Experimental Investigations on Surface of Rupture in Sand.

By

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It seems rather peculiar that there has been great stagnation in studies on earth pressure, notwithstanding the rapid progress in other civil engineering practices and the exact computations of stresses usually possible for steel works. The reason may be the complexity of soil phenomena and the attractiveness of the classical theories of granular earth pressure, because the theories formulated by Coulomb and Rankine, in view of the interest thereby aroused, have been very attractive, as theories, to their successors.

In the preceding article, these Memoirs Vol. 2, No. 6, some experiments on the internal granular movements of sand were reported by the present author with special regard to the effect of the forward movement of a retaining wall in the vertical position, the turning of the wall about its base and the effect of partial sinking of the base of a sand pile*, in which the first two have been further investigated more closely as well as in several different ways, noticing principally the aspect of the surface of rupture which seems to be very important in the computation of sand pressure behind a wall.

Experiments and Results.

In the present note the internal granular movements of sand observed under several conditions of boundaries will be reported. The granular materials used and the apparatus employed in the ex-

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*Similar experiments were reported by Forchheimer: Z. Öst. Ing. u. Arch.-Ver. Bd. 34, 1882.

periments are as follows: the granular substances are chiefly river sand dried and sifted to a grain size of 0.86 mm dia. mixed with an unspecified proportion of finer ones. The apparatus employed was of two kinds, the one being a box having glass sides and measuring 101.7 cm long, 51 cm wide and 50.8 cm deep, and the other a smaller one measuring 45 cm long, 20 cm wide and deep, to investigate the surface of rupture in the distant portion from the side wall in order to eliminate the frictional effect which seems to be quite considerable, in both boxes the front wall being represented by a movable partition. Dry loosely packed sand was filled in the box and the different surfaces were marked by a number of lines of black coloured sand, to serve as indicators of the movement.

To investigate the feature of the surface of rupture in sand, it has been very convenient, in the author's opinion, to consider two standard cases, one of them being the forward movement of a plane retaining wall in the vertical position and the other being the turning of a plane wall hinged at the lower edge. Figs. 1 and 2 show them respectively. In the preceding paper (these Memoirs Vol. 2, No. 6) we find a complete series of these granular movements (See Photo. No. 76 to 81 and Photo. No. 70 to 75); and as the experiments have been chiefly observed on the glass side wall, it is therefore necessary to eliminate the frictional effect between glass and sands. For this purpose the experiments have been made quite distant from the glass wall and after the operation the sand mass was cemented by water and cut off at many sections. This experiment was very simple and quite suggestive to furnish a future development on studies of several soil phenomena, serving as a visible demonstration for three dimensional problems in space. These were described in article 8.

Fig. 1 shows an early movement, the sliding wall having been allowed to move forward. Most of the sand, which had been loosely packed, has settled uniformly, having flowed down the back of the wall and down the surface of the rupture, whose inclination seems to keep a constant value dependent on the sand used. Various kinds of sand have their own proper angle of surface of rupture as they have their proper value of angle of repose that only comes into play when the free surface is in motion. In the author's opinion, for earth pressure calculation it is necessary to determine the angle of surface of rupture for every kind of granular soil material, as the angle of repose has been already measured for many granular substances.

In the following we quote frequently such feature of the surface of rupture as mentioned about Fig. 1 and we therefore, as abbreviation, define this type of surface of rupture "Standard Type I."

Fig. 2 shows an early movement, the tilting wall being allowed to turn about its base. In this experiment the surface of rupture was slightly convex; the reason why may be explained by the fact that the movement of the tilting wall causes no displacement at the base and maximum displacement at the upper surface, varying uniformly the horizontal and vertical components of displacement along the tilting partition; while in the former case of sliding wall the horizontal displacement is always constant with respect to every point of the vertical wall.

In order to differentiate this tilting case from the former sliding one, we call this curved type of surface of rupture with respect to the tilting wall "Standard Type II" which will be quoted again in Fig. 9.

Through all the series of experiments the surface of rupture for sliding walls develops in the same parallel way, i.e. the angle of surface of rupture may be said to be a parametre to define a speciality of sand used, while in the tilting case the surface of rupture, through all the series of angular changes always develops different values, because the initial conditions of boundary, if considered separately, from time to time are always completely different.

1. Kinds of Experiments Investigated. The experiments which have been made by the author may be classified as follows:

(a) Surface of rupture for a retaining wall which slides on a sand surface.
(b) Surface of rupture for inclined walls.
(c) Surface of rupture for L-shaped retaining walls.
(d) Surface of rupture for stepped walls.
(e) Effect of surcharges.
(f) Effect of water, with which sand was saturated.
(g) Effect of friction between glass and sand.

2. Plane Walls on Sand Surface. The experiments shown in Fig. 1 were of the plane walls which have been driven forward on the wooden bed of the apparatus. In order to investigate the effect of the bed, on which the wall slides, the sliding wall was based on a sand surface.

Fig. 3 shows the surface of rupture, in the case above mentioned. The effect of the sand bed was not sufficiently remarkable to be specially mentioned, although the apparatus used seems to have been quite sensible enough to show a delicate difference from the above two.

In the figure we find many parallel surfaces of rupture that indicate the Standard Type I.

3. Inclined Walls. For inclined walls the experiments have been made in two ways, the one being of such batter as shown in Figs. 4 to 6 and the other being of such one as shown in Figs. 7 to 9; the former may be called the positive batter and the latter the negative one.

Fig. 4 shows the experimental results for the surface of rupture, when the wall inclined at about 18 degrees to the vertical sliding wall, with which the inclined wall was rigidly connected, is driven in forward, keeping the inclination always constant.

Figs. 5 and 6 show the experimental results for the inclined wall of approximately 58 degrees to the vertical. The longitudinal section of the surface of the rupture exerted in these cases may be said to be approximately a straight line and with the increase of the angle between the inclined wall and the vertical plane the surface of rupture seems, as we find in Fig. 5, to approach to the vertical plane and seems also to be somewhat curved.

For the early movement, as in Fig. 5, a single plane of rupture is observed but afterward, as in Fig. 6, there are two different planes of rupture at both sides of the vertical at the foot of the inclined wall back. It is interesting in this case to find the second surface of rupture adjacent to the inclined wall. Upon further movement there seems to occur some curvilinear surfaces as seen similar to those in Fig. 20.

