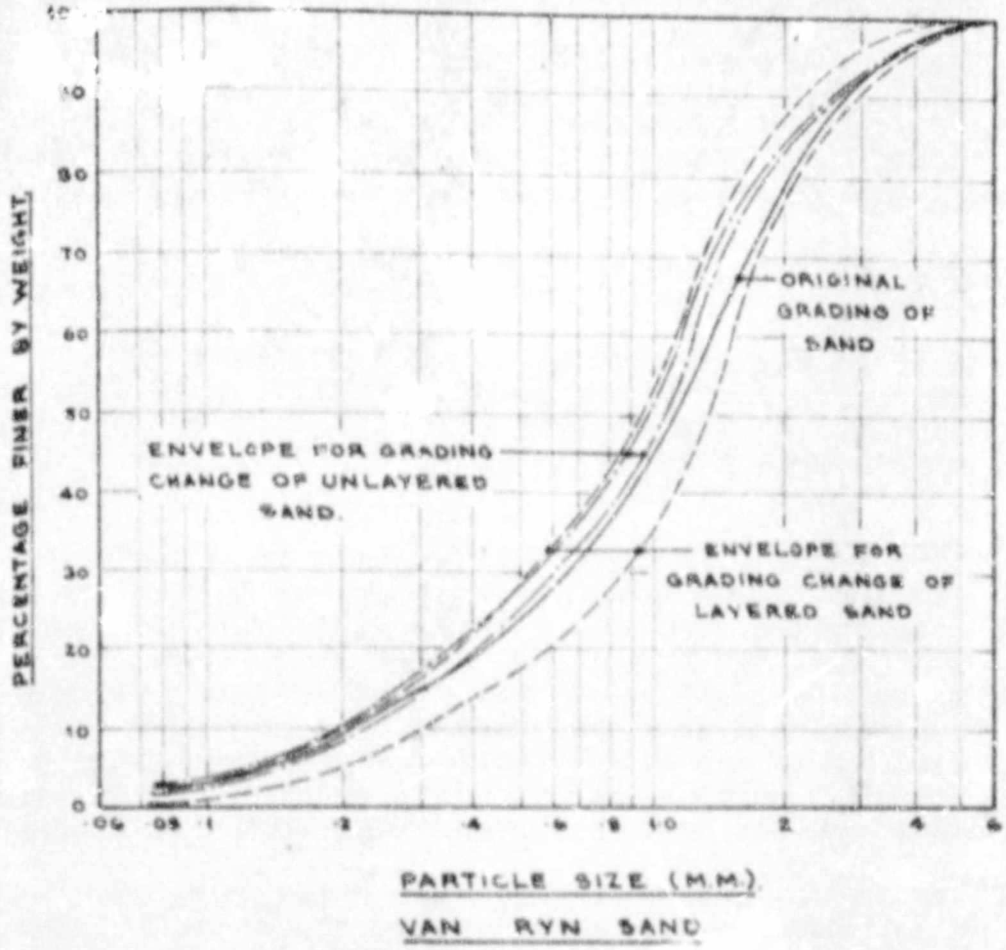
See Page 42



FINE	MEDIUM	COARSE	FINE
SAND			GRAVEL

THE EFFECT OF INTERNAL LAYERING ON CHANGES OF GRADING.

THESE GRADING CURVES SHOW HOW CHANGES OF GRADING ARE INCREASED BY THE PRESENCE OF INTERNAL LAYERING IN A SAND. THE PHOTOGRAPH GIVES THE APPEARANCE OF A HOMOGENEOUS SAMPLE OF VAN RYN SAND AFTER TESTING.

within the sand layer. This filter structure is envisaged as a series of almost microscopic "voissoir arches" bridging the voids in the soil, the relation between the particle sizes of succeeding layers in each small voissoir arch being such that no soil particles can pass through into the void beyond.

This almost microscopic arching action within a sand could actually be seen in some of the test cylinders.

The rapidity with which this structure is established in a soil layer will depend on conditions at the boundary of that layer of soil. If the soil itself is layered internally in the manner described, the production of a stable structure will be slower.

When flow starts, for example, a layer of fine material near the bottom of the test cylinder would possibly be washed through its supporting layer of coarser particles. The layer of fines immediately above this would now tend to be washed through two coarse layers and so on right up the height of the sample. The nett result would be that the bottom of the sample would grow progressively finer while the upper half grew progressively coarser. This process would continue until a balance was struck and a stable filter structure formed.

To investigate the practical importance of this internal layering, a special test was carried out on a sample of van Ryn Sand. In this test the sample was thoroughly mixed in the test cylinder during and after filling. The resultant sample was, as far as could be seen, completely homogeneous and devoid of any layering. The sample was tested in the normal manner.

The initial void ratio of the sample was 0.685 as compared with the sample tested standard procedure which had an initial void ratio of 0.764. As the initial void ratio does notinfluence the changes of grading very much the two samples were comparable.

The superimposed grading curves show a great reduction in the change of grading for the homogeneous sample of sand. The difference between the gradings of the upper and lower halves of the sample is not significant.

On the basis of this test, it appears that the layering and formation of 'filter skins' by segregation of fines has a great influence on whether a sand will behave as a filter within itself or not. The more homogeneously blended the sand, the sooner will a stable filter structure form within it and the less will be the corresponding change in grading.

(iv) <u>The Direction of Flow Relative to Gravity</u>

Gravity could be expected to aid internal changes of grading if the flow were in a vertically downward direction:

(i) by its downward force on the moving particles;
(ii) because, if for some reason the flow were intermittent gravity would hold particles which had moved in the furthest position along their path - there would be no tendency to 'drop back'. The effect would naturally be of greater significance in cases where the hydraulic gradient is near to its critical value of $G-1/1+e$ beyond which the flow forces are capable of bodily transporting the sand particles.

No test was made using vertically upward flow as it was found that the uplift which occurred led to turbulence and 'boiling' in the sample. This was unsatisfactory because the conditions within the test cylinder were so variable and because the 'boiling' prevented the formation of a stable filter grain structure.

A test was carried out using flow in a horizontal direction. In this case the sample cylinder (of van Ryn sand) was laid on its side. Otherwise the testing procedure was unchanged. The hydraulic gradient was high (14.3). This was perhaps too high to show up the effects of gravity, but will serve to show up the effects of horizontal flow.

It was found that there was practically no difference in the grading changes which took place in this type of sand due either to horizontal or vertically downward flow.

Thus provided the hydraulic gradient in action is well in excess of the critical gradient for the sand any grading changes which take place are independent of whether flow is downward or horizontal and hence presumably in any inclined direction between these two limits.

All this series of tests was performed with flow normal to the layering produced while filling the test cylinders. It is impossible to say, without further testing, what effects the direction of flow relative to the direction of the layering would have on the internal stability of a sand.

(v) The Effect of the Magnitude of the Hydraulic Gradient

It is reasonable to expect that the greater the hydraulic gradient and hence the greater the internal flow forces, the greater will be the tendency for migration of the particles to take place within a sand. This must be balanced against the expectation that greater internal flow forces will lead to increased intergranular pressures which in turn will increase the frictional resistance to particle movement.

In this series of tests, the highest hydraulic gradients were used that could be attained without over-elaborate apparatus. The purpose of this was an attempt to force the grading changes to be as large as possible.

Only one rather unsatisfactory test was carried out in this connection using a low head. The sand used was Artificial Sand No. 1 which in the standard filter test showed no significant changes of grading. The hydraulic gradient for the standard test was 14.2 while that for the low head test was 2.77.

The initial void ratios for the samples were 0.479 and 0.856 respectively, while the final values were 0.476 and 0.457. Hence there was considerable consolidation in the sample tested under low gradient.

There was no significant change in grading of the sand used in this test.

In this case, although the test under low head was started with the sand in a very loose condition, the difference in hydraulic gradients had no visible effect.

