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Supplement to the "Proceedings" and "Meddelanden" of the Institute

Erosion problems from different aspects

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STOCKHOLM 1964

Preface

For the stability of riverbanks and waterfront slopes, erosion is of great importance and can be the cause of local damage and initiate landslides. Such events are frequent in Sweden and have to be considered in the design of protection works for earth structures etc.

Several years ago Mr. *W. Kjellman*, former head of the *Swedish Geotechnical Institute*, prepared a report in connection with an investigation sponsored by the *Swedish Road Board* on erosion problems. This report, written in 1955, was presented at the Yugoslavian Conference on Soil Mechanics the following year. It was later published in Yugoslav in the magazine *Gradevinar*, No. 5, 1958. It may be of interest to have the English version included in the present review.

Dr. *P. A. Hedar*, associate professor at *Chalmers University of Technology*, has made parallel studies from a practical point of view and has published some papers on protection works. The present contribution is confined to a re-evaluation of the design of filters, involving the use of mixed filters, formerly common in road and canal construction. Mr. *S. Andersson*, M. Sc. (Eng.), who has collaborated with Dr. Hedar, has a contribution dealing with comparison of test results with some existing formulas, and this is presented under a separate heading.

Mr. *R. Söderblom*, Swedish Geotechnical Institute, has regarded the erosion of clays from an aspect of chemistry. His paper is a reprint from the proceedings (from Pergamon Press) of the International Clay Conference, held at Stockholm, in 1963.

In the papers included here, symbols are used which are common in the relevant literature and which, unfortunately, differ in some respects from those settled by the International Society of Soil Mechanics.

Stockholm, October, 1963

SWEDISH GEOTECHNICAL INSTITUTE

UNORTHODOX THOUGHTS ON FILTER CRITERIA

by

WALTER KJELLMAN

PRESENT FILTER CRITERIA

In a protective filter consisting of quite uniform layers the grain size of any layer must exceed, say, $\frac{1}{4}$ of the grain size of the adjacent coarser layer, lest the grains of the former escape through the pores of the latter. This criterion can be written

$$d^f > \frac{1}{4} d^c \dots\dots\dots (1)$$

In a filter made up of graded layers, on the contrary, many fine grains are allowed to escape from the finer layer, provided that the coarsest grains of this layer remain in place. According to the doctrine universally adopted, the stability is secured if the following two conditions are fulfilled:

- a. Those grains in the finer layer which are coarse enough not to be able to escape must constitute at least, say, 15 % of the layer.
- b. In order not to be able to escape, these grains must be larger than, say, $\frac{1}{4}$ of the so-called 15 % grain size in the coarser layer.

The criterion thus arrived at can be written

$$d_{85}^f > \frac{1}{4} d_{15}^c \dots\dots\dots (2)$$

Eq. (2) is the filter stability criterion most commonly used. It includes Eq. (1) as a special case. Sometimes criteria with other figures than those in Eq. (2) are used, but they are always built up in the same way as Eq. (2).

GENERAL CONSIDERATIONS

We shall not bother about the figures in Eq. (2), but we shall examine the reasonableness of the doctrine. We concentrate on the above condition a, and can then, for the sake of simplicity, assume the coarser layer to be uniform.

When the filter is exposed to percolating water for the first time, fine grains of the finer layer escape through pore channels of the coarser layer. Simultaneously, coarse grains of the finer layer accumulate at the boundary surface between the two layers, and block more and more the entrances to these channels. If all entrances are blocked, the grain migration soon ceases completely. But

if any entrance remains open, migration through it continues and develops into piping. Thus, according to the Author's conception, stability requires that the finer layer shall contain so many coarse grains that they block all entrances to the pore channels of the adjacent coarser layer.

Let us now examine the present doctrine in the light of this conception. Its basic idea is that the stability of the finer layer is secured if its relative content of coarse grains exceeds a certain definite percentage. There seems to be no reason why this should be so.

One would rather expect the absolute content of coarse grains per unit area of the filter, i. e. the relative content times the layer thickness, to be the decisive factor. This would mean, for instance, that a layer containing only 5 % of coarse grains is just as stable as one containing 15 %, if the former is three times as thick as the latter.

Unfortunately this is not correct either, and the problem is much more complicated. The cause of this is that the coarse grains are not uniformly distributed in the volume of the layer; they are dispersed at random. This can be clarified by the following line of thought.

Let us assume that the material for the finer layer is taken from a large store which as a whole has a prescribed percentage of coarse grains. Furthermore we assume that this mass is perfectly mixed so that the coarse grains are dispersed at random in the mass. If we take out from the mass a sample which is very large in comparison with a coarse grain, e. g. 1000 times as large, this sample has in all probability a percentage of coarse grains that is very close to the prescribed percentage. But if we take a sample which is only, say, 5 times as large as a coarse grain, then there is a great risk that its percentage of coarse grains deviates considerably from the prescribed percentage.

Even if the finer layer is so cautiously spread out that segregation is completely avoided, its percentage of coarse grains will, consequently, vary considerably in directions parallel to the layer. Thus, there is a risk that in some part of the filter area the finer layer will not contain enough coarse grains to block all entrances to the pore channels of the adjacent coarser layer. If the thickness of the finer layer is given, this risk increases as the area becomes larger. If the area is given, we can reduce, but not quite eliminate, the risk by increasing the thickness.

Thus there are five variables in our problem, viz., the thickness and the area of the finer layer, the diameter and the percentage of coarse grains, and the risk of piping. We shall try to find a relation between these variables.

NEW CRITERION FOR GRADED LAYER ADJACENT TO UNIFORM COARSER LAYER

When piping of the finer layer tends to occur through a pore channel in the coarser layer, all grains located in a certain definite portion of the finer layer move towards the entrance of the channel. We shall call this portion the "active

body". If it contains at least one coarse grain, piping is stopped. In order to compute the probability of this event, we must first study the shape and magnitude of the active body.

For this purpose, laboratory tests have been performed at the Swedish Geotechnical Institute in Stockholm. For the sake of simplicity the tests were made with dry sand, the force of gravitation being used instead of the seepage force as driving agent. The apparatus consisted of a container in the shape of a vertical cylinder, 50 cm in height, of half-circular cross-section, 50 cm in diameter. The bottom and the half-circular wall were made from steel-plate, the plane wall from lucite. The bottom was provided with a half-circular trap-door, concentric with the half-circular wall. Two sands of different colours were placed alternately in the container in horizontal layers, 1 cm thick. When the trap-door was opened, so that the sand began to run out, the boundaries of the active body were clearly visible through the lucite. Photos taken during two such tests are reproduced in Figs. 1 and 2.

The investigation showed that, to a close approximation, the active body can be assumed to be a column perpendicular to the layer, provided that the thickness of the layer is not too small. We designate the diameter of the active body by αD , where D is the diameter of the opening in the floor and α is a factor depending on several variables in a still unknown way. Thus, if the thickness of the layer is T , the volume of the active body is $\frac{\pi}{4} (\alpha D)^2 \cdot T$.

We shall now apply this result to a graded filter layer having an area A , adjacent to a coarser uniform layer, whose pore channels have a width slightly below D . In order to simplify the computation, we assume that all those grains of the finer layer which cannot enter the channels, have a diameter D . We also assume that each of these grains, together with the pertaining voids, occupies a volume $\frac{\pi}{4} D^3$. (This implies a void ratio of 0.50.) Finally, the relative content of such grains is called n . (Thus, there is one grain D to every $\frac{1}{n}$ volumes $\frac{\pi}{4} D^3$ of the layer.)

The active body can be taken to consist of $\alpha^2 \frac{T}{D}$ elements having a volume of $\frac{\pi}{4} D^3$ each. The probability that any arbitrary element contains no grain D is $1-n$. The probability that the whole active body contains no grain D is then $(1-n)^{\alpha^2 \cdot T/D}$, and this is therefore the risk of piping through the pore channel under consideration.

