$$H_o = \frac{2c}{s} \tan (45 + \frac{\varphi}{2})$$

and below this depth it should increase in simple proportion to depth. Hence the preceding conclusions are utterly incompatible with Rankine's theory while, at the same time they are strikingly confirmed by experience.

The limitations to the validity of Coulomb's method for computing the total lateral pressure exerted by cohesive soils on the timbering of cuts are briefly mentioned (loc. cit.). This validity seems to be limited to cohesive soils with a high sand content.

No. J-4 EFFECT OF THE TYPE OF DRAINAGE OF RETAINING WALLS ON THE EARTH PRESSURE

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Notations.

s = unit weight of the fill, solid and water combined
s_o = unit weight of water
φ = angle of internal friction
δ = angle of wall friction
q = smallest amount of rainfall per unit of area and unit of time required to maintain a continuous flow in the backfill
k = coefficient of permeability of the backfill
h = height to which the water rises in a standpipe at any point of a fill
$n_w = h\, s_o$ stress in the water neutral stress in the fill
ε = angle between an arbitrary plane section through the heel of the wall and the back of the wall
ε_1 = angle between the plane of rupture and the back of the wall
H = height of the wall
E = lateral pressure required to maintain the equilibrium of an arbitrary wedge
E_1 = lateral pressure corresponding to the wedge of maximum thrust
w = total liquid pressure on an arbitrary plane section through the fill

The types of drainage and of saturation are indicated by indices in the following manner:
E, E_1, ε, ε_1, etc., refer to backfill with inclined filter (Fig. 3) during rainstorm;
E', E_1', ε', ε_1', etc., to a backfill with a vertical filter (Fig. 2) during rainstorm;
E'', E_1'', ε'', ε_1'', etc., to a backfill with any type of drainage after a rainstorm.

Effect of rainstorms on the stability of retaining walls. The failure of retaining walls backfilled with fine-grained material occurs almost exclusively during heavy rainstorms. The increase of the unit weight of the fill due to the rain is always irrelevant. The physical characteristics of the backfill material also remain unaltered. Therefore the effect of the rain can only be due to a change in the