Figs. 7 and 8 show the results for the negative batter of approximately 20 degrees; the horizontal displacement of the wall, in the experiments, with respect to Fig. 7 was about 2.0 cm and that of Fig. 8 about 4.0 cm.

Fig. 9 shows the experiment for the negative batter of approximately 37 degrees; the horizontal slip was about 2.0 cm.

In the last two figures we observe at the same time the angle of repose which come into play on the free sand surface, along the natural slope from the left corner of the top surface.

For the further increased negative batter it may be easily estimated that the less amount of the sand mass may have a tendency to move down along the surface of the rupture and consequently that the sand pressure which acts on the retaining wall of the negative batter may be very much smaller than that of the positive batter.

4. L-Shaped Walls. In the case of L-shaped walls the length and the position of the horizontal arm of the L was effective and experiments have been made in the following four different cases:

(a) Horizontal arm of the L is quite long (Fig. 10).
(b) Horizontal arm of the L is quite short (Fig. 11).
(c) Horizontal arm of the L is moderate (Fig. 12).

(d) Horizontal arm of the L is fixed at an intermediate position of the vertical wall (Fig. 13).

As general characteristics of the surface of rupture in the L-shaped walls we find V-shaped surface of rupture at the free end of the horizontal arm of the L and the rupture of Standard Type I behind the wall. When this horizontal arm is quite long, relative to the height of the wall, the surface of rupture takes such a feature as shown in Fig. 10, where we find the V-shaped surface of rupture and the rupture of Standard Type I, the two arms of the former intersecting with the horizontal sand surface and the latter appearing behind the vertical wall as usual.

When the horizontal arm of the L is short relative to the height of the wall, the surface of rupture takes the form shown in Fig. 11, where the left arm of the V-shaped rupture intersects with the vertical wall and the right arm with the top surface of the sand; the rupture of Standard Type I, appears as in the former case, behind the wall.

Fig. 12 shows the experiment for the moderate arm of the L and the figure indicates many surfaces of rupture which have been induced in the course of the further sliding motion.

If the horizontal arm is fixed at the intermediate position of the vertical wall, the feature of the surface of rupture above this arm is approximately the same as in the previous case of the L-shaped wall and the rupture of Standard Type I appears under the horizontal arm, leaving a trapezoidal void between the lower surface of the arm and the surface of the rupture of Standard Type I above mentioned.

Fig. 13 shows the early movement in the experiment of the wall of this kind and, as mentioned above, the rupture of Standard Type I under the arm appears very clearly, while such a rupture has not yet appeared at the instant of the figure near the top surface, though this appears naturally upon the further development of the granular movement.

Fig. 14 shows the case of a certain failure, caused by faulty construction: the fixed part of the horizontal arm has acted like a hinged joint and turned as is seen in the figure. The granular movement in this case was very complicated but it may be explained by the foregoing characteristics of the sand movement.

5. Stepped Walls. For stepped walls the problems are very complex and it is quite difficult to ascertain the exact characteristics applicable to any shapes of the wall; the proportion of the height and width of each step, the number and position of the steps, etc. are effective.

The experiments have been made in several cases, varying the number of steps and changing the position of the steps and proportion of the length.

In this article we treat a series of experiments, varying the number of steps from one to four. The dimensions of the walls are to be measured approximately from the figures, scaling the width of each step about 5 centimetres.

When the wall is shifted horizontally, a curved surface of the rupture from the foot of the lowest step is observed; this surface appears generally as a continuous curved line, but is sometimes discontinuous because of the heterogeneousness of the granular substances and the special shapes of stepped walls.

In all the cases one observes without exception a dead triangular mass of sand which keeps resting on the step and is carried away; the moving volume of the sand appears showing a ν-shape. (Figs. 15 to 18).

Figs. 19 to 21 show a series of a continuous movement and it is very interesting to find the systematic order of the newly appeared surface of rupture. Figs. 22 and 23 are of other experiments and it may be therefrom possible to confirm the method of surface of rupture with respect to the stepped walls.

Figs. 24 to 26 show the effect of the width of the step and that of the special steps as shown in figure (Fig. 26).

6. Effect of Surcharges. The experiments of the effect of surcharges have been made in two ways; the one is of the surcharge placed on the far side of the surface of the rupture from the wall, and the other is of the surcharge placed on the near side.

In both cases the weight of the surcharges was about 18 kg consisting of two weights, of which the larger one was 10 kg and the smaller one 8 kg; these have been placed on a block, 43.2 cm long, 23.5 cm wide and 1.5 cm thick, whose weight was 0.6 kg.

Fig. 27 shows the former case and Fig. 28 the latter one. From the experiments it seems, to the author, that the surcharges have very little effect on the shape of the surface of the rupture and that the rupture of Standard Type I is the proper nature of dry sand, which even the external forces like surcharges can hardly change.

In Fig. 28 we find under the loads the vertical effect of the surcharges. This effect indicates the degree of the distribution of the loads and for this purpose Fig. 29 will do, where we see the deformation of the horizontal coloured layers of sand. If the sand layers deform proportionally to the intensity of the load, the apparatus used is one of the best and simplest methods of experiment for such investigations.

7. Effect of Water. The experiments to investigate the effect of water upon the surface of rupture seem to be very important for the purpose of soil mechanics and these are ample problems to study for every proportion of sand and water. The experiments which we here treated are only a few of the problems of a special kind among them.

Fig. 30 shows the experiment of the collapsing feature for the sand saturated with water, when the vertical wall is driven in the horizontal movement. In this experiment the saturated sand has been placed only above the estimated surface of rupture of Standard Type I.

As the indicator of the movement of the saturated sand, the white marked sand was used, while for the part of dry sand the common black coloured sand was used.

As a result of the sliding motion the saturated sand has collapsed as shown in Fig. 30; the method of collapse in this case was quite different from the foregoing many cases and surface cracks in the free sand surface are visible.

As the second problem, Fig. 31 shows one of the experiments to investigate the effect of water, as a cementing material, behind the wall; the water has been poured far and deep enough to reach the estimated surface of rupture of Standard Type I. The water which has been poured behind the wall, in the dry sand, acted as cementing materials to the back filling sand.

Upon the removal of the wall we observed thereby no collapsing of the wet sand, which continued to stand vertically in its original position. That is to say, in this case there is no use of retaining wall at least at this moment.