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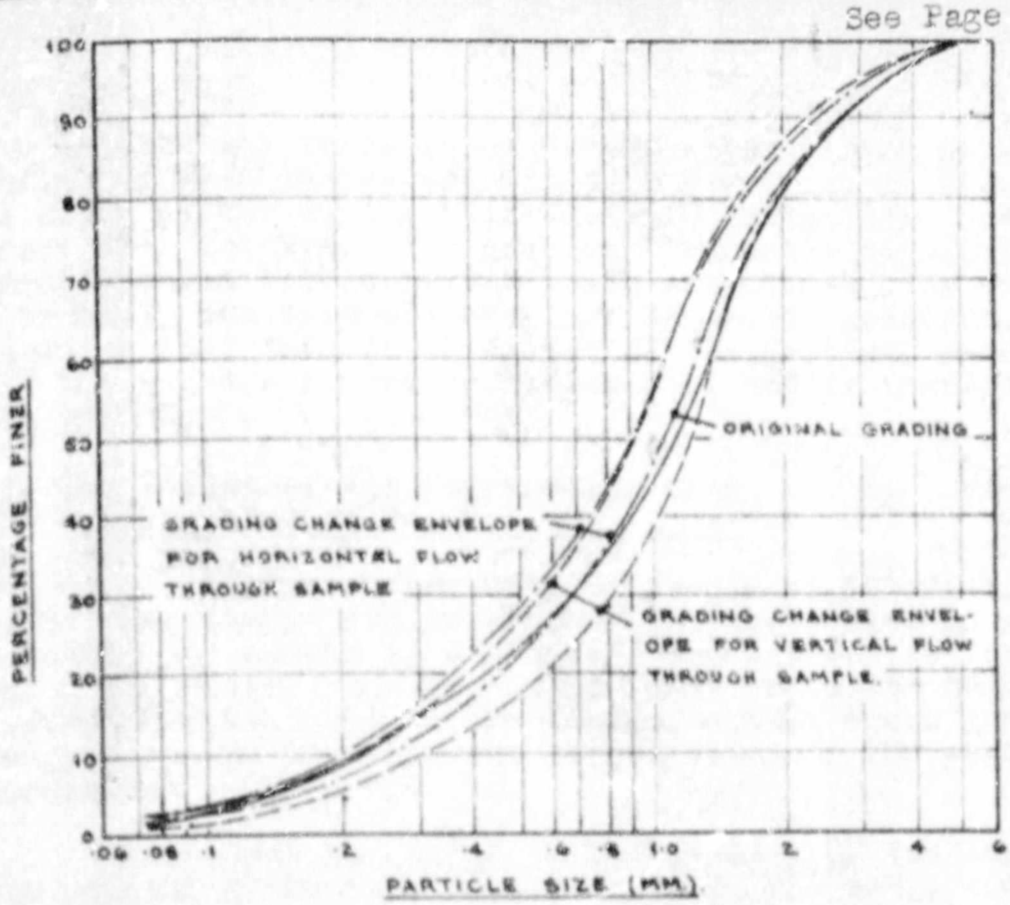
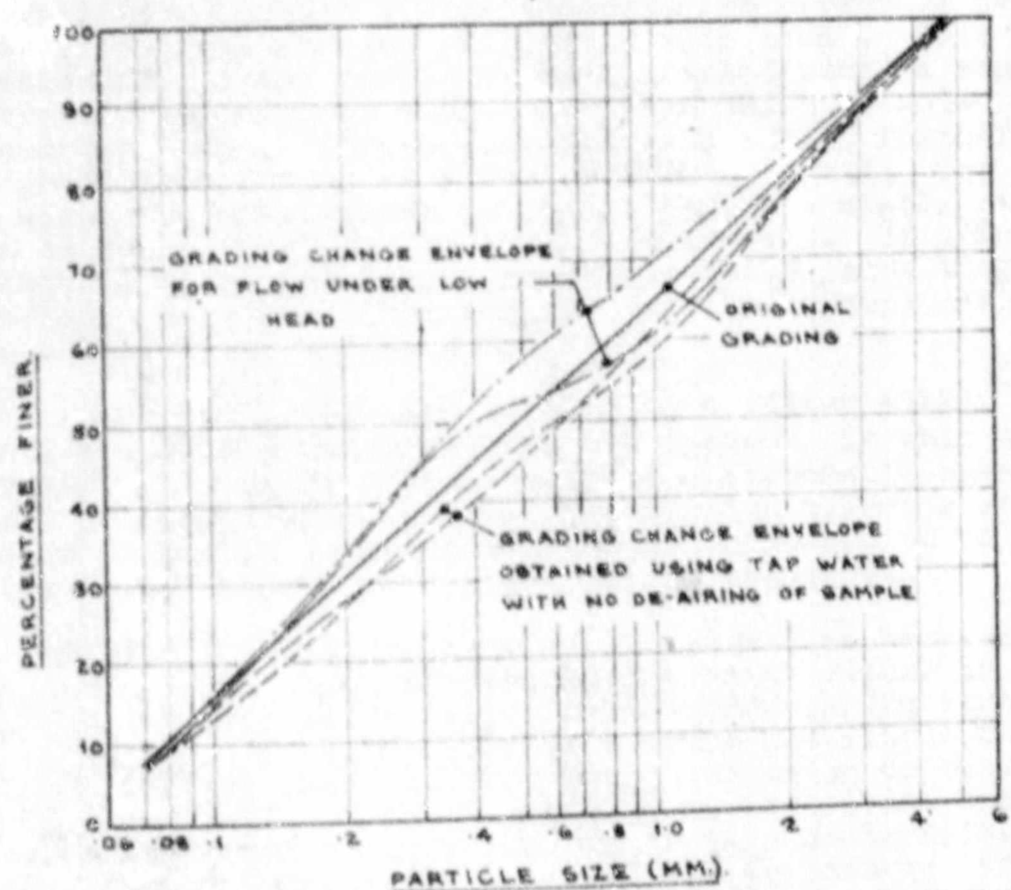


THE DIRECTION OF FLOW RELATIVE TO GRAVITY.

TESTS ON SAMPLES OF VAN RYN SAND SHOW THAT PROVIDED THE HYDRAULIC GRADIENT IS GREATER THAN CRITICAL THE DIRECTION OF FLOW RELATIVE TO GRAVITY HAS NO SIGNIFICANT EFFECT.



VARIATION OF HEAD AND DE-AIRING EFFECT.

TESTS ON ARTIFICIAL SAND No. 1 SHOWED NO REAL DIFFERENCE IN GRADING CHANGES BETWEEN TESTS RUN ON LOW AND HIGH HEADS AND BETWEEN SAMPLES WHICH HAD OR HAD NOT BEEN DE-AIRED.

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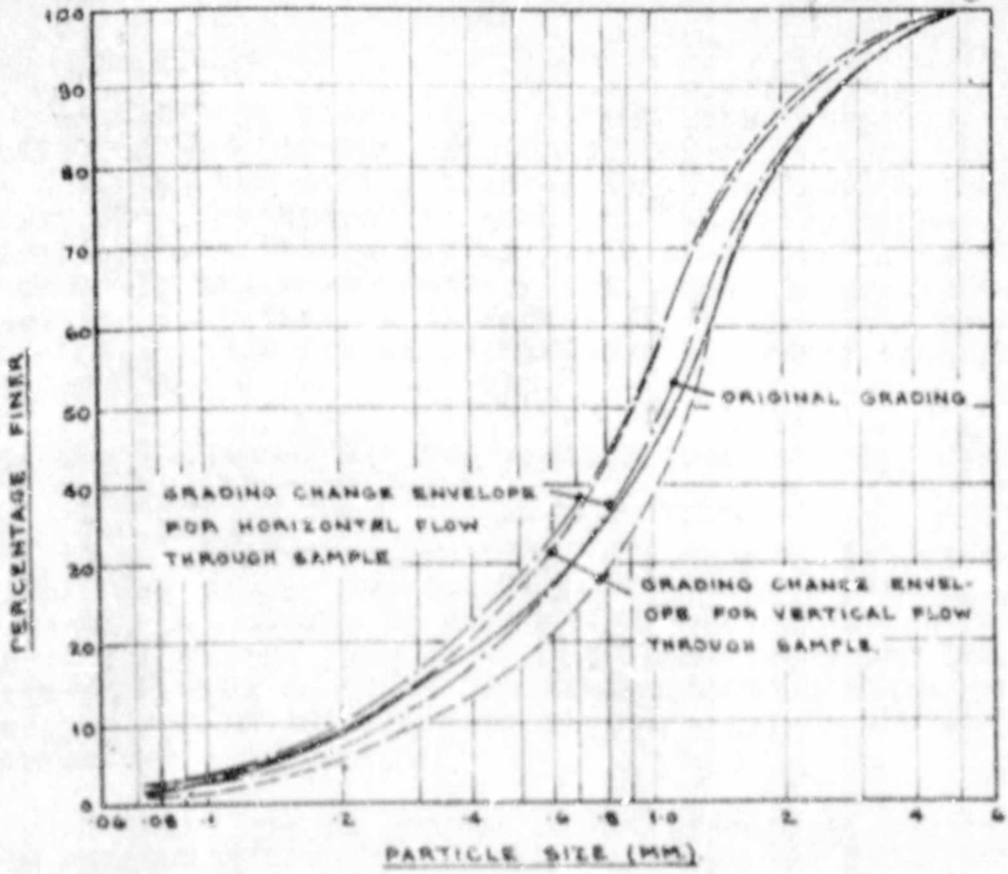
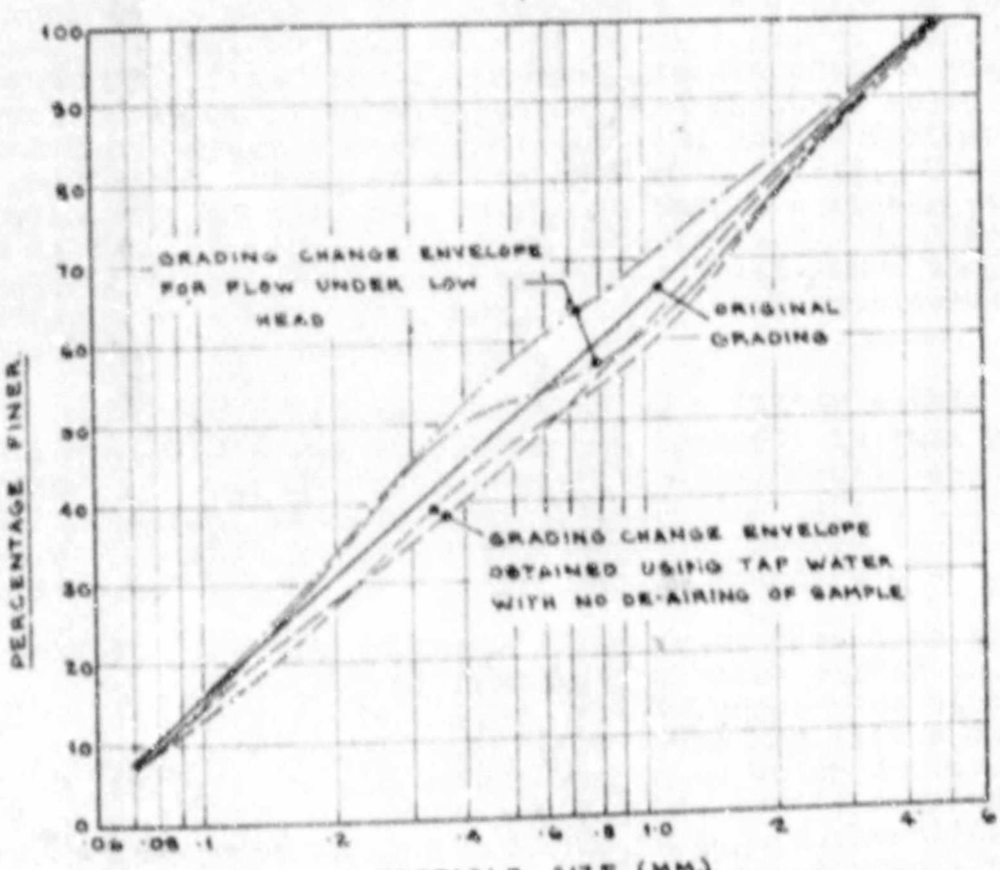