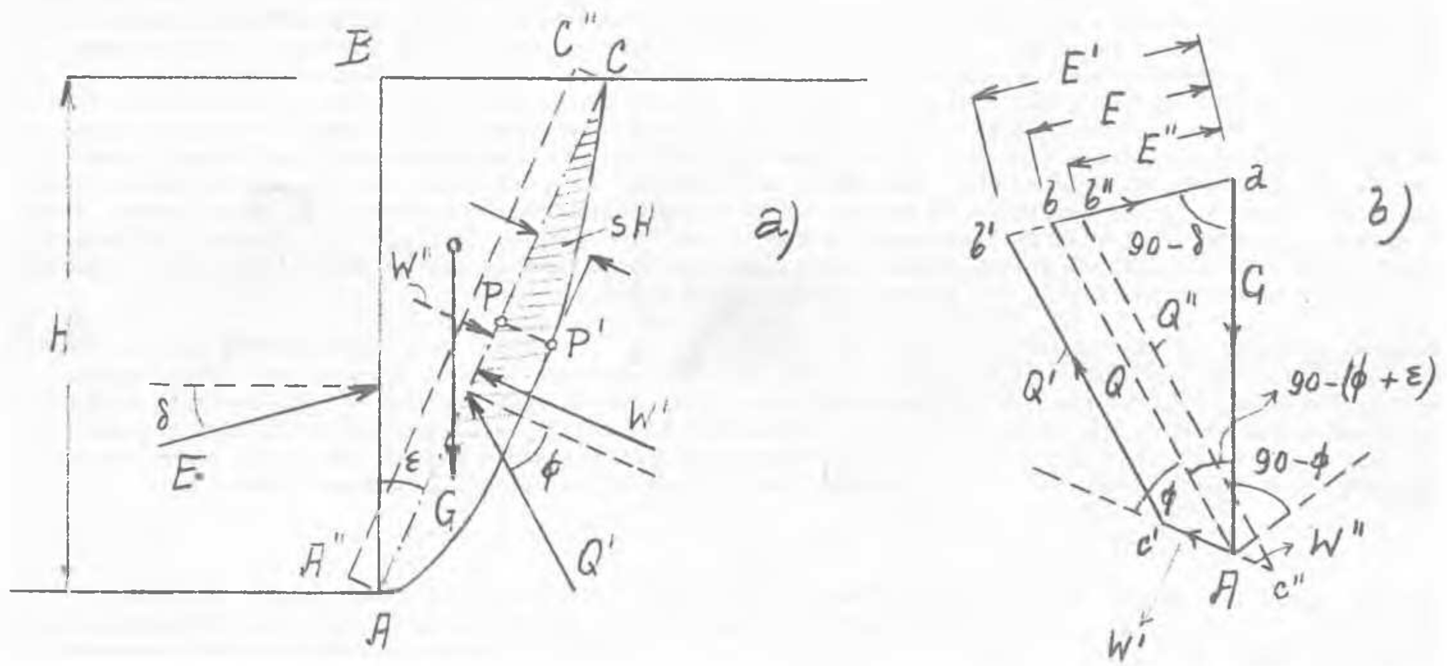

Fig. 1

state of stress in the water contained in the backfill. For a given rainfall, this change depends on drainage conditions. The following paragraphs contain the description of a method of estimating the effect of known drainage conditions on the lateral pressure during rainstorms for fine-grained, cohesionless soils.

Fundamental assumptions. The problem is solved on the following assumptions: the effect of the rain on the unit weight, s, is negligible; the yield of the wall suffices to mobilize the entire frictional resistance along both boundaries of the sliding wedge and the surface of rupture is plane. We first determine the conditions for the equilibrium of an arbitrary wedge, A B C, Fig. 1 a and then we determine the boundary of the wedge which satisfies Coulomb's "maximum condition."

The normal pressures which act on the section A C, Fig. 1 a, consist of an effective and a neutral component. (1) The frictional resistance against sliding along A C is due exclusively to the effective normal pressure. Hence the problem can be solved only if the neutral stresses are known over the entire area A C.

Conditions of equilibrium of an arbitrary wedge. To illustrate the method of determining the neutral stresses n_w along the right boundary A C, Fig. 1 a, of an arbitrary wedge, A B C, we assume that the retaining wall, Fig. 2 a, is backfilled with a fine-grained, cohesionless material such as silty sand. The backfill rests on the horizontal surface of an impermeable base, A_1 A_2, and the vertical back of the wall is drained by means of a coarse-grained filter, A B. We further assume the following numerical values: $H = 8$ m, $\varphi = 38^o$ and $\delta = 15^o$. If the quantity of water furnished by the rain is sufficient to maintain a continuous flow through the fill towards the filter, the flow will be as shown by the flow net in the figure. The lines of flow (solid) and the lines of equal standpipe level (dotted) are determined by the known laws of hydraulics. In any point, P, of the section, A C, Fig. 2 a, the neutral stress n_w is equal to h s_o. The flow net also shows that the quantity of water q per unit of time and unit of area required to maintain the continuous flow of water through the fill during a rainstorm decreases with the distance from the left side of the fill. At this rim it is equal to the coefficient of permeability, k, of the fill. Curve K, Fig. 2 b, shows the relation between the ratio q/k and the distance ℓ, from the left rim of the fill. In a fairly humid climate the rainfall is likely to exceed