The coarser layer can be supposed to have a grain size $4D$ and to be in a dense state, so that its grains lie in a triangular pattern. The boundary surface between the two layers then contains $A/4D^2 \sqrt{3}$ entrances to pore channels. The probability that piping does not occur through any of them is

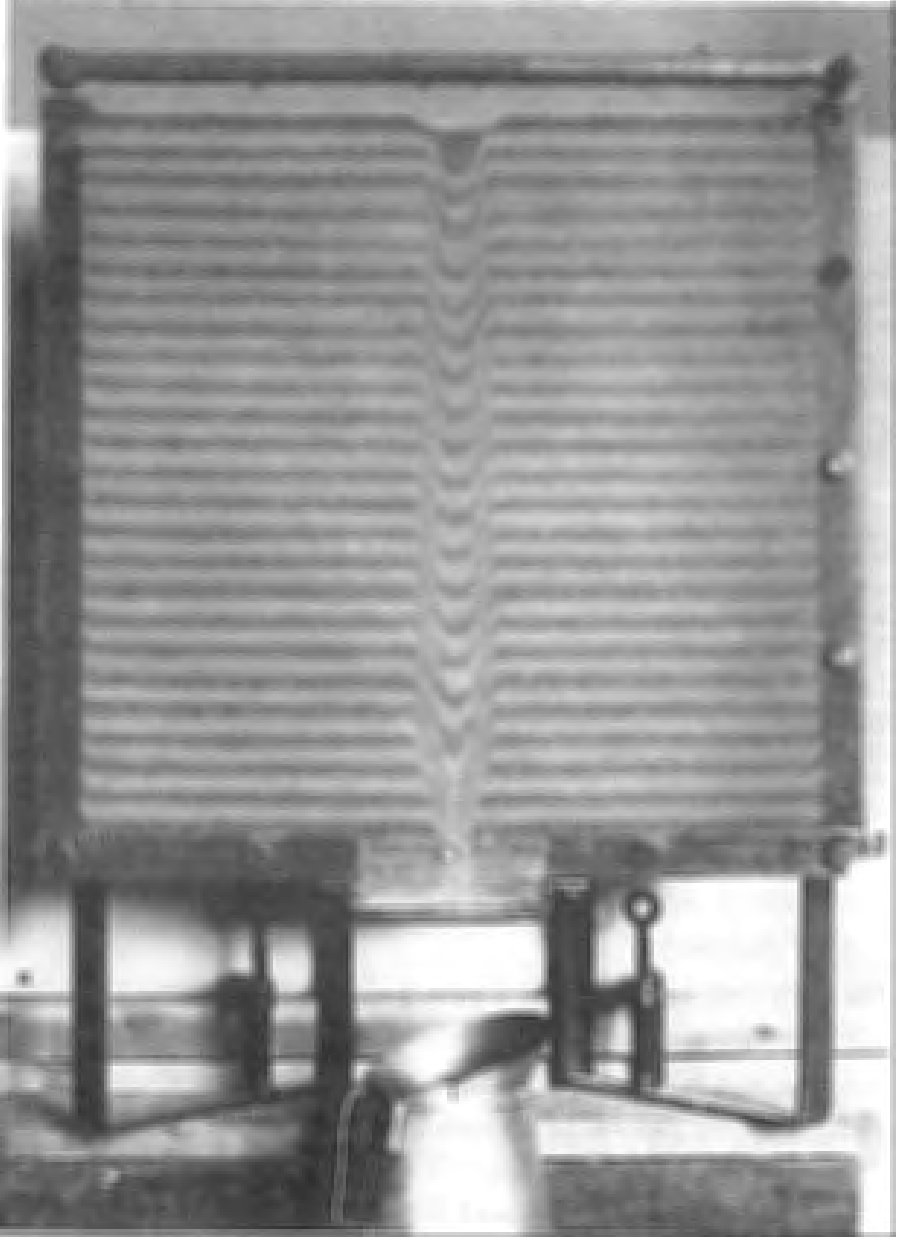


Fig. 1. Active body. (Layer thickness 50 cm. Hole diameter 1.6 cm.)

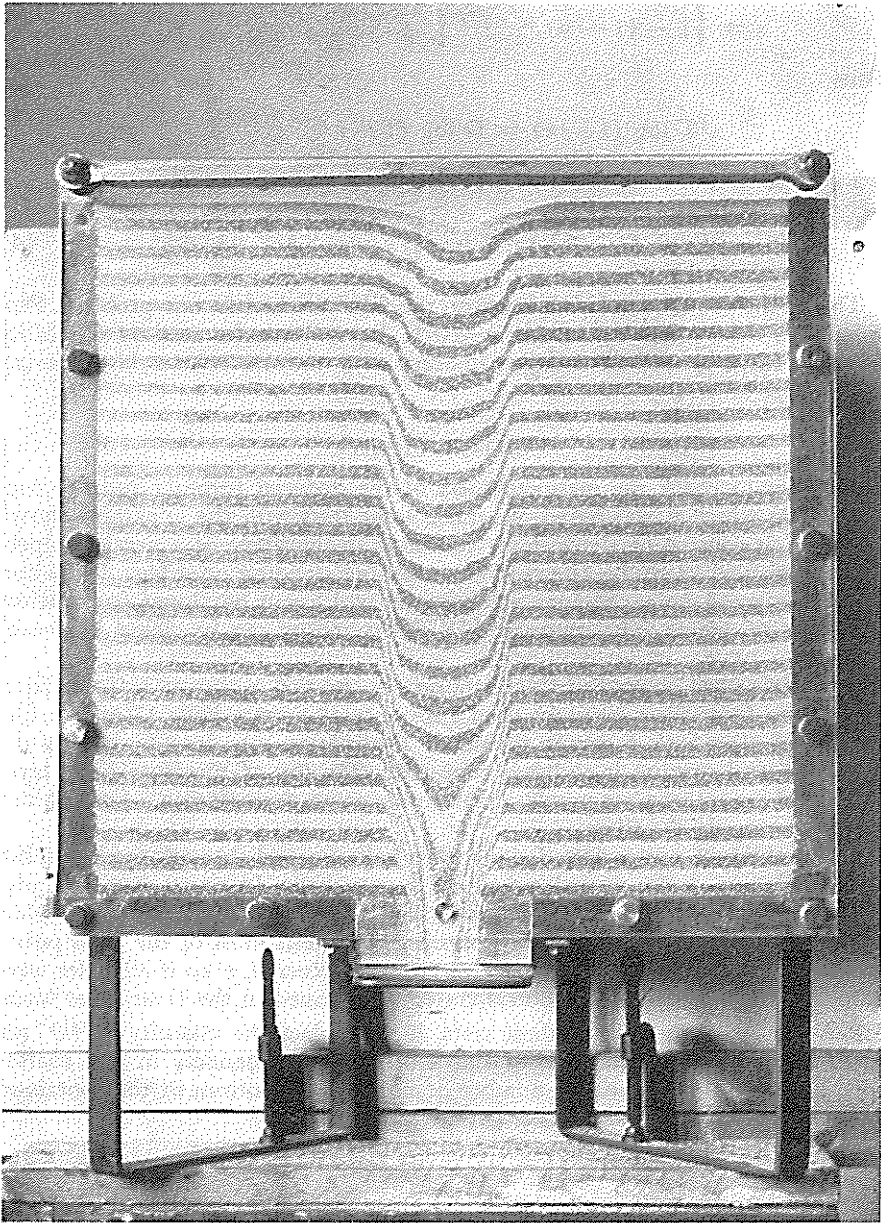


Fig. 2. Active body. (Layer thickness 50 cm. Hole diameter 5 cm.)

$$s = \left[1 - (1 - n) \alpha^2 \cdot T/D \right] A/4D^2 \sqrt{3}$$

Thus

$$\alpha^2 T \log (1 - n) = D \log (1 - s \cdot 4D^2 \sqrt{3}/A) \dots\dots\dots (3)$$

If *s* is close to 1, as it always is in practice, Eq. (3) can be transformed into

$$\alpha^2 T \log (1 - n) = D \log \left[(1 - s) \cdot 4D^2 \sqrt{3}/A \right] \dots\dots\dots (4)$$

This is the required relation between the five variables in our problem. Provided α is determined by further research, Eq. (4) can be used as a stability criterion for a graded filter layer adjacent to a uniform coarser layer having a grain size of $4D$.