This experiment is enough to afirm that the investigation of the back filling materials is also very important in view of economy of materials for the retaining wall in order to diminish the earth pressure to be exerted on the wall.

8. Effect of Friction Between Glass and Sand Upon Surface of Rupture. For the purpose of observing the moving feature, from time to time, of the surface of rupture, it was necessary to use the apparatus which has a glass side; while as the frictional effect of the glass surface, caused by the sand mass, seemed to be very considerable, the sand mass, after operations, was wet and fixed with plain water, applying the cementing action of water which the last experiments in article 7 have shown, and cut off into several blocks of sand poorly saturated with water, on which we have observed the variation of the surface of rupture along the movable partition wall, showing, however, the similar feature in every section as shown in Fig. 33. The angle between the surface of rupture and the horizontal at the central part of the wall length has been observed to be smaller than that observed at the glass.

For example, this angle observed at the central part of the retaining wall was about 58 degrees, while that observed at the glass side was about 67 degrees.

In Fig. 32 one sees the variation of the angle of the surface of rupture above mentioned and the experimental results are shown in Fig. 33.

The effect of water, whether there occurs deformation by it in the inner sands or not, seems to have been very slight in the experiments for such purpose as the measuring these angles.

For the preservation of the blocks, one may use other proper cementing materials, on which the author will have the opportunity to report in the near future.

Summary and Conclusions.

In regard to fine sands loosely packed, the internal granular movements caused by the sliding of the vertical and inclined plane walls, L-shaped walls and stepped walls etc. were investigated experimentally and the general conclusions to be drawn from the results of the experiments may be summarized as follows:

1. The surface of rupture caused by the sliding of the vertical plane wall appears in a characteristic feature as shown in Fig. 1, which seems to be one of the most important deformation phenomena and is called by the author rupture of "Standard Type I."

2. For the inclined plane wall, the experiments have been made by both positive and negative batter; Figs. 4 to 6 show the former cases and Fig. 6 is very interesting to give the V-shaped surface of rupture, which we know mathematically too. Fig. 7 shows one of the latter cases. It is simple and easy to make the computation of the moving volume from the photographic prints. For the increase of the positive batter the surface of rupture, which starts from the foot of the wall, seems to become sharp.

3. With respect to L-shaped walls, the experiments furnish the V-shaped surface of rupture: at the free end of the horizontal arm of the L the two arms of the V intersect, whose right arm seems to become sharp when the horizontal arm of the L is long. A rupture of Stardard Type I appears behind the wall (Figs. 10 to 13).

4. Though the problems were complex and accurate investigation has been very difficult for stepped walls, we found principally that there came regular movement of dry sands as shown in Figs. 15 to 18.

The ν-shaped surface of rupture accompanied by a dead triangular sand mass on each step was remarkable. The formation of the branch from the right arm of the ν as shown in Figs. 20 and 22 is sometimes visible. The further researches on the similar subjects wait the future experiments. Caused by the width of the step, the shape of the ν varies (Figs. 24 to 26).

5. With respect to sands completely saturated with water, surface cracks appear (Fig. 30).

6. By pouring of a proper amount of water into the back filling sand it is possible to induce cementing power (Fig. 31) and from the analogous point of view it seems to be worthy of further studies on the back filling materials behind the retaining walls to diminish the earth pressure as well as to save the materials of the wall.

7. The effect of the surcharge upon the surface of rupture seems to be slight in view of the deformation or of the granular movement of dry sands (Figs. 27 and 28), but problems of the sand pressure caused by it are out of the question here under consideration.

8. The effect of the friction between glass and sand mass upon the surface of rupture is rather great and therefore for the measurement of the angle, one must measure it at the central part of the wall length, as many investigators have noticed.

For the mere investigation of the feature of the surface of rupture, the photo-investigation by using glass side wall is quite convenient to observe the granular movement, furnishing a similar figure to that in the portion free from the effect of the friction above mentioned. The method of formation of sand blocks by pouring plain water through a spray is very practical and can be applied on the spot to the measurement of the angle of the surface of rupture as well as for the investigations of several kinds of soil phenomena, serving as a visible demonstration for three dimensional problems in space in granular substances.

Sapporo, May, 1932.

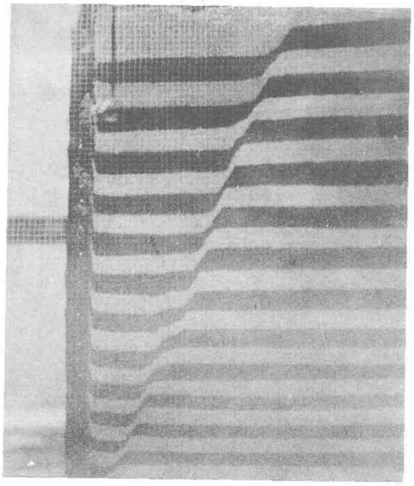


Fig. 1.

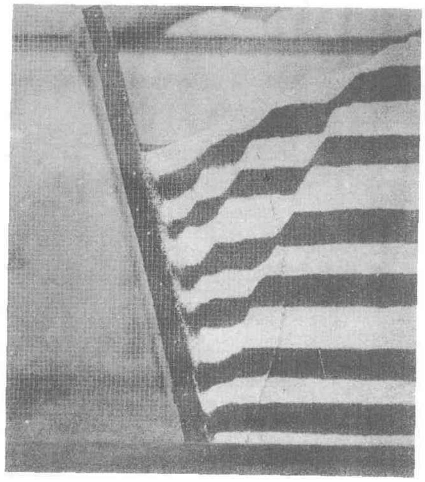


Fig. 2.

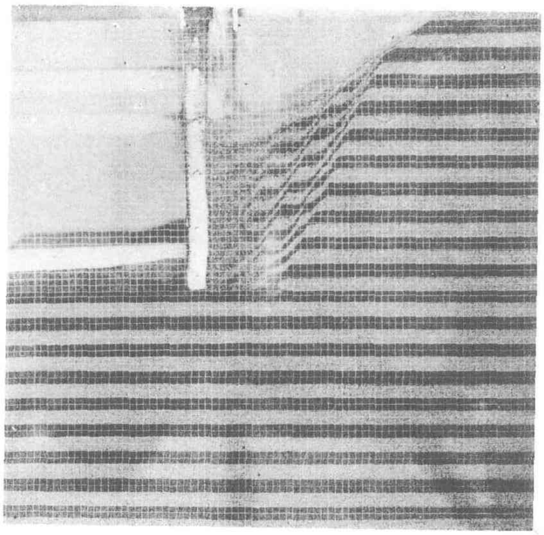


Fig. 3.