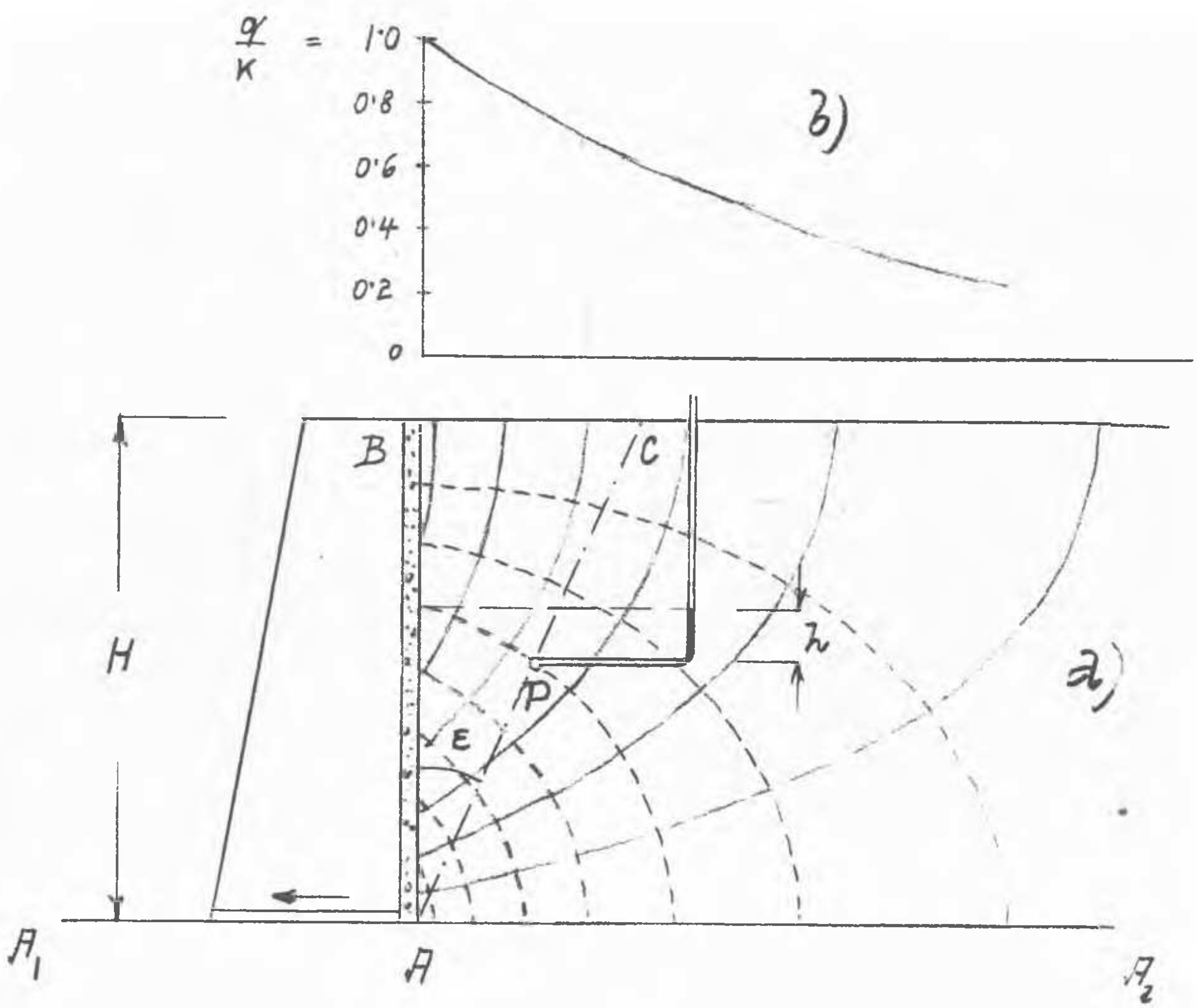

Fig. 2

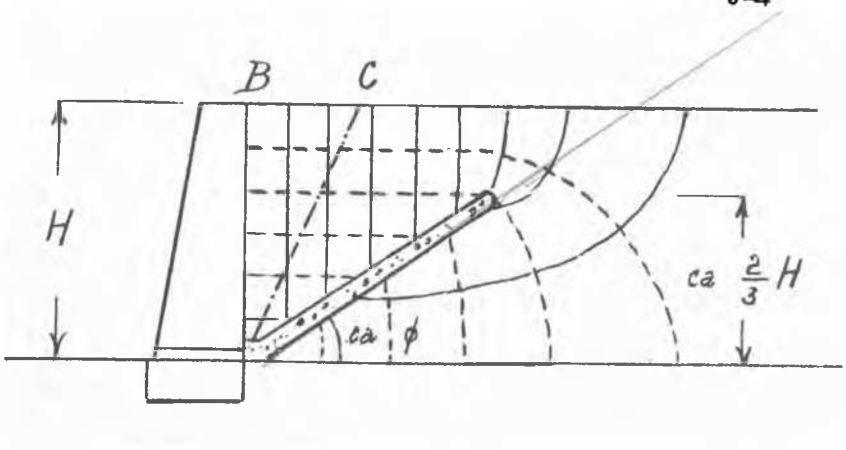

Fig. 3

for a period of thirty minutes an amount of 20.10^{-4} cm per second. Hence if the coefficient of permeability of the fill is smaller than this value the condition for maintaining a continuous flow is satisfied.

In Fig. 1 a the ordinates PP' of the curve AP'C represent the values $n_w = h\, s_o$ for the different parts of the plane of rupture AC in a period of continuous flow. The resultant neutral force W' passes through the center of gravity of the shaded area and acts at a right angle to the plane AC, while the effective reaction Q' acts at an angle φ to the normal on AC. The conditions for the equilibrium of the wedge ABC are shown by the polygon of forces ab'c' A, Fig. 1 b. This polygon shows that the lateral resistance required to maintain the equilibrium of the wedge increases with the force W'. In order to eliminate this force we can provide the backfill of the wall with an inclined filter as shown in Fig. 3. From the flow net in Fig. 3 we can see that the values n_w are equal to zero for any point located between the filter and the back of the wall, including any point of the surface of rupture, AC. On such conditions we obtain the polygon of forces abA, Fig. 1 b.