CHECK TESTS

In order to check the reasonableness of the deduced formula and the conception on which it was based, we made some tests with the apparatus shown in Fig. 3. It consists of a steel-plate container in the shape of a parallelepiped, 50 cm high and 18 cm by 18 cm in cross-section, standing on 4 legs. In its bottom there are 4 holes, 16 mm in diameter, which can be closed from below by means of a gate. The upper end of the container can be closed by means of a lid.

The perforated bottom of the container represented a coarser uniform filter layer. As a finer filter layer we used a mixture of pottery balls 17 mm in diameter and glass balls 6 mm in diameter. The mixing was done by rolling the apparatus and turning it endways repeatedly. On top of the finer filter layer we placed a mass of glass pearls, 2 mm in diameter, representing a fine-grained soil bordering on the filter.

When the gate was removed many glass balls escaped through the holes, but more and more holes were blocked by pottery balls. In many tests all holes were blocked, so that the movements in the filter ceased without a single glass pearl having escaped through the holes. In other tests most of the glass pearls escaped, and then we considered piping to have occurred, even if all holes were blocked afterwards, when a conical crater was formed in the finer filter layer.

We can apply Eq. (3) to these tests, if we replace the quantity $A/4D^2 \sqrt{3}$, which designates the number of entrances to pore channels in the coarser layer, by the value 4, i. e. the number of holes in the bottom of the container. Inserting also $D = 1.7$ cm in Eq. (3) we get

$$\alpha^2 T \log (1 - n) = 1.7 \log (1 - s^{1/4}) \dots\dots\dots (5)$$

Two values of *n* were tested, each combined with two values of *T*, as is seen from Table 1. For each of these combinations 10 tests were made, resulting in a value of *s*. Inserting *n*, *T* and *s* in Eq. (5) we computed α for each combination.

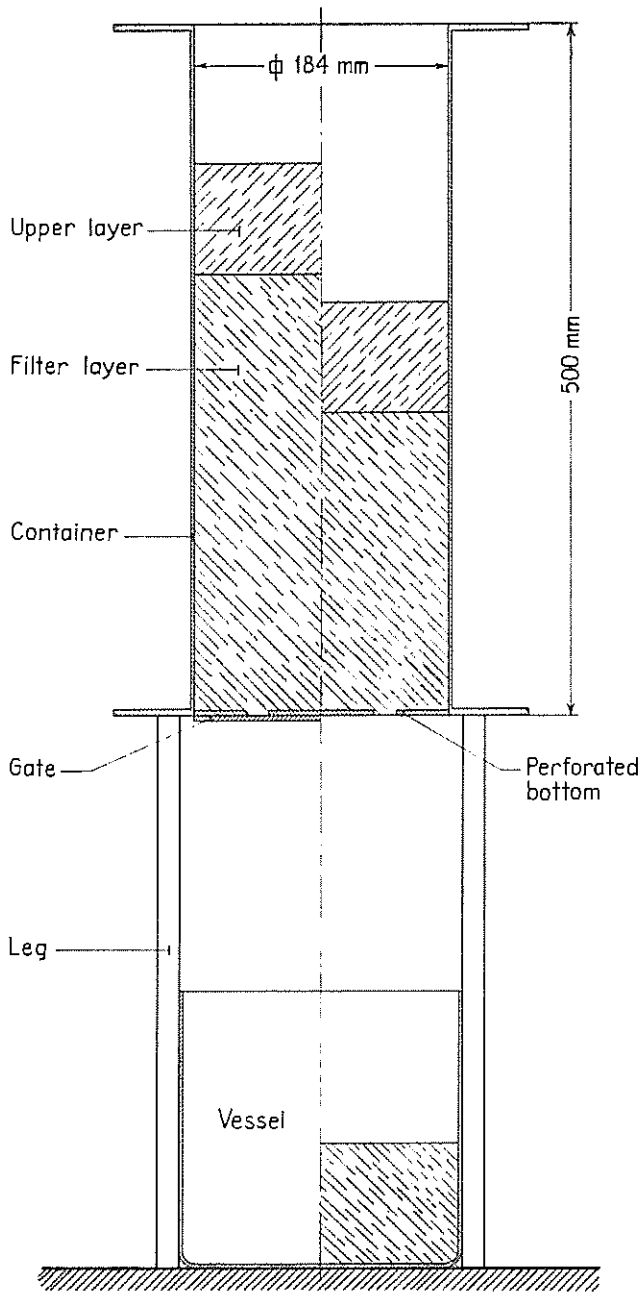


Fig. 3. Apparatus for check tests. Left: at start of test. Right: at end of test.

Table 1.

n	T cm	s	α
0.05	10.3	0.6	2.6
„	15.5	0.9	2.8
0.15	7.0	0.3	1.4
„	10.3	0.8	1.7

The test results given in Table 1 confirm our theoretical conclusion that the stability of a filter layer can by no means be secured by a certain definite percentage of coarse grains in the layer. It is influenced by this percentage, but it also depends in a very high degree on the thickness of the layer. Furthermore, the whole problem is a question of probabilities.

As seen from the table, α increases with increasing T . The obvious reason for this is that the lowest part of the active body is not cylindrical as assumed in the theory but conical (see Figs. 1 and 2). The values of s and α are irregular, because the number of tests was small, the layer thickness was small, and it was often doubtful whether piping occurred or not.

APPLICATION OF NEW FORMULA TO A PRACTICAL EXAMPLE

We consider a protective filter with an area of $A = 1000 \text{ m}^2$ and containing a uniform layer with a grain size of 28 mm bordering on a finer graded layer. According to the present criterion in Eq. (2) the 85 % grain size in the finer layer is $D = 7 \text{ mm}$. According to present practice the thickness of this layer is, say, $T = 30 \text{ cm}$.

With the guidance (though a very poor one) of Figs. 1 and 2 we assume $\alpha = 1.6$. Inserting the values of A , D , T , α and $n = 0.15$ into Eq. (4) we get $s = 0.94$. Thus, the risk of piping would be 6 % in the chosen example. Of course, such a great risk should by no means be taken.

Let us now compute the requisite thickness T for reducing the risk $1 - s$ to, say, 0.1 %, the other factors remaining constant. By means of Eq. (4) we get $T = 37 \text{ cm}$. It is remarkable that the risk is so effectively reduced by this moderate increase in thickness.

SUMMARY

All stability criteria hitherto used for a graded filter layer are based on the idea that the layer is stable, if it has a certain definite percentage of grains large enough not to be able to escape through the adjacent coarser layer. It has been shown in the present paper that this idea is unreasonable.

We have found that the thickness of the finer layer is as important a factor as its percentage of coarse grains. The whole problem is a question of probabilities, and some risk of piping must always be taken. Assuming the coarser layer to be uniform, we have deduced a formula for this risk as a function of the thickness and the area of the finer layer, and of the diameter and the percentage of its coarse grains. The formula contains a factor α , whose dependence on the pore size of the coarser layer and perhaps also on other variables must be studied in tests with percolating water.

If the coarser layer is graded, the above statements are still valid, but the formula will be much more complicated, and will also contain the thickness and the grain sizes of the coarser layer.

By applying the new formula to a practical example it has been shown that, if the present criterion is used and the layer thickness is chosen according to present practice, the risk of piping may be very great.

Extensive laboratory test series with protective filters have been performed in recent years particularly in the U. S. The results of such tests cannot be applied directly to filters in practice, they should be interpreted by means of probability calculation as shown above.

FILTERS AS PROTECTION AGAINST EROSION

by

PER ANDERS HEDAR

The prevention of erosion on beaches of lakes and seas or on river banks is a frequently recurring problem.

A sloping beach or bank of a river, consisting of fine-grained friction material, is often without inherent ability to remain stable under the influence of moving water, and must then be protected from erosion. The same is true in a still higher degree if the friction material is uniform. The foundation of a bridge pier or of a ferry station on a beach (or in the middle of a river) must rest on firm ground, whose stability may not be jeopardized by the undermining effect of running water.

Protection against erosion is usually performed by laying out a bed cover consisting of a number of layers of uniformly graded gravel or stone material so that a shore revetment is obtained, in principle similar to the filter illustrated in Fig. 1. The filter should satisfy the following demands. The grain size in the layers must be chosen so that creep of the grains is prevented when water, owing to difference in water level on each side of the filter, percolates through the filter. The layer of blocks or boulders on the filter bed must be large enough to withstand the force of waves or flowing water.