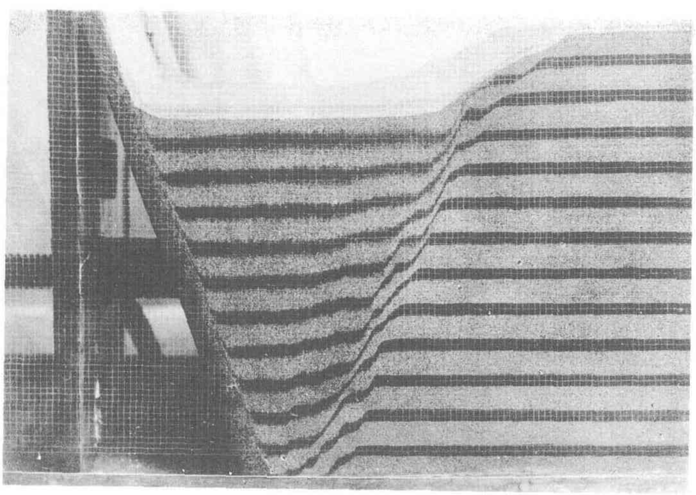


Fig. 4.

F. *Takabeya: Experimental Investigations on Surface of Rupture in Sand.*

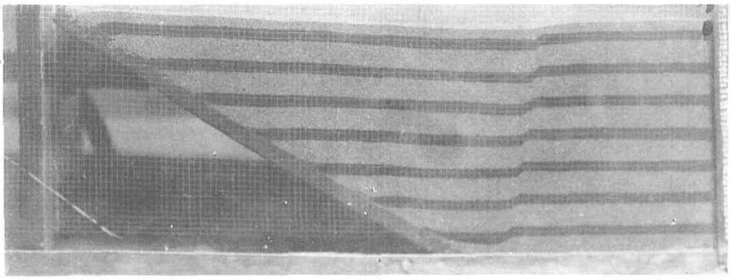
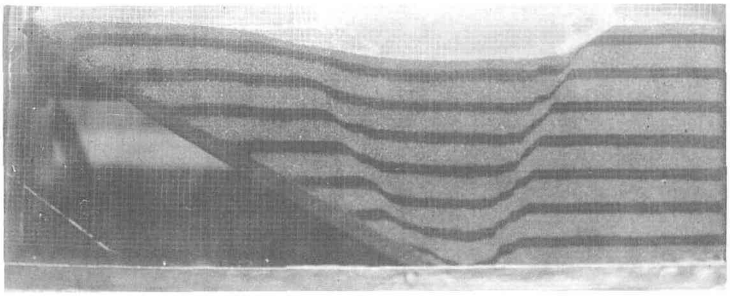


Fig. 5.



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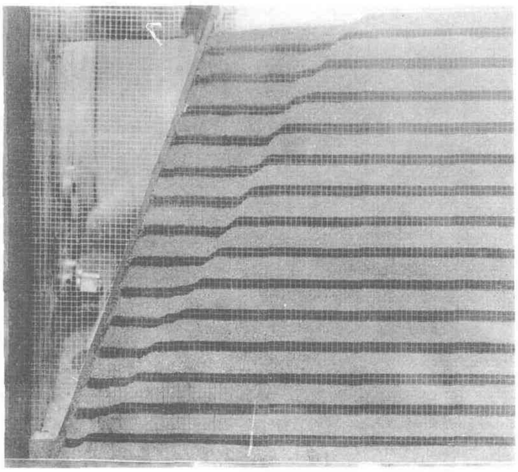


Fig. 7.

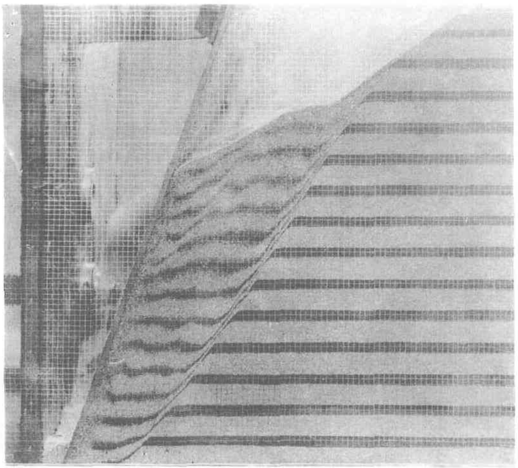


Fig. 8.

Fig. 9.

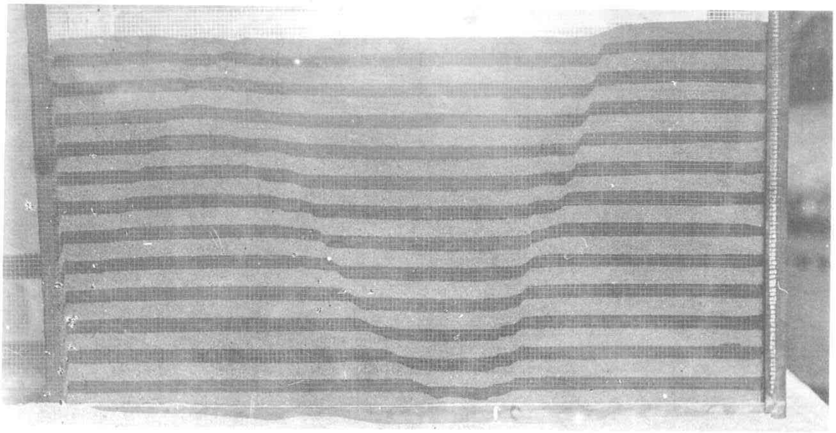


Fig. 10.