THE DIRECTION OF FLOW RELATIVE TO GRAVITY.

TESTS ON SAMPLES OF VAN RYN SAND SHOW THAT PROVIDED THE HYDRAULIC GRADIENT IS GREATER THAN CRITICAL THE DIRECTION OF FLOW RELATIVE TO GRAVITY HAS NO SIGNIFICANT EFFECT.



VARIATION OF HEAD AND DE-AIRING EFFECT.

TESTS ON ARTIFICIAL SAND 121 SHOWED NO REAL DIFFERENCE IN GRADING CHANGES BETWEEN TESTS RUN ON LOW AND HIGH HEADS AND BETWEEN SAMPLES WHICH HAD OR HAD NOT BEEN DE-AIRED.

Although there is no direct experimental evidence to confirm this, it is the opinion of the writer, as a result of his observations during this whole investigation that the effect of a low hydraulic gradient is merely to retard the formation of a stable filter grain structure. The final result is probably the same whatever the hydraulic gradient, always providing that this is in excess of the critical value, so that the seepage forces are capable of bodily transporting the soil grains.

(vi) The Effect of Air Segregation from the Percolating Water

One test was done using a sample of Artificial Sand No. 1. The sample was saturated from above with no attempt to de-air the sample by evacuation and the entire test was run on tap water. The sample at first contained numerous large air bubbles but as the test proceeded these gradually disappeared and the apparent permeability of the sand increased.

There was no change in the grading of the sand. Apart from retarding the rate of flow through th soil, the presence of air bubbles in the voids does not appear to have any effect on possible grading changes.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

When a layer of freshly placed sand of either natural or artificial origin is subjected to the action of percolating water, internal changes of grading will occur. This re-arrangement of the particles will proceed until a stable structure is built up within the sand which is able to withstand the seepage forces occurring and resist further change of grading by acting as a filter within itself. The extent to which the grading has to change before a stable structure can be established varies from sand to sand. In some sands the changes are inappreciable; for single sized sands they are non-existent, in others they are so large as to noticeably alter the character of the original sand.

Strictly, no sand behaves as a filter within itself until a stable grain structure has formed. In this thesis, however, only sands which require a considerable change in their original particle size distribution before a stable filter structure is established are considered to be "sands which do not behave as filters within themselves".

(i) Sands which in their recent past have been subjected to the action of percolating water either in nature as river sands, sands from water-bearing strata, etc., or artificially as filter media are little subject to grading changes and the changes which do occur are generally of small magnitude. Artificial and crushed sands and sands formed by in situ decomposition of other deposits are most likely to undergo large changes in grading before a stable filter structure can be established.

(ii) There is no particular type of grading curve which is clearly characteristic of sands which act as filters within themselves. It is the grain structure which has the controlling influence. Changes in grading which go to establish this structure are incidental.

Nevertheless, river, pit and crusher sands which do not behave as filters within themselves have been found, on the average, to have a greater percentage by weight of particles finer than the No. 200 Tyler sieve size (74 microns) than do sands which behave as filters within themselves. Also, sands which do not behave as filters within themselves generally have a greater scatter (as represented by the ratios D_{85}/D_{15} and D_{90}/D_{10}) than do sands which do behave as filters within themselves.

(iii) For sands of the same gradings and comparable void ratios, a sand consisting of angular fragments is more stable against changes of grading than is a sand consisting of rounded particles.

(iv) The density at which a sand is placed has little or no influence on the magnitude of the internal grading changes likely to take place in that sand when used as a filter layer. A low density may, however, lead to channelling and cause local changes in grading.

(v) A sand will be more stable against changes of grading and the internal filter grain structure will develop more rapidly if the soil is completely homogeneous throughout than if it is poorly mixed and contains randomly distributed coarser and finer zones.

(vi) Apart from 'boiling' and other internal instability caused by upward flow, any changes in particle size distribution will occur irrespective of the direction of flow relative to gravity.

(vii) Grading changes will take place provided the hydraulic gradient is large enough to bodily transport the soil particles. A stable structure will be formed more rapidly under a high hydraulic gradient than under a low one.

Recommendations for the Selection and Use of Sands Required to Behave as Filters within Themselves.

(i) River sands and sands from natural water-bearing strata are to be preferred to artificial and crusher sands and sands formed by in situ decomposition of geological deposits.

(ii) For normal river, pit and crusher sands the percentage of particles finer than 74 microns (No. 200 Tyler sieve) should be limited to 5% by weight. The sand should be as uniform as possible with the ratio D_{85}/D_{15} not exceeding 4 to 5 or alternatively the ratio D_{90}/D_{10} should be limited to between 6 and 7.

(iii) Sands for filter layers should be placed in as dense a condition as possible to prevent the initiation of internal grading changes by the formation of piping channels through the layer.

(iv) Filter layers should be made as homogeneous as possible with a minimum of layering due to segregation of fine material. This can be achieved either by mixing the sand after it has been placed or by thorough mixing in the dry before placing, followed by placing the sand in a damp condition.

CHAPTER V

TESTS ON MODEL FILTERS

INTRODUCTION.

Having investigated the effects of percolating water on the gradings of isolated layers of filter sands, the next step is to look into the behaviour of the same sands when used as a layer or zone of a filter bed.

These tests on model filters were carried out using a large diameter pressure filter tank. The object of the tests was to find whether the internal behaviour of a layer of sand with regard to the stability of its grain structure has any significant effect on the performance of the zoned filter of which the layer forms a part. This report will describe:

(i) the construction and operation of the filter tank;
(ii) the design of the experimental filters;
(iii) the behaviour of the filters during the test; and
(iv) the results of the flow measurements taken.

Finally, conclusions will be drawn as to whether the fact that a sand does not behave as a filter within itself has any deleterious effect on its operation as a component of a layered filter.

THE CONSTRUCTION AND OPERATION OF THE PRESSURE FILTER TANK

The general arrangement of the pressure filter tank and its associated hydraulic circuit is shown on the accompanying photograph.

The circuit can be adapted for flow in either an upward or a downward direction. For downward flow, the arrangement is as follows:

A small centrifugal pump driven by an electric motor forces the water in at the top of the filter tank, through the filter bed and out at the bottom of the filter tank. The suction side of the pump is supplied from the bottom of a small supply tank. The discharge from the bottom of the filter tank is re-fed into the top of the supply tank. A bourdon type pressure gauge tapped into the delivery line from the pump registers the pressure developed in order to force the water through the filter bed. For upward flow the arrangement is the same except that the delivery is through the bottom of the tank.

The filter tank consists of a three foot length of 15 inch diameter steel piping with the lower end closed by a steel plate welded to the pipe. A ½ inch plate glass observation window runs the full height of the tank enabling the action of the filter to be observed and photographed. The tank is closed by a ¾ inch thick circular steel plate grooved on its underside to receive the rim of the tank. The top plate is retained by 10 hinged wing-bolts and is sealed shut by a circle of heavy rubber tubing lining the groove.

