference of chip formation is considered to occur from the difference in the mechanism of internal friction in soil. But the detail is not clear.

By the way, in case of “Kibushi” clay, a tensile crack does not appear in front of and below the cutting edge because the value of $|\sigma_1|$ is much larger than c. But in case of plastic loam, sometimes this crack appears although almost always it presents the flow type. The reason why such phenomenon appears is considered to be the fact that the value of $|\sigma_1|$ is nearly equal to the value of c. Therefore the circle c touches the shear rupture line or tensile rupture line (or point) occasionally.

Fig. 15 Correlation between distribution of principal stresses in soil, failure conditions of soils and cutting patterns

![Fig. 15](image)

(a) Sand etc.

(b) Plastic bentonite etc.

Fig. 16 Relationship between failure conditions and stress situations in soil presenting shear type

![Fig. 16](image)

Fig. 17 Relationship between rupture conditions and stress situations in soil presenting flow type

![Fig. 17](image)

Fig. 18 Relationship between failure conditions and stress situations in soil presenting tear type

![Fig. 18](image)
From the viewpoint of another angle, the failure condition of plastic loam is intermediate between flow type and tear type. And it is considered that the value of $\sigma_{1}/c$ has some importance as an index showing the critical point between flow type and tear type. (Here, in the failure condition of soil $\tau = c + \sigma \tan \phi$, $\phi$ is neglected and $\phi$ is considered equal to $c$.)

(3) Tear type: Compacted loam is cut in this type. Its Mohr's stress circle is shown in Fig. 18.

As the circle (c) touches the tensile rupture line (or point), the soil breaks in tensile failure. Neither the circle (a) nor (b) touches the shear rupture line until the circle (c) touches the tensile rupture line. So the shear failure does not occur. When the circle (c) touches the tensile rupture line and a primary crack appears, the circle (b) moves to the left and also touches the tensile rupture line. So a secondary crack appears. Of course, at that time, the distribution of internal stresses in soil has already changed from the one shown in Fig. 15.

By the way, it is notable that the conception of "tensile strength" which is neglected in traditional soil mechanics because of its poor utility, has much importance in the earth-moving mechanics.

5.2 Comparison with cutting of other fields

In the above investigation, the relationship between the cutting patterns of soils and their failure conditions is explained by the distribution of internal stresses in soil. Cutting is performed for various materials besides soil, such as metal, wood, rock etc. In these various fields, in spite of the difference of materials, their methods are very similar (Table 2).

Now we compare the soil cutting with cuttings of other materials. In the experiment made above, it is clear that three cutting patterns appear in soil cutting. On the other hand, it is well known that also three cutting patterns, such as flow type, shear type and tear type appear in metal cutting. In rock cutting, two cutting patterns such as shear type and tear type, appear.

In metal cutting, a less ductile material is apt to present the shear type and a more ductile one is apt to present the flow type. When the cutting condition of certain metal is changed, flow type and shear type appear under their cutting condition respectively. But such a phenomenon does not appear in soil cutting. In soil cutting, however, there occurs transition from flow type to tear type.

In spite of the apparent difference between soil and metal, their stress-strain relationships, stress-strain rate relationships and failure conditions are quite the same (details are published in the 4th report). From these facts, it seems that the state of internal stress in metal cutting is the same as the one shown in Fig. 14. Therefore, the same conception will be applicable to the correspondence of cutting patterns and their failure conditions in metal cutting.

6. Conclusions

In order to establish a fundamental theory for earth-moving machinery, the mechanism of soil cutting is analyzed experimentally. And the following things have become clear about cutting patterns.

(i) Three kinds of cutting patterns, such as shear type, flow type and tear type, appear in soil cutting. For example, sand and plastic bentonite present shear type, plastic "Kibushi" clay and plastic loam present flow type and compacted loam presents tear type.

(ii) In case of shear type and flow type, soil breaks in shear failure. The difference between them is induced from intermittent or continuous appearances of their shear lines.

(iii) In case of tear type, soil breaks in tensile failure.

(v) The difference between the cutting pattern induced by shear failure (shear type and flow type) and the one induced by tensile failure depends upon the ratio of tensile strength to shear strength of soils.

(vi) The most important zones which decide the cutting pattern are the zone located before and above the cutting blade, and the zone located before and under the cutting edge.

(vi) Cutting patterns of soils are compared with cutting patterns of other materials.

Acknowledgement

The authors are indebted to Prof. N. Takenaka and Assoc. Prof. T. Nagao for many reasonable suggestions on this study and to Mr. H. Nakazaki of Takenaka-Komuten Co. Ltd. for the experiment of failure conditions of soils. The authors are also indebted to Mr. T. Takeuchi of Tokyo Univ. and Mr. A. Tsuzuku of Komata Works Co., Ltd., who assisted them in the experiments devotedly.

References

(1) S. Murayama, S. Hata, Journal of the Japan Society of Civil Engineers (in Japanese), 40-3 (1955) 94


(7) Handbook of Precision Machining, Corona Publishing.