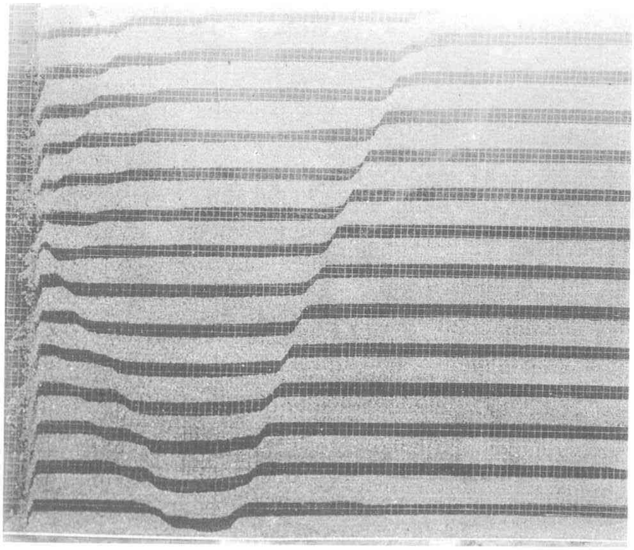
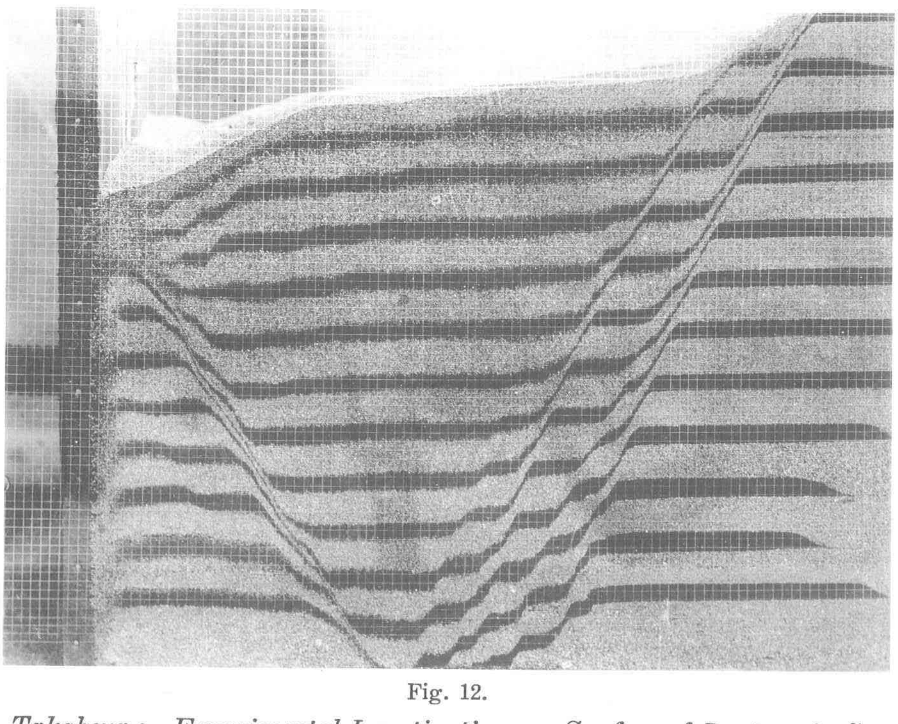


Fig. 11.



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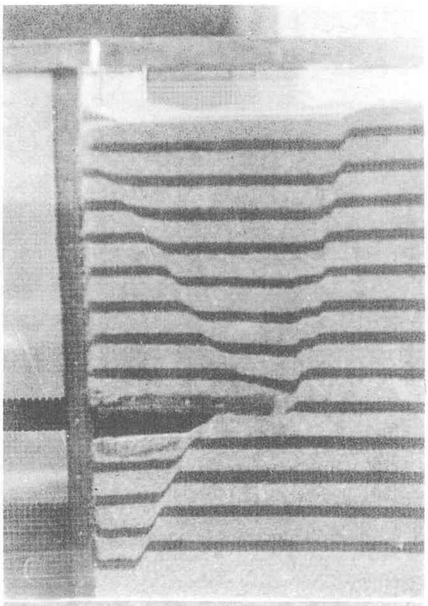

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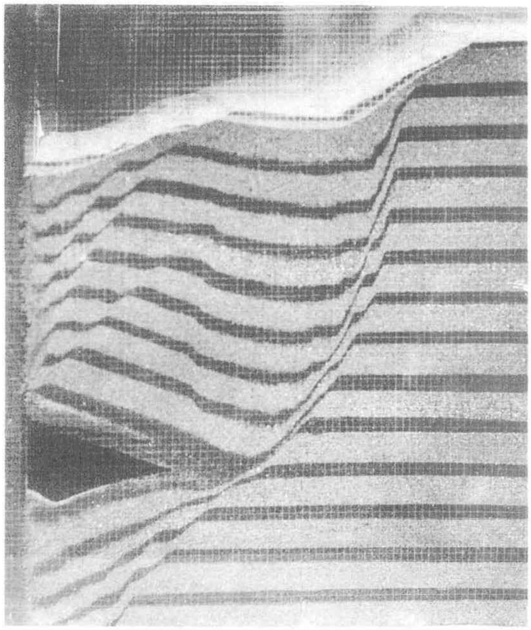

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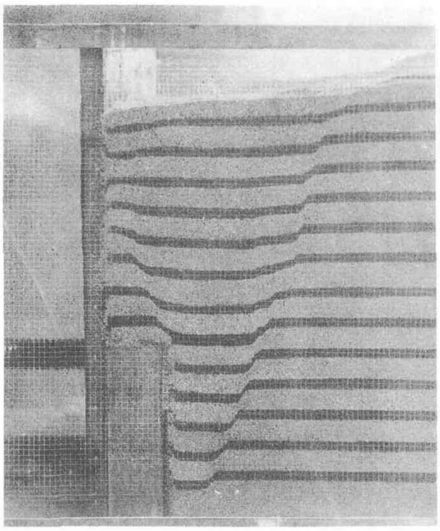