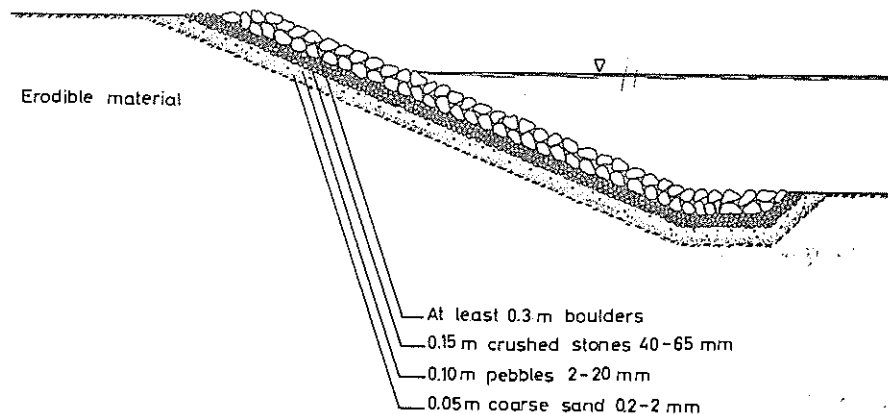


Fig. 1. Traditional filter of classified stone material

It has been found both complicated and expensive to construct such artificial beach revetments. It is practically impossible to deposit the different, uniformly thick, layers of a certain grain size distribution under water, particularly when the work must be carried out in running water or in places exposed to the action of waves. The material has been placed through pipes, and sometimes the uniformly graded material has even to be placed on the slopes in sacks, which have disintegrated with time.

Formerly, attempts were often made to prevent erosion by tipping gravel along the slope and then covering it with blocks of stone. But since the importance of good grain size distribution of the gravel and of a properly dimensioned layer of armour stones for attaining stability was not known, damage often arose and the protection was inefficacious.

If the beach itself consists of well graded gravel and stone material, containing blocks large enough to withstand the action of the water, the fine material is eroded from the surface layer, and natural forces gradually create a stable blanket of stone.

Starting from this observation, it should be possible to simplify the construction of a beach revetment by substituting for the filter of layers of uniformly graded material, a single mixed filter, containing various grain sizes and stones, of a certain thickness, without renouncing demands on stability or protection against erosion. Fig. 2 illustrates the design of such a filter.

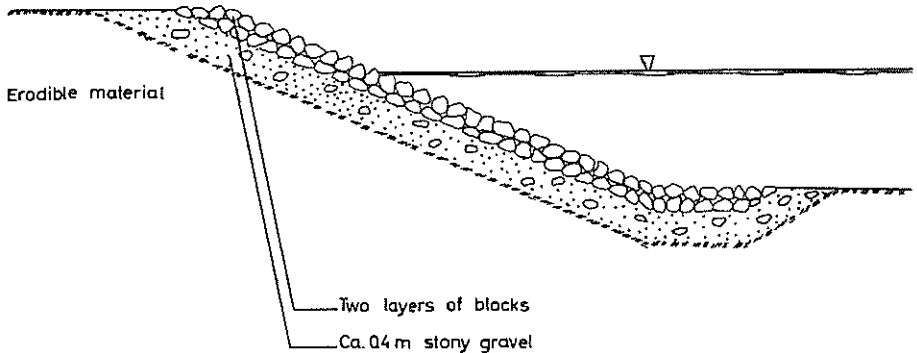


Fig. 2. Filter of well graded material with armour layer of stones

The fine material in the surface layer of the mixed filter will be washed out by the action of the water, which will reduce the thickness of the filter. This must be allowed for, and the filter made so thick that moving water will not penetrate to the soil that is to be protected. A consequence of the loss of fine material is that the layer of boulders must be able to settle down without losing its stability and protective function. Erosion is determined to a certain extent by the fact that the farther the water penetrates into the interstices between the blocks, the more its velocity is reduced. The loss of fine material

continues until the mixed filter consists, at a certain depth, of particles large enough to resist the action of water at that depth. A thicker layer of boulders leads to slower movements of water at the surface of the mixed filter and a consequent smaller loss of material, and less subsidence of the armour layer.

The weight Q in tons of a block in the armour layer is derived from the formula

$$Q = \frac{\pi}{6} s_s k^3 \dots\dots\dots (1)$$

where s_s = the specific gravity of the blocks and

k = the average diameter of the blocks (considered as spheres).

In case of wave action, the diameter k is determined from the following formulas. For the uprush phase of the wave movement the following applies:

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{1.1 (d_b + 0.7 H_b)}{\left(\log_{10} \frac{14.83 H_b}{k}\right)^2 (1.11 \cos \alpha + \sin \alpha)} \dots (2)$$

and for the downrush phase

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{K_{down} H}{16.76 (1.11 \cos \alpha - \sin \alpha)} \dots\dots\dots (3)$$

where s_f = unit weight of water

d_b = depth of water where waves break

H_b = height of breaking waves

H = height of waves at foot of slope

K_{down} = coefficient, which varies according to Fig. 3

α = angle of slope

For flat slopes, Eq. (2) gives the largest diameter of stones, and for steep slopes Eq. (3). The marginal region, where both formulas give about the same size of stone, will have a gradient (vertical on horizontal) about 1 on 3 to 1 on 4. The equation giving the greatest diameter must be used (HEDAR, 1953).

The depth of water at the foot of the revetment is often limited, which may cause the waves to break at or just before the foot of the slope. The author's model tests have shown that in such cases the beach revetment must be designed for the highest wave, which may be formed at a distance from the foot of the slope equal to half the length of the wave.

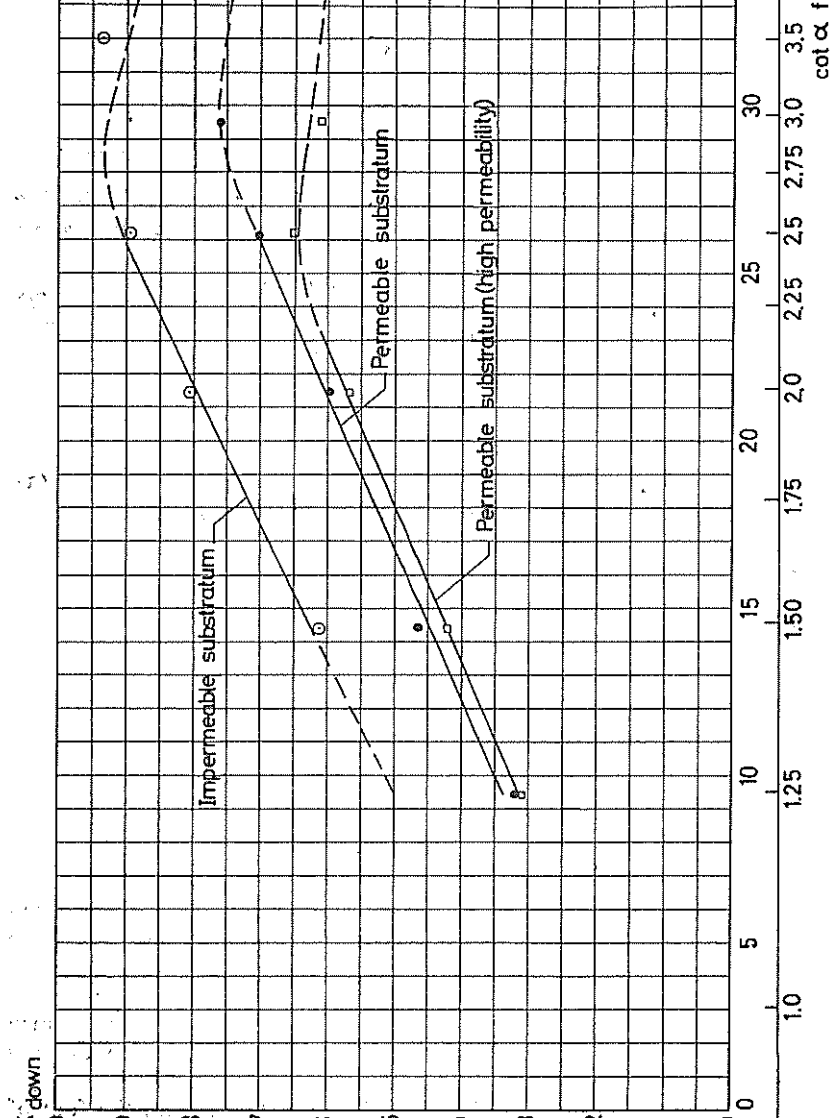


Fig. 3. Coefficient K_{down} as a function of slope gradient

When we are concerned with a waterway with flowing water, the diameter of the stones is determined from the formula