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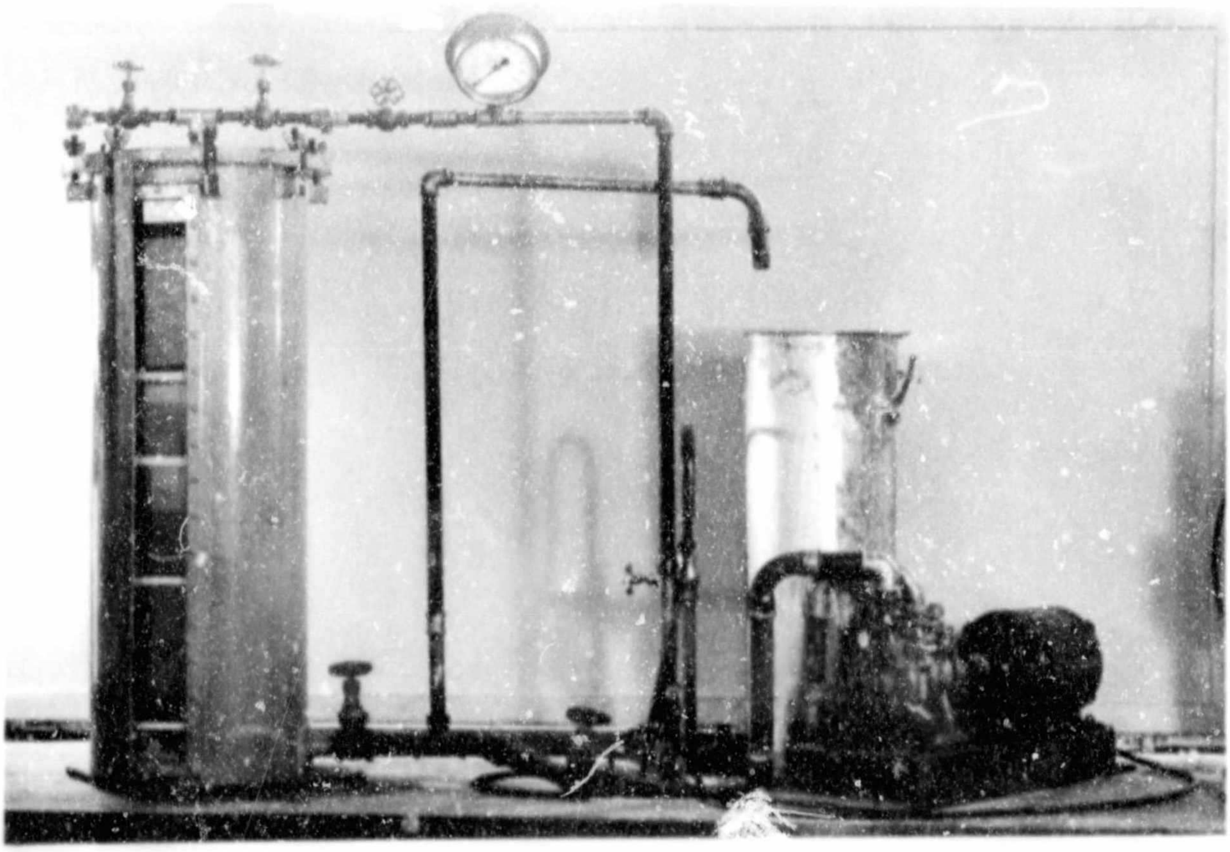
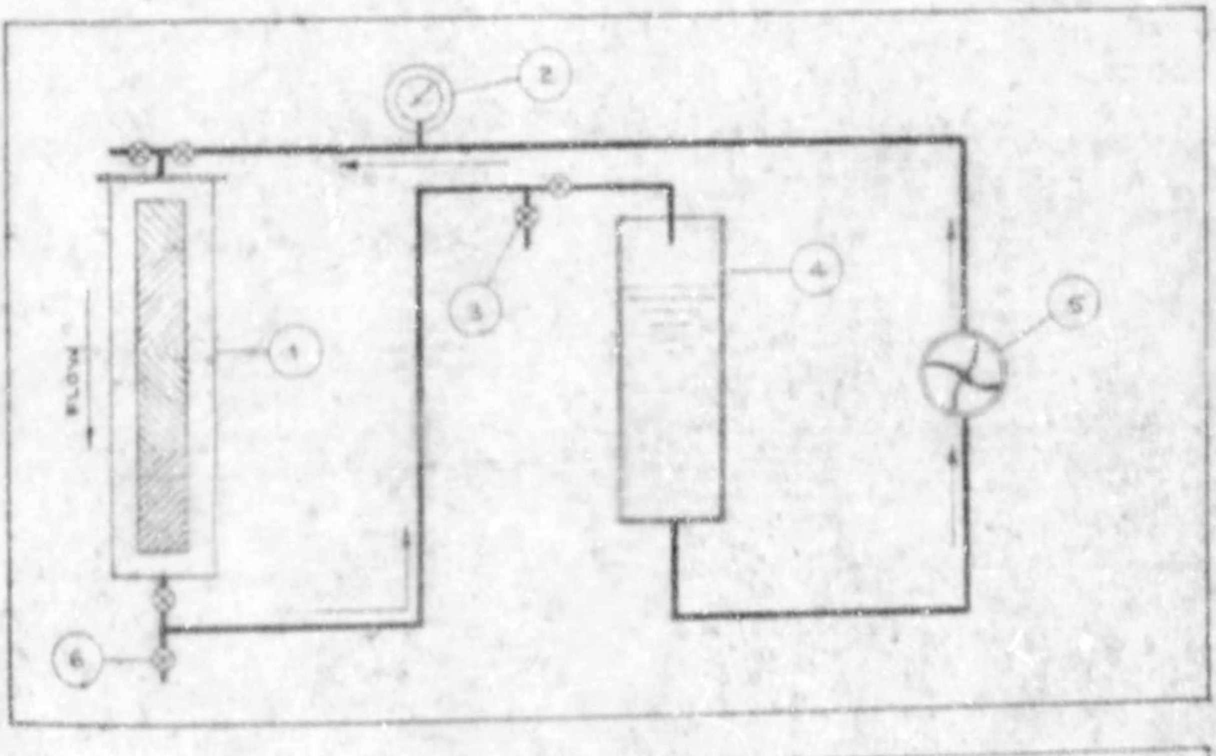


VIEW OF PRESSURE FILTER TANK WITH CIRCUIT DIAGRAM BELOW.



1. PRESSURE FILTER TANK.
2. GAUGE GIVING HEAD ON FILTER.
3. FLOW MEASUREMENT TAP.
4. WATER SUPPLY TANK.
5. CENTRIFUGAL PUMP.
6. TAP FOR EMPTYING TANK.

TESTS ON MODEL FILTERS APPARATUS.

The tank has an inlet through the centre of the top plate and an outlet and drainage valve at the bottom.

The pressure filter tank circuit has the great advantage of being entirely self-contained and can be left to run for days on end with the minimum of attention.

Water loss is very small and it was only found necessary to top up the supply tank once a day. This, and lubrication of the motor and pump was the only attention required.

The centrifugal pump supplied a constant inlet pressure with a very small discharge. The hydraulic gradient naturally adjusted itself to suit the resistance to flow offered by the filter bed.

Flow measurements were taken by simply diverting the discharge into a 2 litre measuring cylinder and measuring the rate of flow using a stop watch.

THE DESIGN OF THE EXPERIMENTAL FILTERS

The tests were carried out in two sections.

In the first section a number of zoned filters were designed using for foundation materials a selection of sands which had been used in the special filter tests. The sands used included examples of sands which underwent extensive grading changes and others in which the grading changes were of no significance. The protective filter layers for these foundation materials were made up of single sized sands thus confining any trouble due to grading changes to the foundation layers.

The object of these tests was to discover if sands which did not behave as filters within themselves obeyed the normal filter design criteria against clogging of the filter layers by leaching out of the fines in the foundation material.

All the filters were designed according to the Terzaghi-Bertram criteria.

The sands used and details of the filter design are as follows:

Sand	Behaviour in Filter Test	$\frac{D_{15}\text{ Filter}}{D_{85}\text{ Foundation}}$	$\frac{D_{15}\text{ Filter}}{D_{15}\text{ Foundation}}$
Crusher Sand 'A'	N.F.	3.5	28
Crusher Sand 'B'	F.	2.4	120
E.R.P.M. Dump Sand	N.F.	2.7	12
E.R.P.M. Ash	N.F.	1.4	334
Bartlett's Sand	N.F.	2.9	52
Artificial Sand No.1	F.	2.1	47