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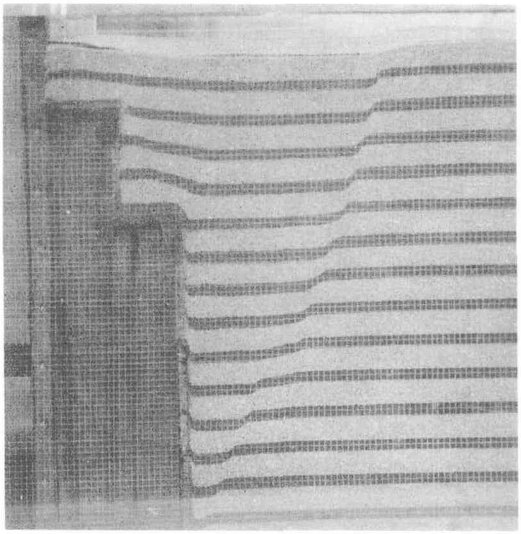
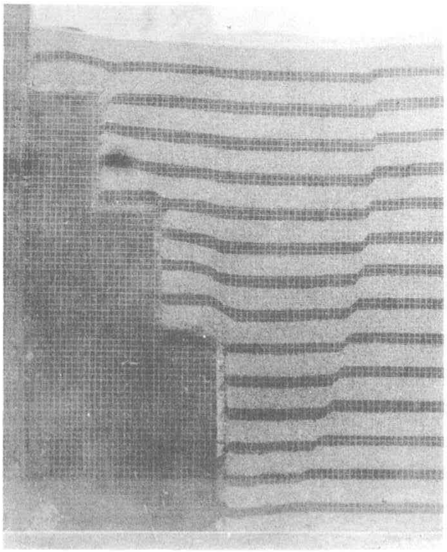


Fig. 16.

F. Takabeya : Experimental Investigations on Surface of Rupture in Sand.



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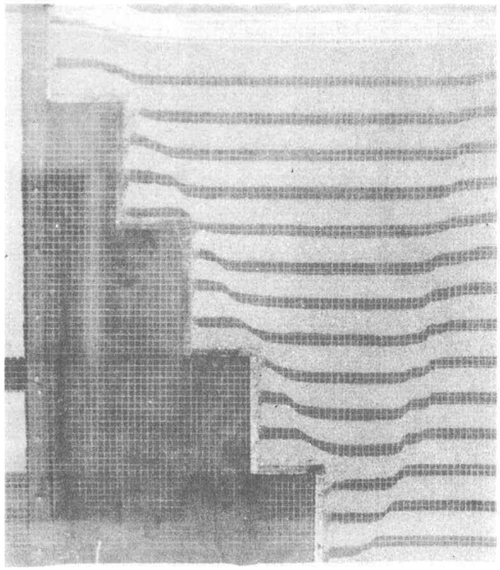

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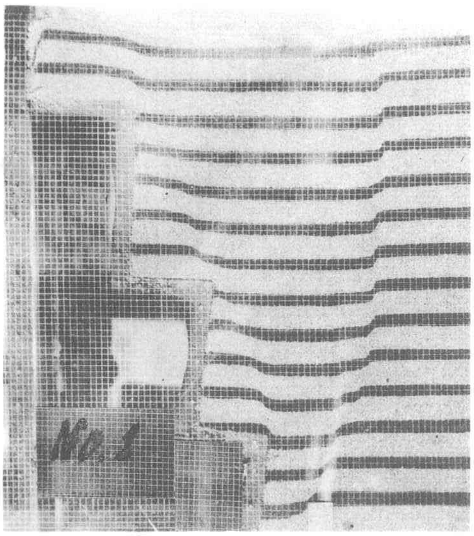

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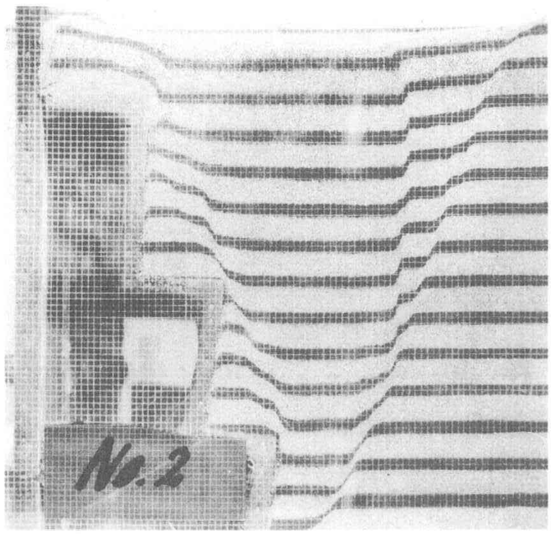
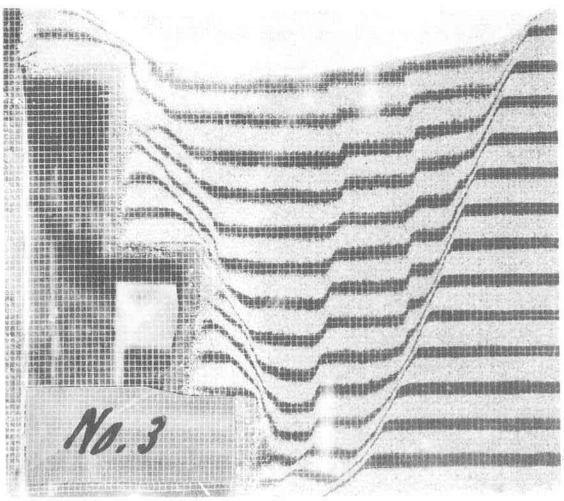


Fig. 20.



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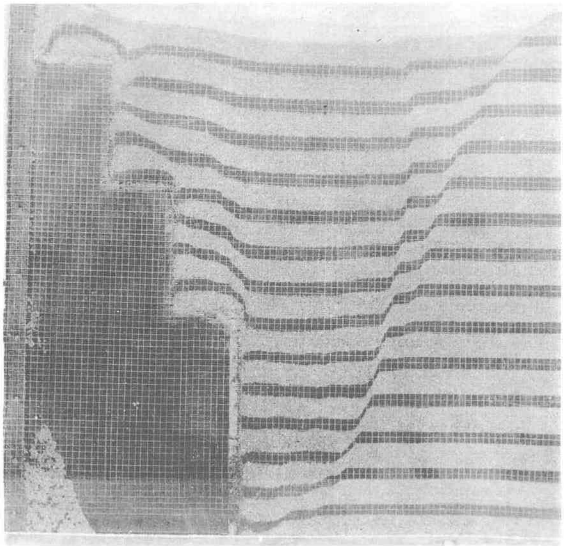
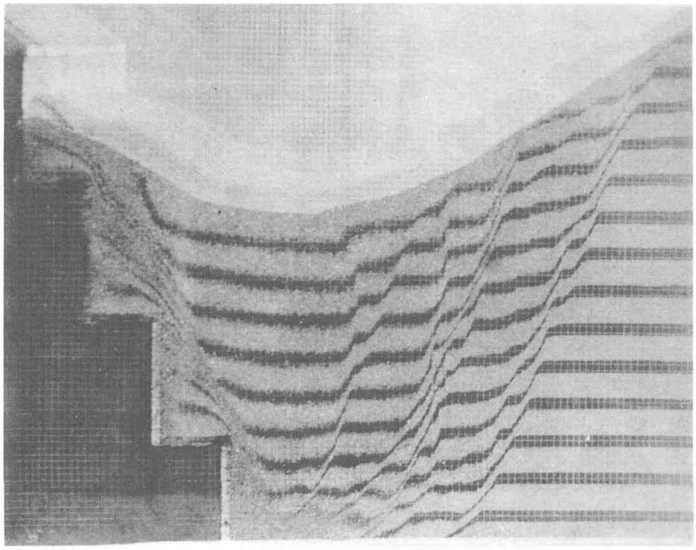