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{v_m^2}{7.5 \left(\log_{10} \frac{14.83 z}{k}\right)^2 (1.11 \cos \alpha - \sin \alpha)} \quad (4)$$

where v_m = mean water velocity

z = depth of water

α = angle of slope in direction of water flow

In 1958, the author, in collaboration with *Sören Andersson*, constructed an open flume, 16 m long, built on two supports, with an electric device by which the gradient of the flume can be varied with a very high degree of precision. The flume is so rigid that the deflection, which is only a fraction of a millimetre, can be ignored. This flume has been used in stability experiments with stone beds at the Chalmers University of Technology, Division of Hydraulics.

The principle of the experiments was as follows. A bed of stones was laid on the bottom of the flume, and was subjected, at different gradients, to the action of water until the limit of the stability of the stones was reached. The coefficient 7.5 in Eq. (4) was determined in these tests.

Rules for the design of the armour layer and the results of some test series with stone armour layers in running water are given by *Andersson* in a separate article (included in the present publication).

In order to elucidate the possibilities of the mixed filter to withstand the action of waves, model tests were made in a wave-flume; the results are given in Table 1.

Table 1. Test data

Wave height H m	Period T sec	Observations at beach revetment
0.04	1.54 and 2.35	Fine particles leave surface of mixed filter and are deposited at bottom of slope 1 on 100
0.06	1.54 and 2.35	Slight subsidence in armour layer
0.09	1.54 and 2.35	Subsidence, armour layer penetrates into mixed filter. Waves break at foot of slope
0.13	1.54 and 2.35	Armour layer not fully stable. Waves break in front of foot of slope. Failure was not possible to force

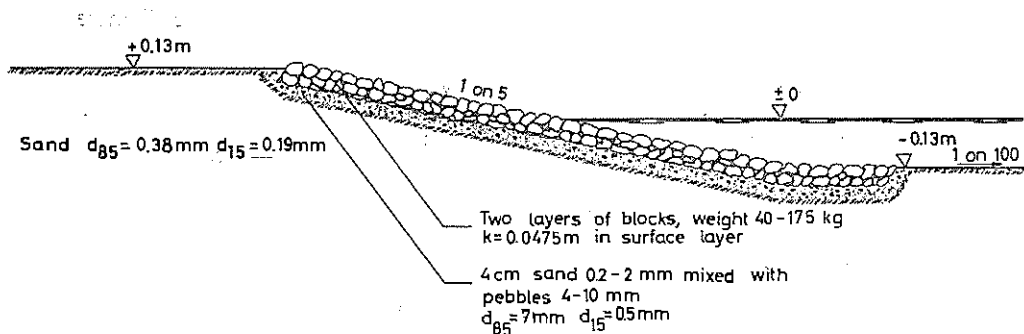


Fig. 4. Beach revetment with mixed filter in wave-flume

The slope, designed according to Fig. 4, was tested at the wave heights and wave periods given in Table 1. If the experimental values are transformed into actual conditions with a significant wave height of 0.85 m, the beach revetment should be made with an armour layer of blocks weighing from 20 to 70 kg on a layer of stony gravel about 30 cm thick. Experience gained in these model tests confirms the view that a simpler design of revetments is often possible. To these experimental tests an actual construction is added.

In conjunction with landscape preservation by the Indalsälvens and Faxälvens Water Regulation Company at Gäddede by Kvarnbergsvattnet, in 1958, a slope was protected in an area that had been filled to eliminate the troublesome sand drift. According to wind observations made by the Swedish Meteorological and Hydrological Institute compared with the results of wave height measurements made on the site, the beach revetment should be designed for a significant wave height of 0.85 m, which was calculated to occur once a decade. The slope protection was made as shown in Fig. 5. On the sand a layer of well graded gravel, at least 20 cm thick, was placed at low water. Above this was spread at least a double layer of boulders weighing about 40 kg or more each.

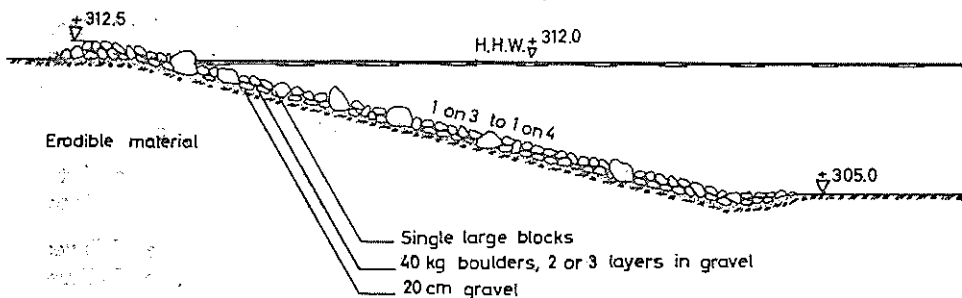


Fig. 5. Beach revetment at Kvarnbergsvattnet, Gäddede



Fig. 6. Gädde, upstream bank. Natural slope cover meets artificial revetment

Gravel was washed into the interstices between the stones, and the removal of fine material was achieved artificially. To give the slope a more varied appearance, large blocks of stone were inserted here and there. These blocks also helped to increase the stability of the slope. The photograph, Fig. 6, was taken while the slope protection filter was being laid. The slope has now (1963) been exposed to the action of waves from Kvarnbergsvattnet for five years without suffering damage.

The results obtained show that it is often possible to continue working along these lines, which implies that the design of erosion protection can be simplified by carefully dimensioning the armour layer of stone and by replacing the different classified layers by a single well graded layer of gravel. The uncritical use of filters of several layers, each of uniformly graded material, as protection against erosion is neither advisable nor economic. In many cases the desired result may be obtained by means of simpler constructions, in closer relation with nature's own way of neutralizing eroding elements and, generally speaking, coinciding with them.

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STABILITY OF ARMOUR LAYER OF UNIFORM STONES IN RUNNING WATER

by

SÖREN ANDERSSON

There are, in the international literature, a large number of formulas and recommendations for the determination of the size of stones necessary to ensure stability of an armour layer in running water. Formulas given, which usually assume stationary, uniform flow, are in principle built up on the basis of shear stress or velocity hypotheses. The following formulas, rewritten to simplify a comparison, have been given as type equations by different authors:

$$\text{SHIELDS (1936)} \quad k = \frac{s_f}{s_s - s_f} \cdot \frac{z \cdot \sin \alpha}{0.06}$$

k = the diameter of the stone if it is regarded as a sphere of the same weight as the actual stone

$s_f; s_s$ = unit weight of water and of stone respectively

z = depth of water

α = angle of slope in direction of water flow

$$\text{MEYER-PETER \& MULLER (1948)} \quad k = \frac{s_f}{s_s - s_f} \cdot \frac{z \cdot \sin \alpha}{0.03 \text{ to } 0.047}$$

where 0.03 must be assigned to complete rest and 0.047 to a situation in which material transport is zero. The last value was obtained by extrapolation of the test values in measurements of material transport.

$$\text{SUNDBORG (1956)} \quad k = \frac{s_f}{s_s - s_f} \cdot \frac{3}{2} \cdot \frac{z}{c_1 c_2} \cdot \frac{\sin \alpha}{\tan \varphi \cos \alpha - \sin \alpha}$$

c_1 and c_2 = coefficients dependent on degree of turbulence and state of density of the material: normally $c_1 \cdot c_2$ may be fixed at 0.087

φ = angle of natural slope of the stones

HEDAR (1960, 1962)

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{1}{K} \cdot \frac{v_m^2}{\left(\log_{10} \frac{14.83 z}{k}\right)^2} \cdot \frac{1}{\tan \varphi \cos \alpha - \sin \alpha}$$

v_m = mean velocity of water, m/sec

K = coefficient, given by *Hedar* at 7.5

ISBASH (1936)

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{v_m^2}{2g} \cdot \frac{1}{1.44}$$

The coefficient 1.44 has been obtained empirically on the assumption that the blocks of stone are dumped pell-mell in running water.

g = acceleration of gravity, m/sec²

The relation between the required diameter of stone, k , and mean velocity of water, v_m , as recommended by different authors and authorities, is illustrated in Fig. 1. The slope has been assumed to be a gentle one, and depth of water equal to 20 k .