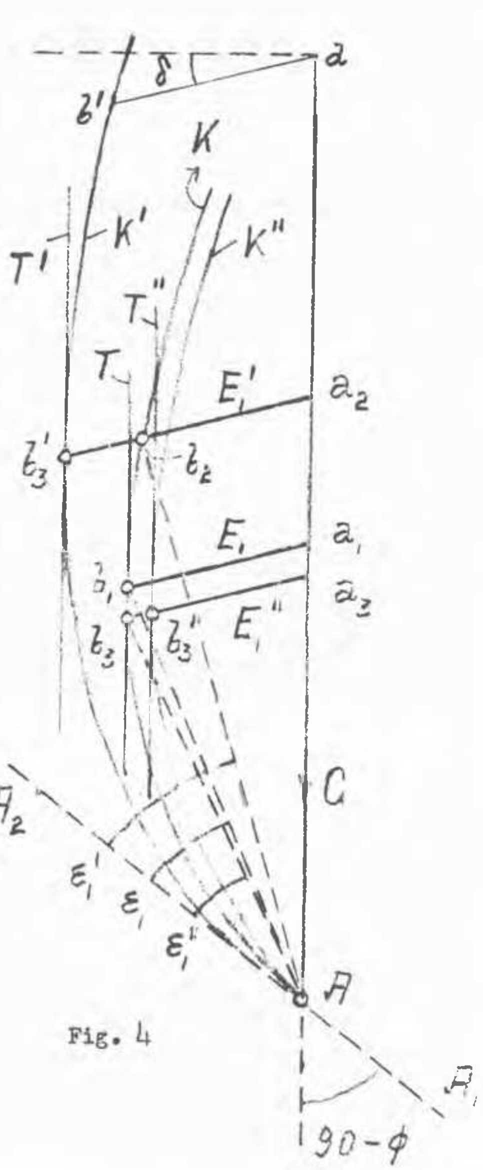

Fig. 4

As soon as the rain stops the water contained in the voids of the soil begins to drain out. However, owing to the fine-grained character of the soil the greater part of the water is retained within the soil by capillary forces. As a consequence the water is under tension. If the depth H of the backfill is smaller than the capillary rise, the tension increases in simple proportion to the height above the free groundwater level. In the case illustrated by Fig. 2 a this groundwater level is identical with the impermeable base of the fill. On the other hand, if the depth H of the backfill is great compared with the height of the capillary rise, the tension in the water seems to be practically the same for every part of the backfill. According to the results of large-scale retaining wall tests with boulder clay (2) this tension was found to be approximately 75 lb per sq ft or 360 kg per sq m for the material tested. Using this value in our example, we find that the stress in the water along the surface of rupture would be represented by the rectangle AA"CC" in Fig. 1 a. The resultant negative pressure, W", acts at a right angle to AC, Fig. 1 a, and passes through the center of gravity of AA"CC". The forces which act on the wedge ABC are determined by the polygon of forces ab"c"A, Fig. 1 b, and the lateral force required to prevent a slip of the wedge is $ab'' = E'' < E$.

<u>The surface of least resistance and the lateral pressure exerted by the sliding wedge.</u> The preceding statements are valid for <u>any</u> wedge whose right boundary AC Fig. 1 a, passes through the heel A of the wall. In order to determine the position of that particular plane AC, along which the slip would actually occur, we must introduce the condition that the value of the lateral pressure, E, E' and E" respectively, obtained from the polygon of forces Fig. 1 b be a maximum. In order to satisfy this condition, we repeat the construction shown in Fig. 1 b for different values of ε. For each value of ε we obtain a value of G and for E. The balance of the procedure will be illustrated by the method for determining E_1'. For the purpose we trace a vertical line through point A in Fig. 4 and plot the weight of the different wedges, for instance G = Aa, in an upward direction from A. From a to the left, at an angle δ to the horizontal, we plot the corresponding lateral pressure E' = ab'. Then we connect all the points b' thus obtained by a curve, K', and draw a vertical tangent T' to this curve. The length of the line a_2b_3' traced parallel to ab' represents the value E_1' which satisfies the maximum condition. In a similar manner we determine the curves K and K" and the corresponding values $E_1 = a_1b_1$ and $E_1'' = a_3b_3''$.