Fig. 22.



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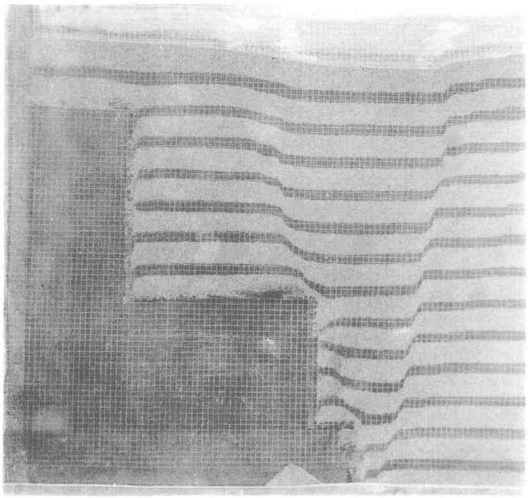

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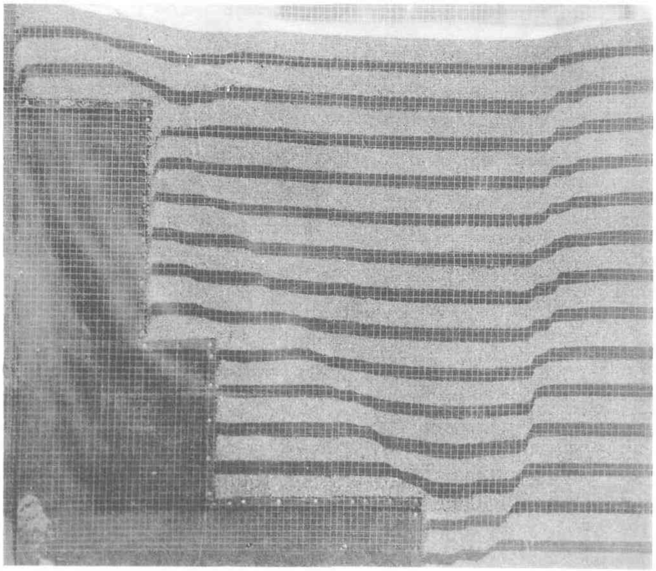


Fig. 25.

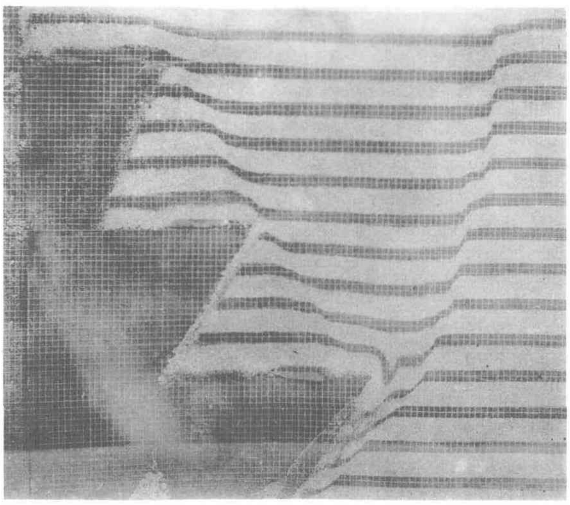


Fig. 26.

F. Takabeya: Experimental Investigations on Surface of Rupture in Sand.

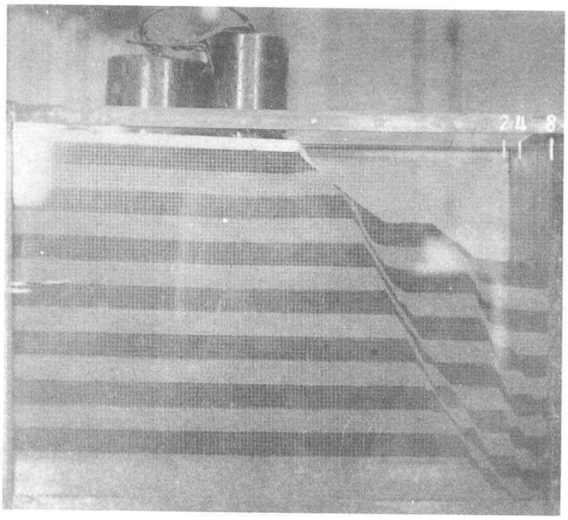
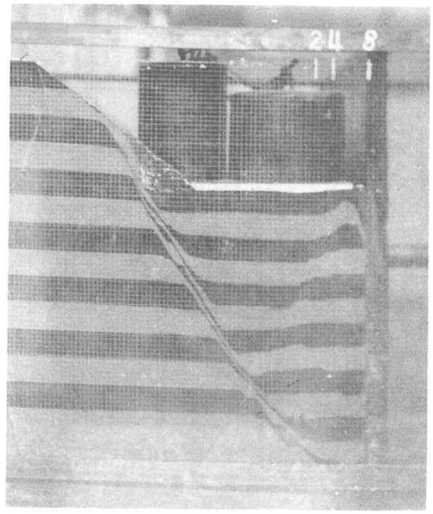


Fig. 27.