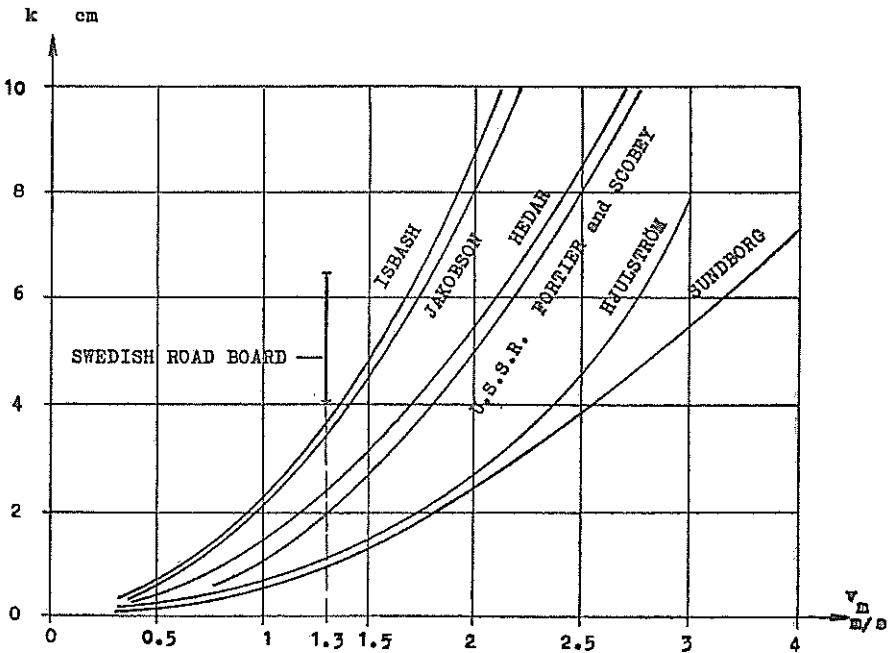


Fig. 1. Required diameter of stone as a function of mean velocity v_m . (For USSR-FORTIER and SCOBAY -curve, see CHOW, 1959)

It will be observed that the various formulas and recommendations give very different values for the diameter of stones required for stability. The primary cause of these differences is probably that the *different workers have started from different, not clearly defined stability limits.*

In order to study the safety factor in the formulas and recommendations, tests were made with plane armour layers of practically uniform stones. Two diameters of stone were studied, $k = 3.2$ and $k = 4.6$ cm (regarded as spheres). The unit weight of the stone was 2.8 in both cases. The stone was crushed, but with somewhat rounded edges. Movements of the stone material were observed at different velocities and bottom slopes. The number of stones moved within a test section has been expressed in a percentage, N , of the total number of stones in the surface layer of the test section. The percentage N may be said to define a *degree of erosion.*

RESULT OF TESTS

From the starting point of the shear stress and velocity hypotheses respectively, the required stone diameter may, in accordance with the equations given above, be written

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{z \sin \alpha}{C} \cdot \frac{1}{\tan \varphi \cos \alpha - \sin \alpha}$$

$$k = \frac{s_f}{s_s - s_f} \cdot \frac{v_m^2}{K \left(\log \frac{14.83 z}{k} \right)^2} \cdot \frac{1}{\tan \varphi \cos \alpha - \sin \alpha}$$

The coefficients C and K can now, with the help of the tests, be determined for different degrees of erosion, Figs. 2 and 3.

The tests showed that the degree of erosion increases slowly with rising stream forces. The tests have also shown that the stone bed does not remain stable when subjected to long-term attacks when the degree of erosion is as high as 20 to 30 per cent. A degree of erosion equal to 1 per cent, for example, cannot be discerned in a study of the bed, which may tolerate even greater velocities before the critical degree of erosion of 15 to 20 per cent has been attained. The depth of water equivalent to a degree of erosion of 1 per cent may thus be increased by ca. 25 per cent without jeopardizing the stability of the bed of stones. The equivalent increase in water discharge and mean velocity amount to ca. 40 per cent and 15 per cent respectively.

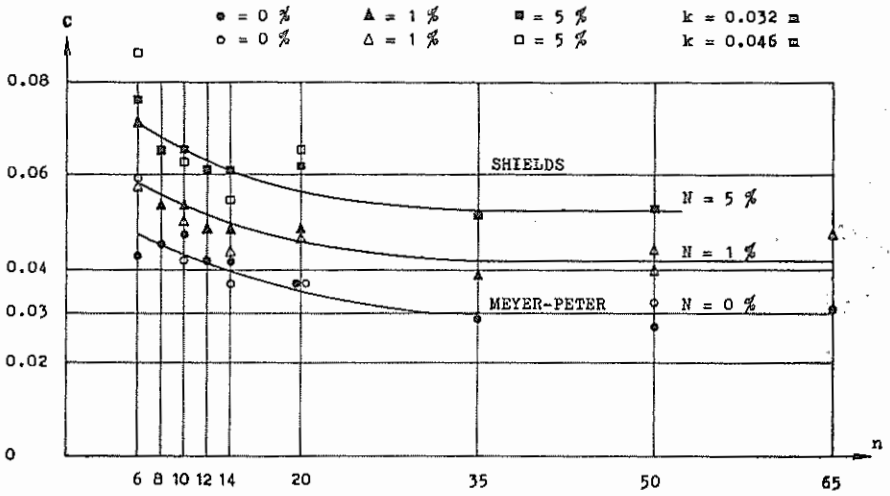


Fig. 2. Coefficient C as a function of degree of erosion N and inclination $1:n$ of bottom slope

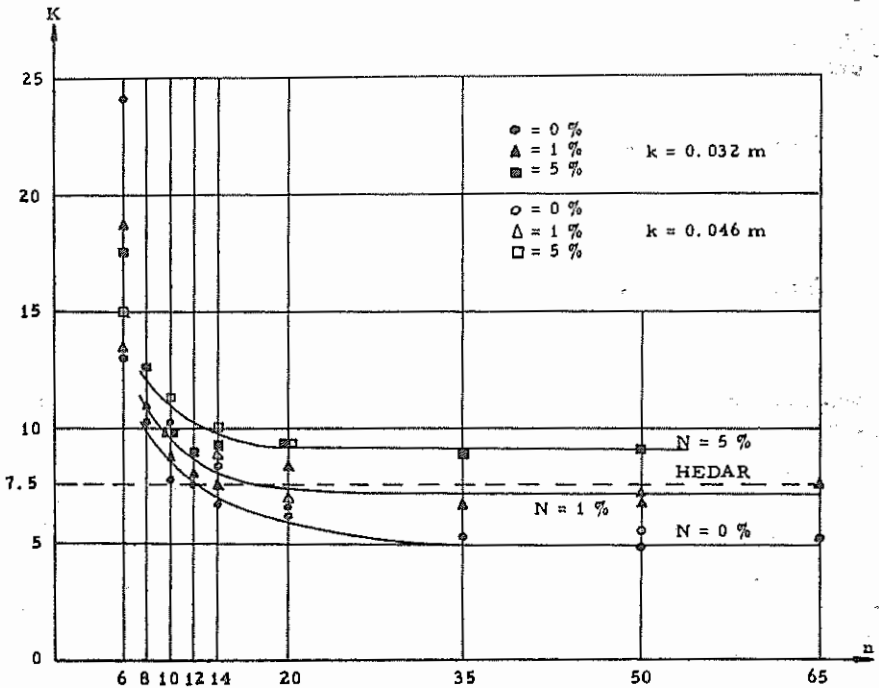


Fig. 3. Coefficient K as a function of degree of erosion N and inclination $1:n$ of bottom slope

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SOME LABORATORY EXPERIMENTS ON THE DISPERSION AND EROSION OF CLAY MATERIALS

by

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ABSTRACT

A laboratory study has been made of the influence of dispersing agents on the erosion and sedimentation of clays. Water with dispersing ability has been found to have a great eroding effect on clay, while water with a coagulating effect on colloidal systems has a small effect. The influence of some natural waters on specimens of clay has also been studied.