The method for determining the value ε_1' is based on the following fact, shown in Fig. 1 b: for equal weights G, both the reactions Q and Q' intersect the direction of G at an angle $90 - (\varphi + \varepsilon)$. For $G = A\,a_2$, Fig. 4, and $b_2b_3' = E_1' - E$, the reaction Q is represented by the line Ab_2 and the angle $90 - (\varphi + \varepsilon_1)$ is equal to the angle a_2Ab_2. Hence if we trace A_1A_2 at an angle $90 - \varphi$ to the direction of G, the angle ε_1' is equal to b_2AA_2. In a similar manner we can determine ε_1 and ε_1''. The numerical results for the intensity of the lateral pressure and for the angle ε between the sliding surface and the back of the wall are the following:

$E_1 = 14.8$ t	$\varepsilon_1 = 28^\circ\ 0'$
$E_1' = 20.0$ t	$\varepsilon_1' = 35^\circ\ 30'$
$E_1'' = 10.0$ t	$\varepsilon_1'' = 26^\circ\ 30'$

To this list we add the following values:

W = 32.0 t for the wall acted upon by the pressure of water alone, and

$E_w = 39.8$ t for the wall acted upon by a saturated fill with the standpipe level at the elevation of the upper rim. (No drainage, weep-holes completely closed.)

Range of practical application of the procedure. This range is determined by the condition that the fundamental assumptions are justified. No continuous flow through the voids such as shown by the flow net in Fig. 2 a can possibly occur unless the water content of the backfill has previously adapted itself to the change in the effective state of stress in the fill, produced by the rain. In highly permeable backfills such as clean sands, the quantity of water furnished by a rainstorm does not suffice to establish a flow throughout the fill. In highly compressible, very feebly permeable soils such as clays and certain types of fine silts the rainstorm merely produces a softening of the top layer because the change of the voids ratio associated with the change of the stresses proceeds at a very low rate from the surface downwards. Therefore, the validity of the procedure is limited to soils with a medium permeability, order of magnitude 1.10^{-4} cm per sec, and a low compressibility, such as silty sands and certain types of glacial till and loamy residual soils.

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