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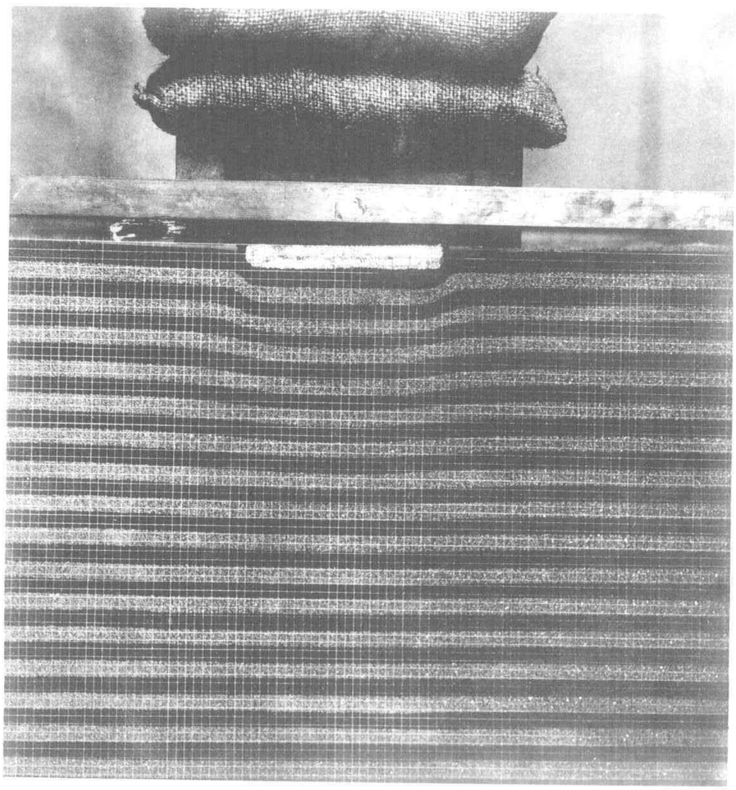

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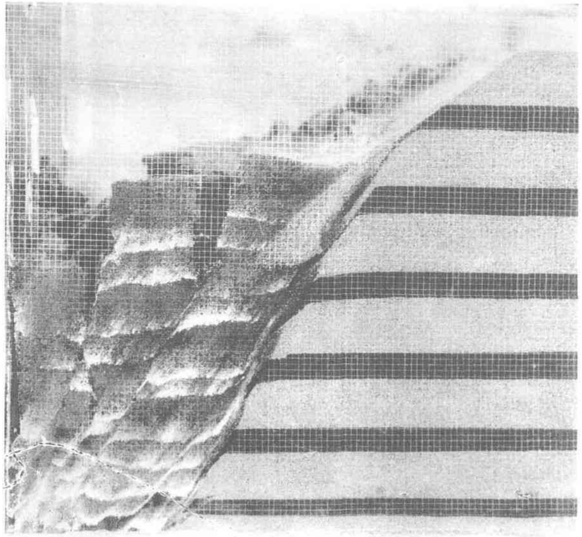

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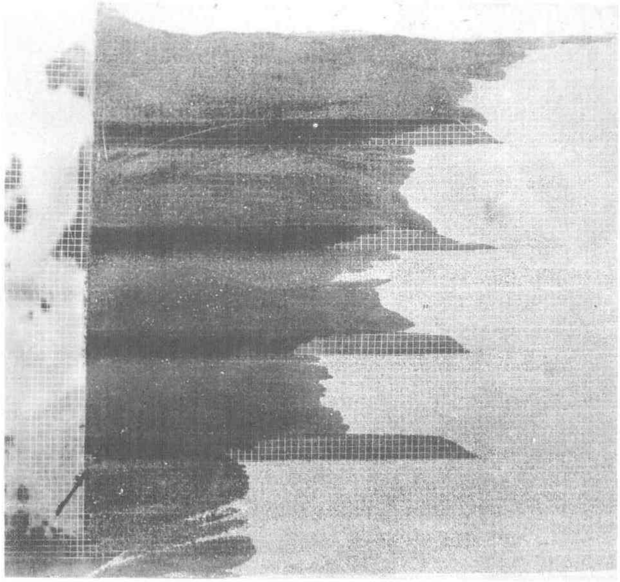

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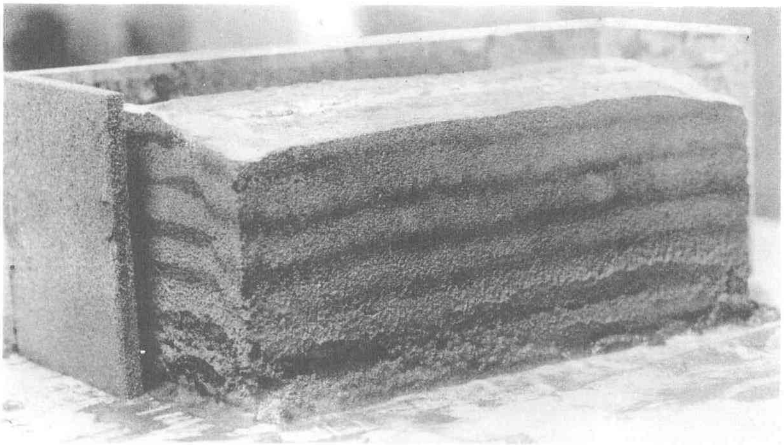

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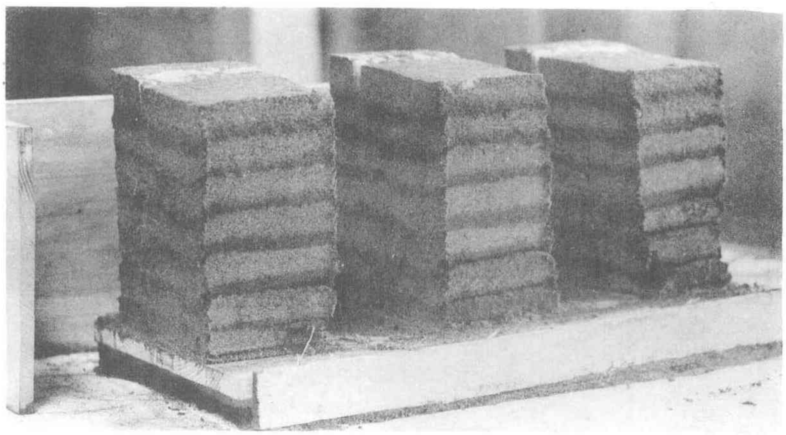

Fig. 33.