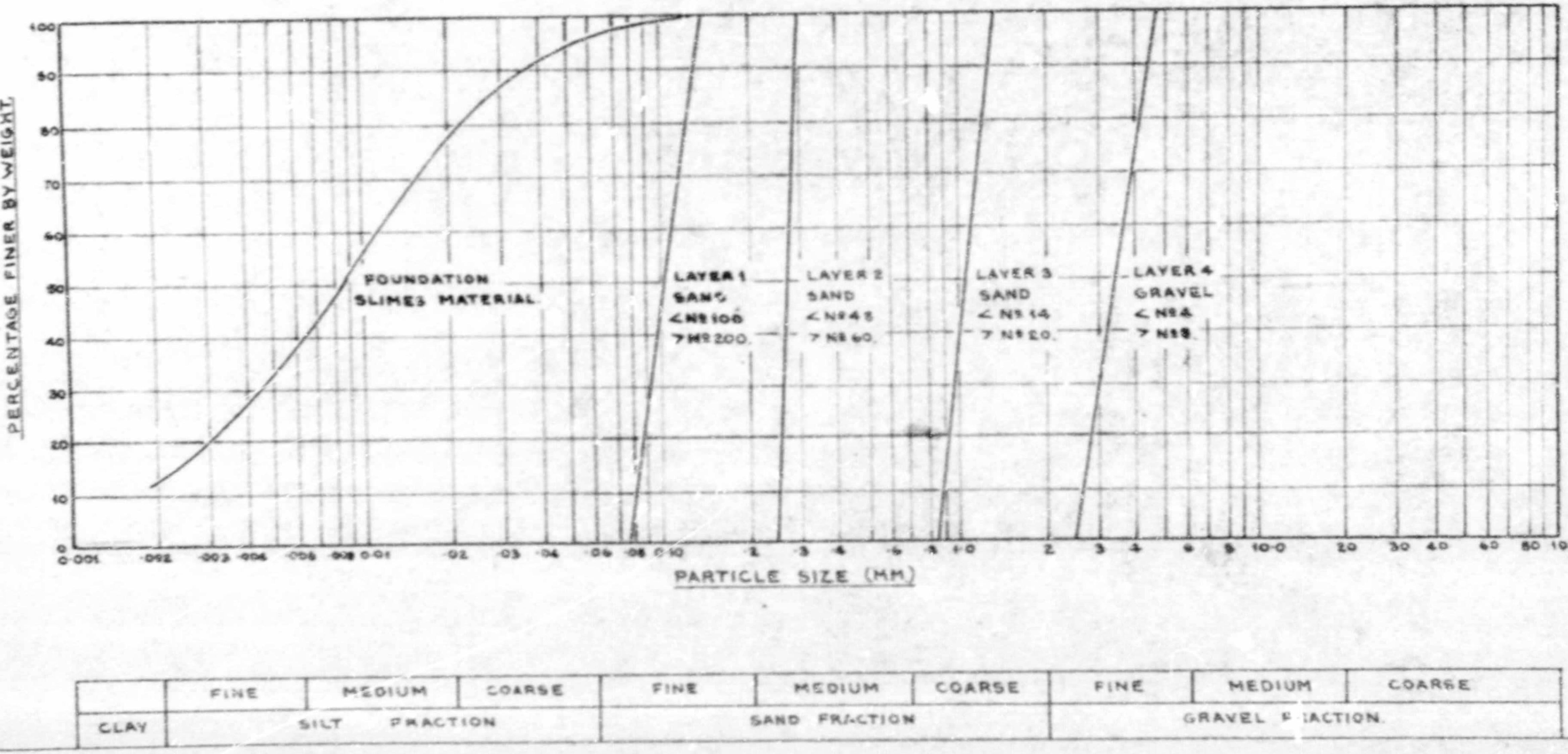
In this table:

"F." denotes "the sand is a filter within itself."
"N.F." denotes "the sand is not a filter within itself."

MODEL FILTER TESTS.

GRADINGS OF FILTER №1.

THE FILTER CONSISTED OF A SLIMES FOUNDATION RETAINED BY FOUR LAYERS OF SINGLE SIZED SAND OF INCREAS- COARSENESS. THE DESIGN SATISFIES THE TERZAGHI CRITERIA AND WAS SUCCESSFUL IN THE TEST.



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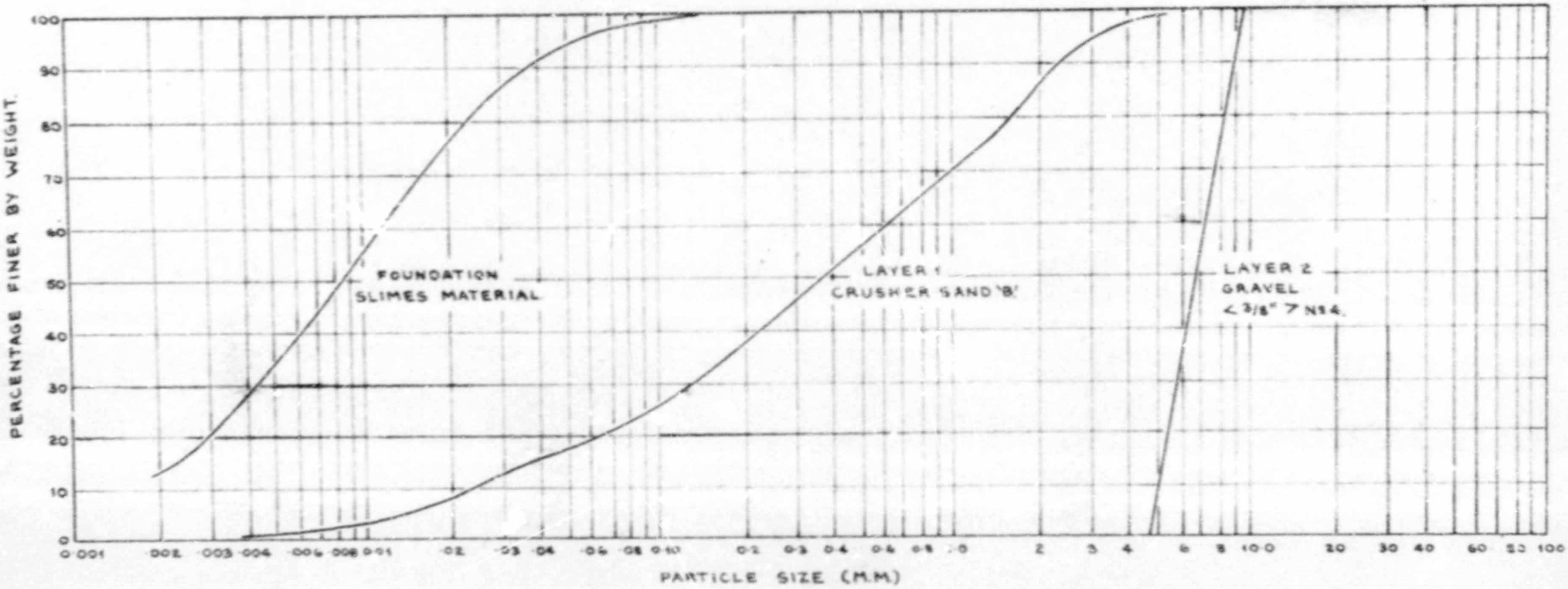
MODEL FILTER TESTS.

GRADINGS OF FILTER No 2.

THE FILTER CONSISTED OF A SLIMES FOUNDATION RETAINED BY A LAYER OF WELL GRADED CRUSHER SAND FOLLOWED BY A LAYER OF SINGLE SIZED GRAVEL. THE DESIGN SATISFIES THE TERZAGHI CRITERIA BUT FAILED BY PIPING IN THE TEST.



	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE
CLAY	SILT FRACTION			SAND FRACTION			GRAVEL FRACTION.		

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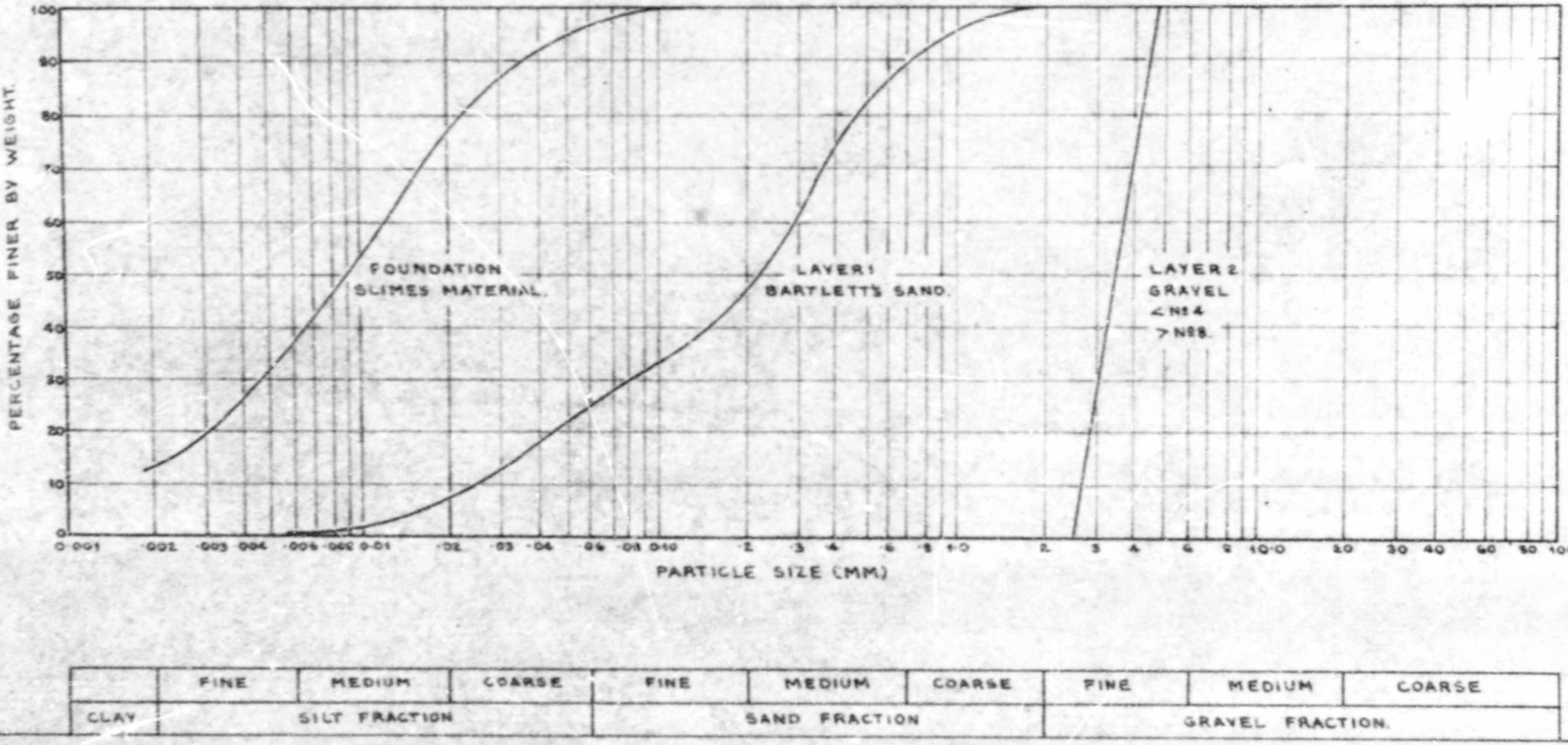
MODEL FILTER TESTS.