INTRODUCTION

The question of natural erosion by water is of great interest in Sweden, in soil mechanics especially, for the case when the parts of the soil removed have played an important role for the stability of riverbanks.

Some laboratory experiments have been performed at the Swedish Geotechnical Institute on the type of erosion in which the clay particles may be released from the soil by the influence of dispersing agents in the water and then transported as wash-load. The studies are thus mainly confined to the dispersion phenomena in the clay boundary, as well as to the influence of the degree of dispersion on the transport capacity of the water.

A SURVEY OF THE LITERATURE AND GENERAL CONSIDERATIONS

The chemical processes involved in the erosion of clay riverbanks are intimately connected with similar problems in agriculture, for example, and are studied in chemical soil science.

Middleton, Slater and Byers (1934) and Lutz (1935), in their studies of the erodibility of soils, found dispersion to be of influence. Lutz points out several chemical factors influencing the erosion of clay by rain water. In his opinion, the resistance to erosion of a certain clay is due to the non-hydrated condition and the high degree of flocculation of the colloidal fraction. The electrokinetic potential seems less important.

Peele (1937) found that calcium carbonate increased and organic matter decreased the susceptibility of a soil to erosion. Brown (1937) has published a

method for reducing the erosion by adding organic matter to the soil to increase the formation of aggregates. It should be noted that the organic matter here in question is not to be mistaken for the humic substances discussed in the present paper.

It may be mentioned in this connection that Davies (1937) has worked out a method for determining, by chemical flocculation, the amount of eroded material.

It is also expressed that natural humates form protective colloids on clay particles and can transfer them into colloid solution, whereupon the sol is transported with the water in the ground (cf. Aaltonen, 1923). According to this view, the soil may lose its content of colloidal material, which can be later precipitated, including the humus, when suitable conditions arise.

An example of natural dispersion is said to occur in the case of Nile mud (Holdridge, 1953), the suspended clay of which is prevented from precipitation by organic matter until the high concentration of sea-salt causes sedimentation at the delta.

The problem of the sedimentation of clay particles in various waters is treated by several authors; see, for example, Jessberger, 1961.

River erosion in Sweden has been studied mainly from a mechanical point of view. The relation between the velocity of water and the grain size of the eroded material has been studied by Hjulström (1935) and Sundborg (1956). Arnborg (1958) has discussed some mechanical influences on erosion of clay.

River water is usually polluted with a variety of materials, which may influence erosion. Söderblom (1960) found that clay specimens treated with humus could be strongly dispersed within a narrow pH-range. In the tests made, this process led to the formation of highly sensitive clays.

Thus disaggregation is to be expected in clay riverbeds, especially if the water contains dispersing agents, and the clay particles can be easily transported as wash-load. In preliminary studies of some water-courses, attention has been paid to such polluting materials in the water. In most cases the water transports humus, which may disperse the clay and form sols, but in some cases the water is too acid.

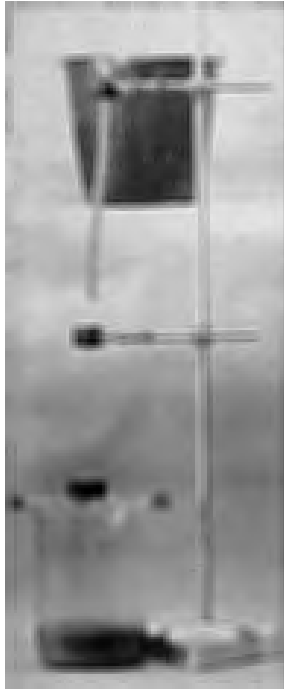
In the following will be reported some experiments demonstrating the disaggregation of clay by water and the ability of water to transport particles.

PRELIMINARY EXPERIMENTS ON THE INFLUENCE OF DROPPING WATER ON CLAY SPECIMENS

In order to simulate the natural combination of chemical and mechanical effects qualitatively in the laboratory, clay specimens were exposed to dropping water. The apparatus used is shown in Fig. 1. In the tests, water flows from a vessel to a spout where it drops on the specimen. The polluted water with its erosion products is collected in a vessel below the specimen.

In the test series, waters of known composition and natural waters from various sites in the neighbourhood of Stockholm were used in order to check

(a)



(b)



FIG. 1. a. Apparatus for erosion studies. b. Details of the drop test arrangement.

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FIG. 2. Test specimens treated with (from left to right): humic water + 0.5 per cent NaOH; humic water; humic water + 0.5 per cent HCl.

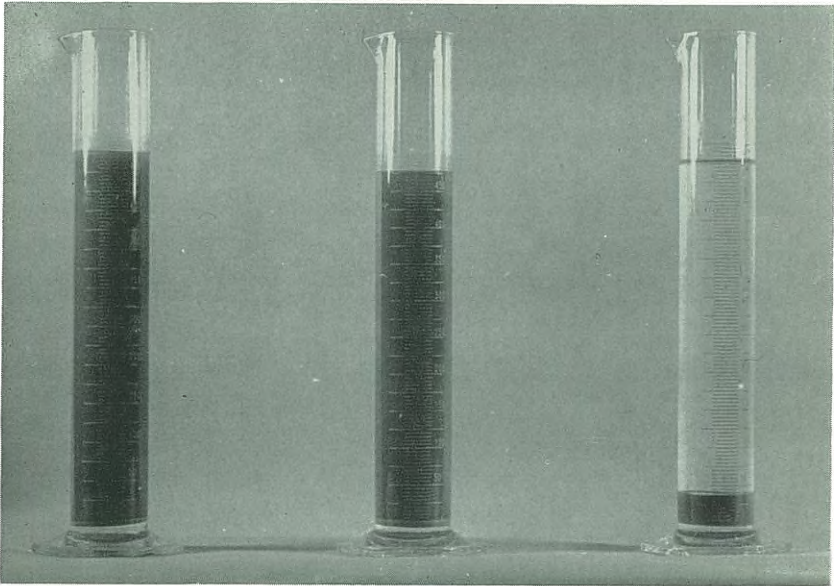


FIG. 3. Sedimentation test (from left to right): distilled water + 1 per cent $\text{Na}_4\text{P}_2\text{O}_7$; distilled water; distilled water + 1 per cent HCl.

the relative eroding efficiencies. In each series three identical specimens were exposed to the action of the various waters.

In these preliminary studies clay samples from the store of the consulting department of the Institute were utilized; in future tests the samples will be chosen to fulfil more specified requirements to correspond to the natural conditions.

The specimens chosen were glacial clays with low content of organic matter depending on the fact that the organic material may change the erosion effect. Further, such clay types were selected which showed distinct dispersion, respectively coagulation, when treated with the actual waters. Earlier affected clays, for instance quick clays, were not used in the tests. In the experiments with natural waters, clays with pH-values greater than 7 were used to avoid too acid conditions for the dispersing reaction. The natural waters are sometimes rather acid but their buffer capacities are generally low, so that the pH-value of the system should depend mainly upon the pH-value of the clay.

The time of exposure to the drop tests was 24 hr in all cases. The height from which the water dropped was about 10 cm in test series A, and about 20 cm in series B and C.

In the first series of experiments, A, the action of three chemically treated distilled waters, with extraordinary dispersing and coagulating effects, was studied. The liquid used in Test A1 was a solution of 1 per cent sodium pyrophosphate, in Test A2 distilled water, and in Test A3 1 per cent hydrochloric acid.

The muddiness of water provided evidence that the pyrophosphate solution had the strongest disaggregating effect on the clay.