GRADINGS OF FILTER Nº 3.

THIS FILTER CONSISTED OF A FOUNDATION OF SLIMES RETAINED BY A LAYER OF WELL GRADED NATURAL SAND AND FOLLOWED BY A LAYER OF SINGLE SIZED GRAVEL. THE FILTER FAILED BY PIPING IN THE TEST ALTHOUGH THE DESIGN SATISFIED THE TERZAGHI CRITERIA.



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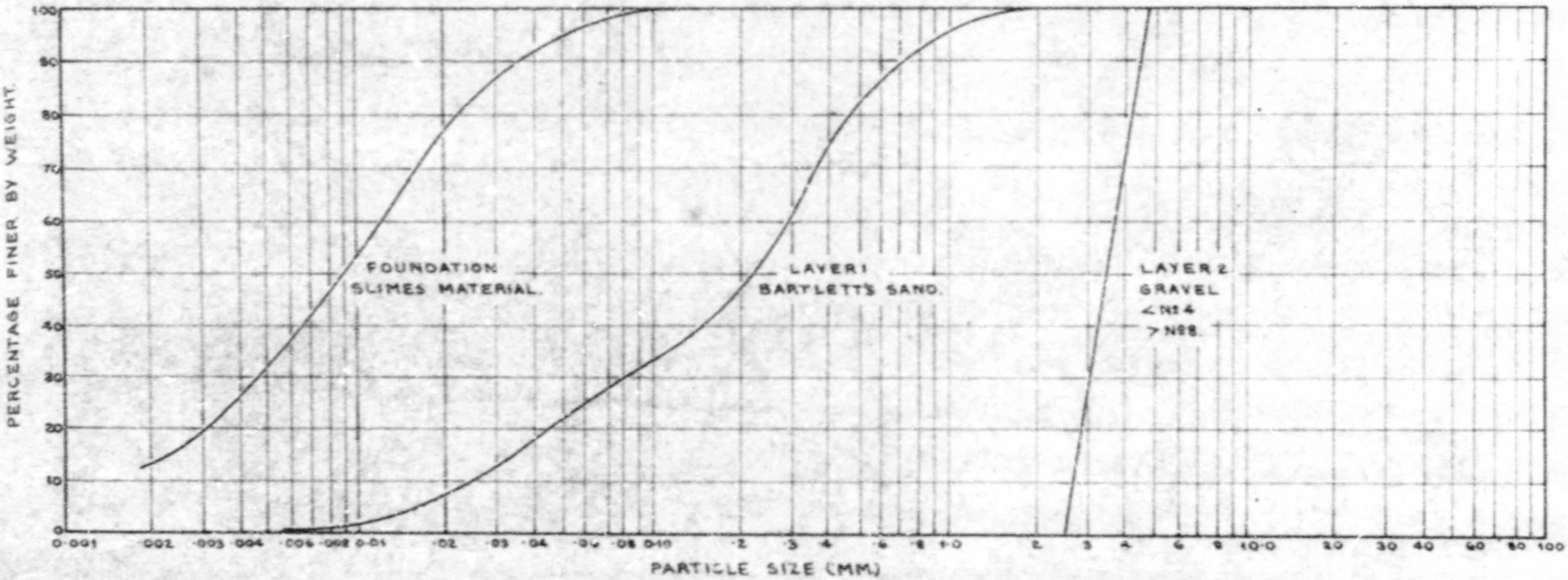
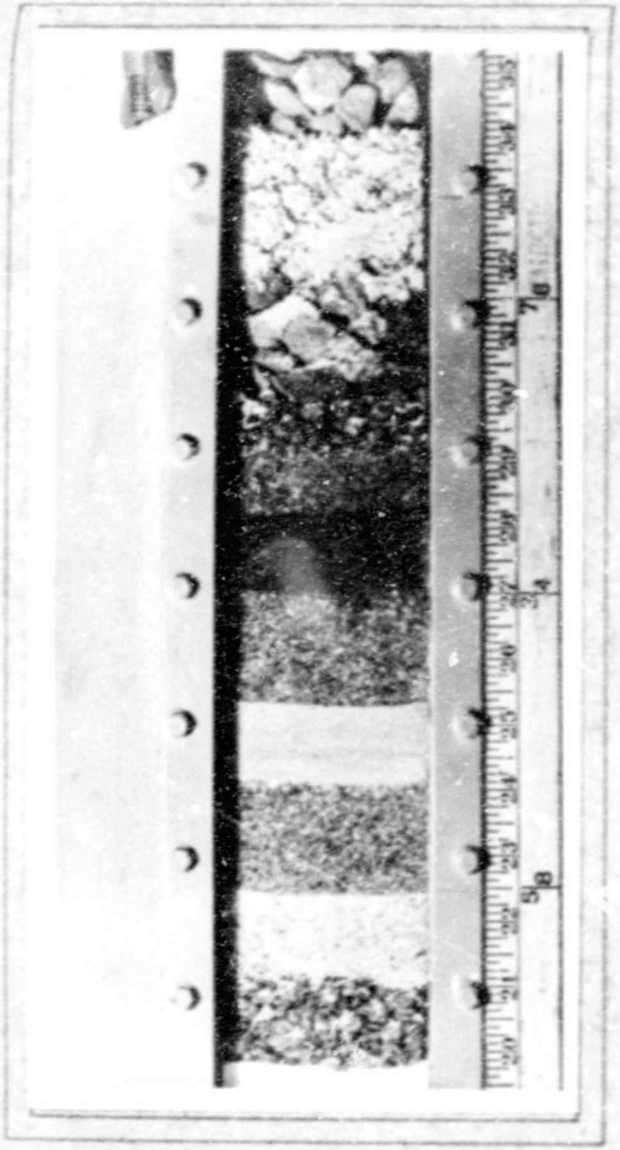
MODEL FILTER TESTS.
GRADINGS OF FILTER Nº 3.

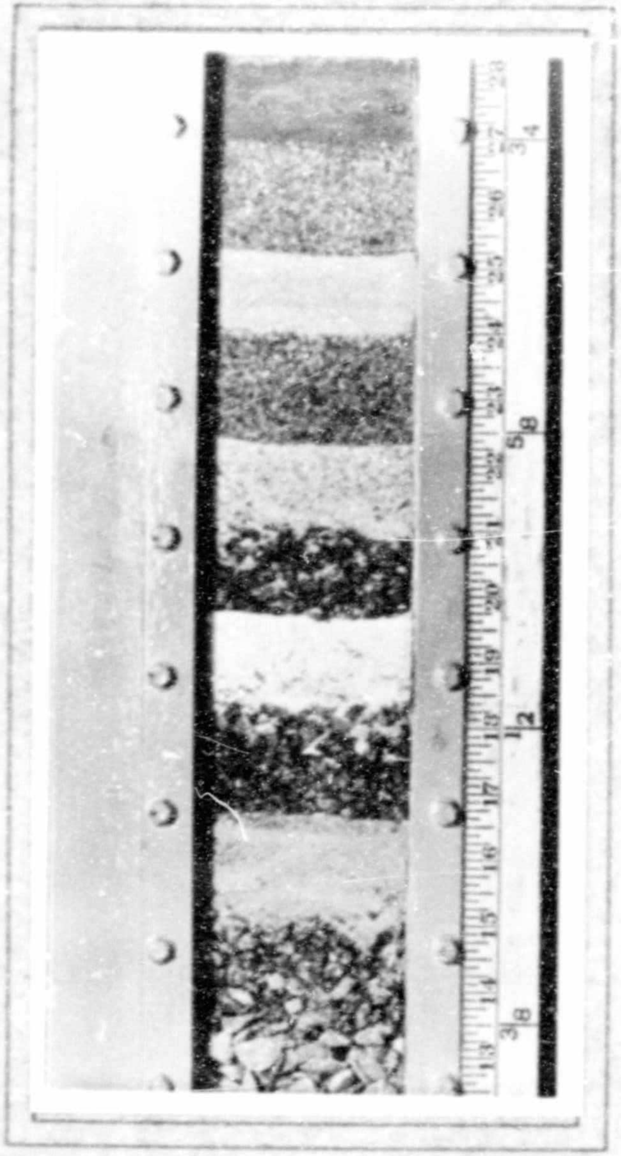
THIS FILTER CONSISTED OF A FOUNDATION OF SLIMES RETAINED BY A LAYER OF WELL GRADED NATURAL SAND AND FOLLOWED BY A LAYER OF SINGLE SIZED GRAVEL. THE FILTER FAILED BY PIPING IN THE TEST ALTHOUGH THE DESIGN SATISFIED THE TERZAGHI CRITERIA.

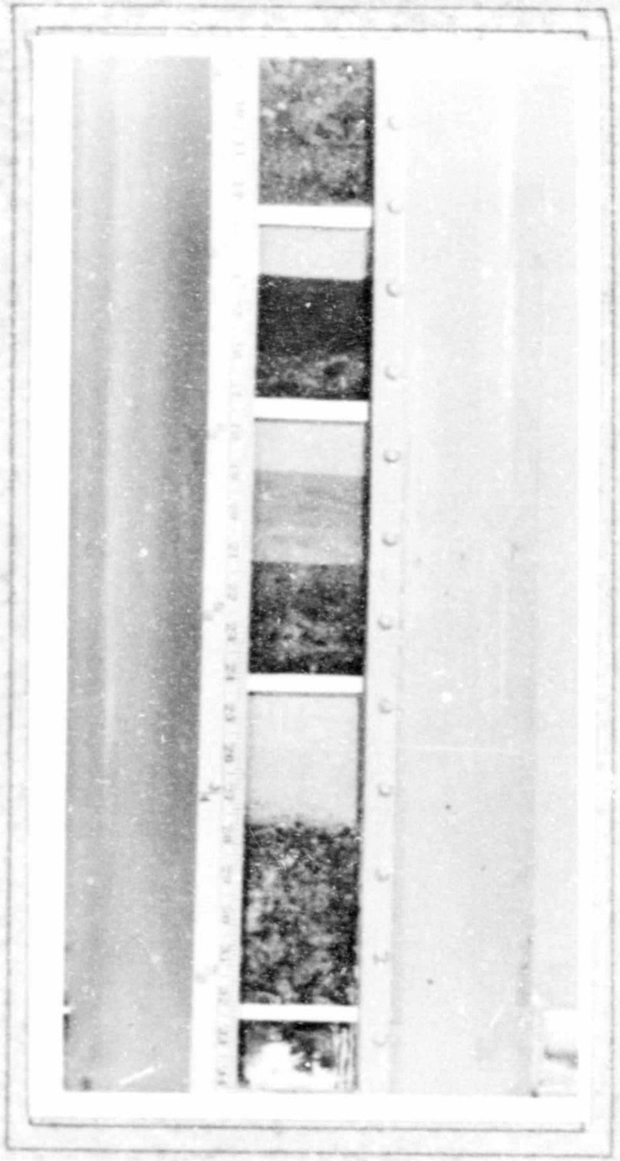


	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE	FINE	MEDIUM	COARSE
CLAY	SILT FRACTION			SAND FRACTION			GRAVEL FRACTION.		

See Page 48







TESTS ON MODEL FILTERS.

SERIES No1 : FILTER LAYERS BEFORE TESTING.

SANDS RETAINED TOP TO BOTTOM:

LEFT: E.R.P.M. ASH, BARTLETT'S SAND, E.R.P.M. DUMP SAND.

RIGHT: CRUSHER SAND 'A', CRUSHER SAND 'B', ARTIFICIAL SAND No1.

SERIES No2 : FILTERS BEFORE TESTING.

TOP TO BOTTOM:

FILTER No3, FILTER No1, FILTER No2.

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It can be seen from the table that all the filter layers satisfy the requirements of the design criteria; viz:

$$\frac{D_{15}\ \text{FILTER}}{D_{85}\ \text{FOUNDATION}} < 4 \text{ to } 5 < \frac{D_{15}\ \text{FILTER}}{D_{15}\ \text{FOUNDATION}}$$

In the second section of the tests two similar filters were compared against a third. In each case the foundation material was an artificial rock-flour, a "slime" residual from the cyanide gold extraction process. This material was so fine that the entire particle size analysis had to be carried out by hydrometer. The material was indurated with a powerful flocculating agent so that a special deflocculator had to be used, the solution was neutralised and allowance had to be made for the fact that the specific gravity of the liquid in the suspension was appreciably greater than unity.

The first filter layers of the first two filters were composed of sands with similar gradings covering a large range of particle sizes. One of these, Crusher Sand 'B' behaved as a filter within itself, the other, Bartlett's Sand was not a filter within itself.

The first two filters were two-layer systems, the third or control filter was a four-layer system composed of single sized sands.

The object of these tests was to see if a sand which was a filter within itself gave a better protective filter action than a similar sand which was not a filter within itself. Also, to get some indication of whether the Terzaghi design criteria, set up as a result of tests on single sized sands are applicable to sands covering a large range of particle sizes.

Details of the design of the first layers of the filters are as follows:

Sand	$\frac{D_{15}\ \text{Filter}}{D_{85}\ \text{Foundation}}$	$\frac{D_{15}\ \text{Filter}}{D_{15}\ \text{Foundation}}$
Crusher Sand 'B'	1.3	18
Bartlett's Sand	1.1	16
$<$ #100 $>$ #200 Sand	2.6	34

All these ratios are well within the specified limits.

THE BEHAVIOUR OF THE EXPERIMENTAL FILTERS DURING THE TEST

As the photographs show, the filters for each series of tests were placed in the filter tank one on top of the other.

The tank was filled in the dry, each layer being added to its predecessor with the greatest of care by sprinkling on by hand in half-inch layers, each layer being well-tamped using a flat circular tamper 6 inches in diameter. The accompanying photographs of the first series of tests were taken of the dry filter layers. The photographs clearly show

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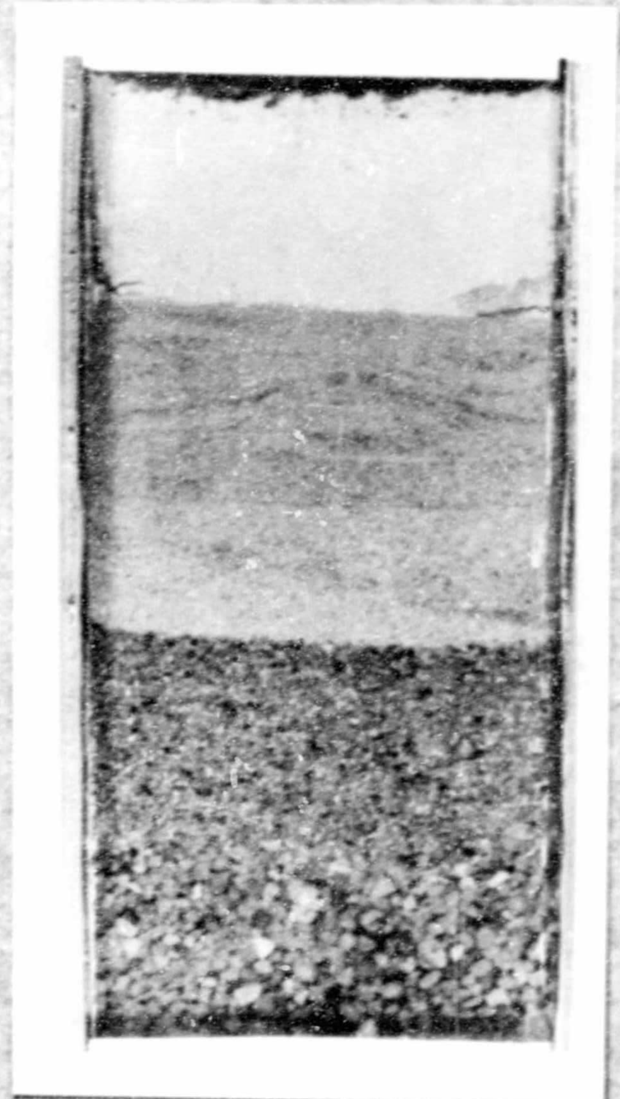