The test results are shown in Table 1, and the composition of the water used can be seen in Table 2. From Table 1 it is seen that the pyrophosphate solution causes an erosion of the clay which is roughly 17 times greater than that caused by distilled water.

In the second series of experiments, B, the action of natural water from Rosenkälla, about 40 km north-east of Stockholm, with a high content of humus was studied. This water has a rather strong dispersing effect within a certain pH-range (cf. Söderblom, 1960). In Test B1 the water was treated with 0.5 per cent sodium hydroxide, in Test B2 untreated, and in Test B3 treated with 0.5 per cent hydrochloric acid.

Figure 2 shows that the dispersing alkaline solution was strongly erosive. The untreated water also caused some erosion. The test results are shown in Table 1.

In the third series of experiments, C, the actions of natural waters from C1 Rosenkälla, C2 brook at Svärta, about 10 km north-east of Nyköping, and C3 Tuna stream, about 20 km west of Nyköping, were tested. The test results are shown in Table 1. Some erosion appears in Test C1.

These experiments illustrate the eroding effect of various waters. In the tests the concentration of the chemicals, especially that of hydrochloric acid, is considerably higher than that of acids in nature. This also explains the disaggregation caused by this substance.

TABLE 1.—

Sample	Soil	Test No.	Properties before drop test					Water + additive
			H ₃ ^a	H ₁ ^a	H ₃ /H ₁ ^b	w ^c	w _P ^d	
Clay A	Glacial clay	A1	253	22.1	11.4	—	—	Distilled + 1% Na ₄ P ₂ O ₇
Clay A	Glacial clay	A2	253	22.1	11.4	—	—	Distilled
Clay A	Glacial clay	A3	253	22.1	11.4	—	—	Distilled + 1% HCl
K 8175 No. 2540	Glacial clay	B1	55.8	4.1	13.6	54	48	Rosenkälla + 0.5% NaOH
K 8175 No. 2540	Glacial clay	B2	55.8	4.1	13.6	54	48	Rosenkälla
K 8175 No. 2540	Glacial clay	B3	55.8	4.1	13.6	54	48	Rosenkälla + 0.5% HCl
K 8175 No. 3762	Glacial clay with sandlayers	C1	57.1	3.7	15.5	41	37	Rosenkälla
K 8175 No. 3762	Glacial clay with sandlayers	C2	57.1	3.7	15.5	41	37	Brook at Svärta
K 8175 No. 3762	Glacial clay with sandlayers	C3	57.1	3.7	15.5	41	37	Tuna stream

^a The H₁-value is a relative strength value determined by fall-cone test on remoulded clay. The H₃-value refers to the strength of the undisturbed clay (cf. Karlsson, 1961).

LABORATORY EXPERIMENTS ON SEDIMENTATION IN VARIOUS WATERS

In order to study the ability of various waters to keep particles in suspension, laboratory investigations were performed on the sedimentation of clay particles.

Clay of the same type as was used in the above drop tests was dispersed in

DROP TESTS

Observations on surface of specimen	Observations on water	Eroded material, gr/litre	Properties after drop test				
			H ₃ ^a	H ₁ ^a	H ₃ /H ₁ ^b	w ^c	w _F ^d
Strongly affected. Some pieces detached	Very muddy. Clay pieces and silt on bottom	5.6	178	0.34	523	—	—
Somewhat affected	Muddy	0.33	172	12.8	13.4	—	—
Almost unaffected	No change	1.1	140	15.4	9.1	—	—
Strongly affected. Cavities. Prevented fr. collapse	Very muddy	4.2	27.1	0.33	82.1	50	29
Somewhat affected	Muddy	2.1	51.1	6.0	7.4	54	51
Somewhat affected	Not muddy. Some precipit. on bottom	1.5	90.6	8.25	11.0	50	49
Somewhat affected	Somewhat muddy	0.07	—	—	—	—	—
Not affected	No change	Undeterminable	—	—	—	—	—
Not affected	No change	Undeterminable	—	—	—	—	—

^b H₃/H₁, sensitivity according to fall-cone test.

^c w, water content.

^d w_F, fineness number (near to the liquid limit, cf. Karlsson).

the various waters by means of a mixer to a suspension and was then poured into graduated glasses. The rate and type of sedimentation was observed.

The arrangement is shown in Fig. 3. The picture, illustrating the parallel test to series A above, was taken after the waters in the cylinders had been standing 24 hr under sedimentation. In the case of sodium pyrophosphate, most of the clay particles were still floating. In the case of hydrochloric acid all particles had sedimented.

TABLE 2.—WATERS USED

Water ^a	Chemical additive	Colour and properties	Site conditions	pH-value	Sedimentation test. Ability to carry particles
Filtered	1% Na ₂ P ₂ O ₇	—	—	9.2	Good Silt sedimentates
Filtered	None	—	—	5.2	Fairly good
Filtered	1% HCl	—	—	< 2	Poor Particles sedimentate
Unkälla (ic)	None	Dark brown	Peat moss in Uppland	5.3	Good Silt sedimentates
Unkälla (ic)	0.5% NaOH	Dark brown. Strong dispersing effect	Peat moss in Uppland	11.8	Good Silt sedimentates
Unkälla (ic)	0.5% HCl	Dark brown. Coagulating effect	Peat moss in Uppland	< 2	Poor Particles sedimentate
Water at Kåreå (ic)	None	Yellowish brown. Some suspended material	Brook with visible erosion. Near Nyköping	7.3	Good Silt sedimentates
Water from Månåsa (ic)	None	Light brown. Slight amount of suspended material	Small stream. Near Nyköping	6.2	Good Silt sedimentates

^avalues of natural waters vary with climatic conditions and temperature.

The test results are given qualitatively in Table 1. It will be observed that in Test B3 the humic substances obviously settled together with the clay particles, as indicated by the change in colour.

In this connection a series of preliminary experiments, which are also of importance for quick clay formation, have been performed. Glacial-clay material was suspended in humus water from Rosenkälla. The suspension was poured into a solution of sodium chloride, and the coagulated system of humus and clay was allowed to settle. The "cake" obtained was carefully handled during the treatment. It was consolidated in a filter press and afterwards leached with weakly alkaline water, until the filtrate was coloured brown by humus. The treated cake had a quick consistency.

DISCUSSION AND CONCLUSIONS

The drop experiments described above have shown that the coarsibility of a certain clay to a given mechanical influence is greatest in the case of high content of a dispersing agent in the water. The liability of a clay to become dispersed depends on its type, content of humus gels, salinity, etc. In the presence of water, the clay will be disaggregated to an extent which is also dependent on the properties of the water, i.e. its content of dispersing agents.

For quantitative studies, the drop test method is too rough. Especially for the long-term influence in nature, other methods and times of testing must be used. Of the natural waters utilized the Rosenkälla water was the only one which during the very short test had a considerable influence on one of the various clays. Moreover, the water from the brook at Svärta was enriched with silicates.

It may be mentioned in this connection that these processes are similar to those present in the formation of quick clays. In the rather short-term drop tests, A1 and B1, with waters of strong dispersing effect, the clay samples, of fairly normal sensitivity, were transformed into quick clays.

The sedimentation experiments have shown that ability to keep colloidal clay particles in suspension is greatest in the case of a dispersing water. In the case of a typical coagulating water with, for instance, 1 per cent hydrochloric acid, the clay suspension will rapidly break and sediment.

The tests showed that the three natural waters were able to carry clay particles. It should be mentioned, however, that the pH-value of the rather concentrated suspension is obviously affected by the clay. This means that the dispersing or coagulating effect observed in the laboratory may be different in natural conditions.

The natural wash-load may be dispersed by means of humic substances. When a polluted water meets sea-water, the wash-load will coagulate and settle.

The sediments may later be exposed to new conditions. If the salt is leached out for some reason or other, as was the case in the "cake" experiment mentioned above, the humus may act as a dispersing agent, and a

humus-dispersed quick clay will be formed. Reactions of this kind must be taken into consideration in the discussion of the formation of quick clays by salt leaching.

The experiments performed have given additional evidence on the disaggregation phenomena in clays at the boundary surface to water, which may probably be applied to natural conditions. Further investigations will therefore be performed, both in the laboratory and in the field.

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