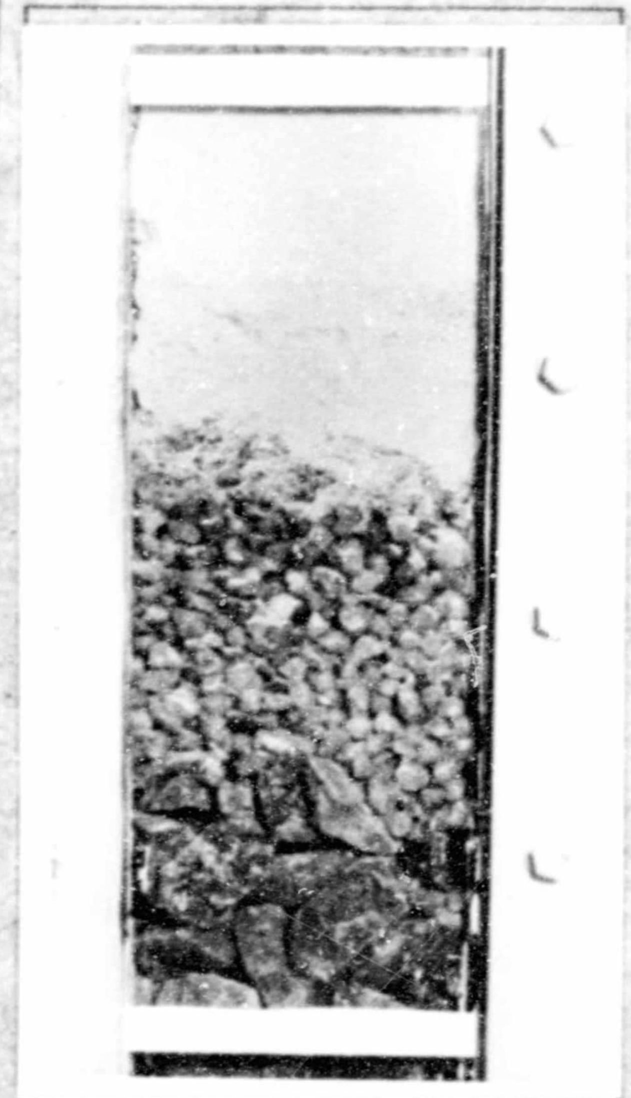

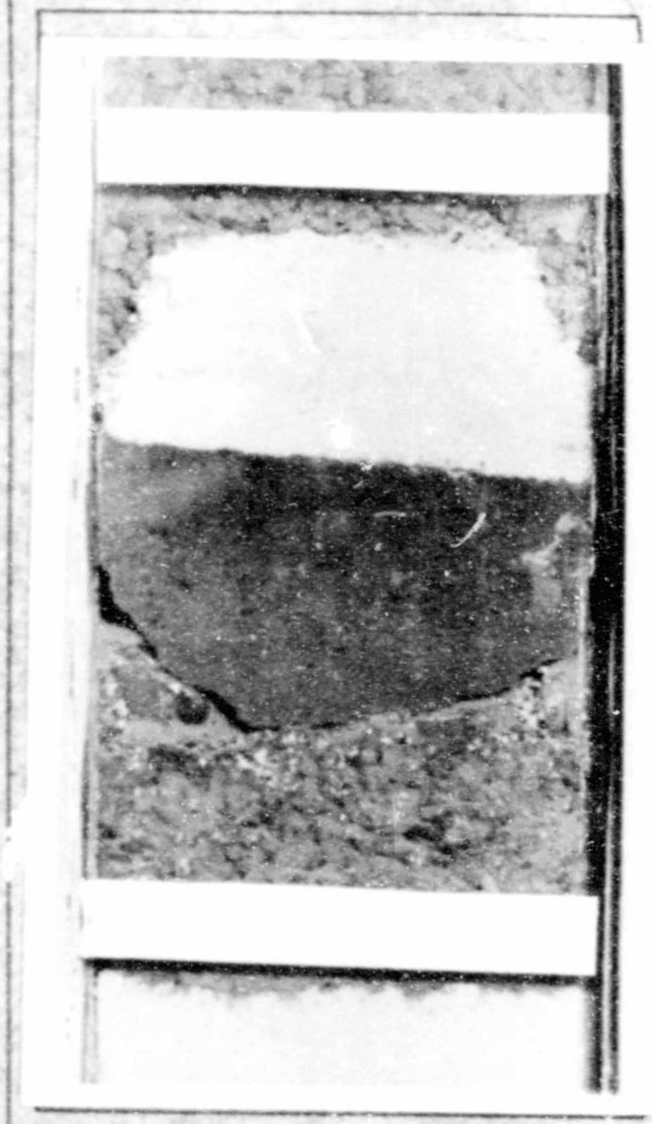

TESTS ON MODEL FILTERS SERIES № 2.

LEFT: FILTER № 1 AFTER TEST.
THIS FILTER FUNCTIONED PERFECT ' AND SHOWS NO SIGNS OF FAILURE.

CENTRE: FILTER № 2 AFTER TEST.
SOME LEACHING OF FINES AND SLIGHT PIPING HAS OCCURRED.

RIGHT: FILTER № 3 AFTER TEST.
A COMPLETE FAILURE BY PIPING AND CLOGGING OF A FILTER LAYER.

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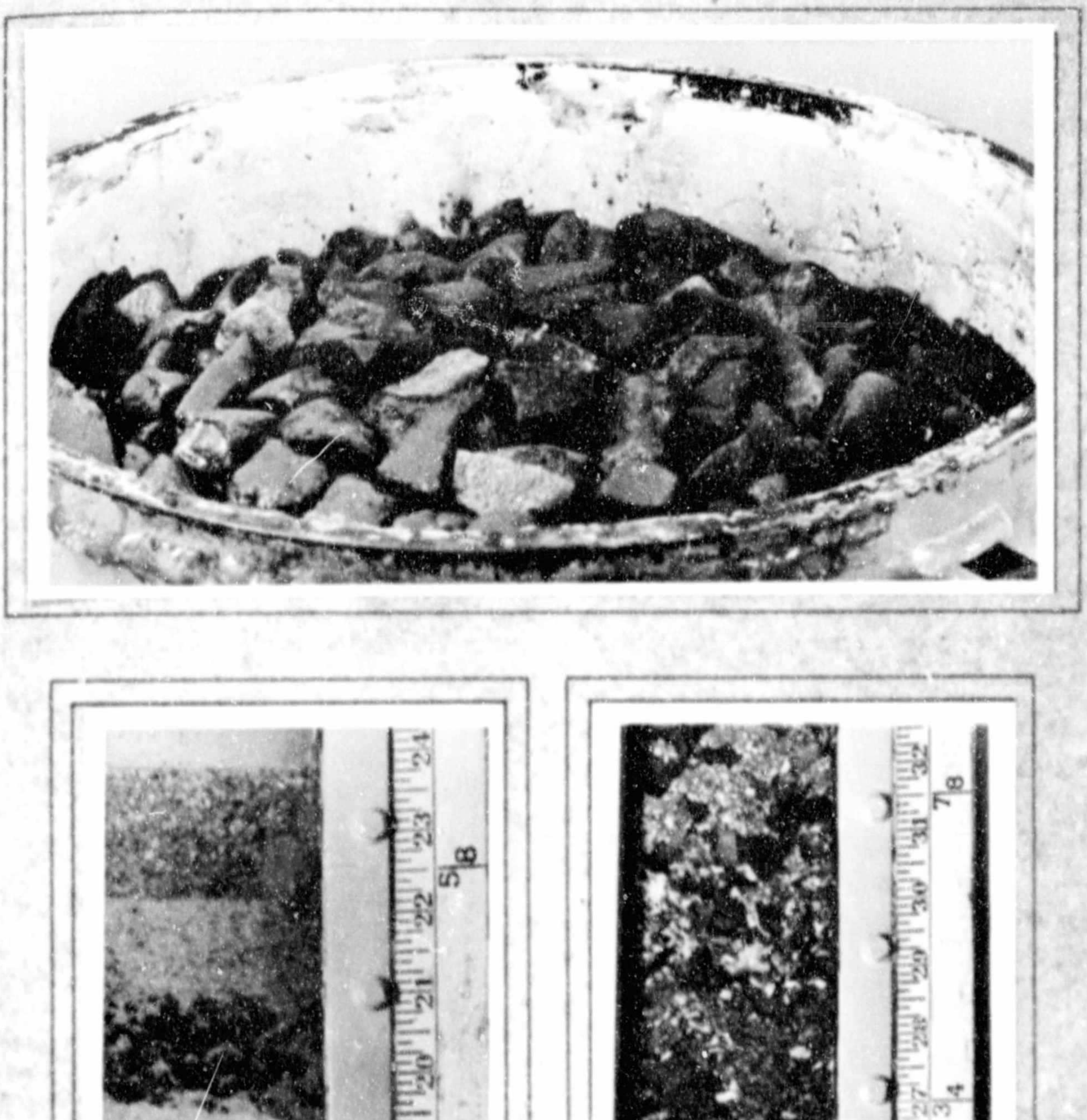


THE RESULTS OF PIPING ACTION IN FILTERS.

ABOVE: DOMING OF THE TOP ROCK LAYER IN THE PRESSURE FILTER TANK DUE TO PIPING AROUND THE EDGES.

BELOW, LEFT: THE START OF A PROGRESSIVE PIPING FAILURE. THE DIRECTION OF FLOW IS DOWNWARD.

BELOW, RIGHT: WHAT PIPING FAILURE CAN LEAD TO IF ALLOWED TO PROGRESS.

that the quantity of fines which fell through into the filter layers below was in certain cases quite appreciable. This does not represent a failure of the filter as it is inevitable that sufficient fine material must fall into the filter to allow the larger particles in the foundation sand to form stable "grain structure bridges" spanning the voids in the boundary between filter and foundation and preventing further passage of fine material.

Once the filter tank had been filled with dry sand, the filter beds were saturated with water from the bottom upwards by filling the disconnected discharge pipe with water. The upward flow was very gentle, the head causing flow never exceeding a few feet. This method of filling the tank caused no visible disturbance to the filter layers.

Immediately downward flow was started, a general re-arrangement of the grains in the filter layers took place as the filter particles moved to form arching structures stable enough to withstand the flow forces. A very small additional quantity of fine material washed through into the filter layers below. Apart from this the filters all behaved perfectly until piping failure developed through weak zones of the filter bed. These weak zones always occurred at the boundaries between the tank and the filter layers where the compaction achieved by tamping was poor.

The mechanism of these piping failures was as follows: The flow tended to concentrate itself through the poorly compacted, more permeable zones of the filter. The seepage forces through such a region would increase until suddenly, with a rush of material into the filter, a pipe would open up. The sides of the pipe would then rapidly be eroded away until the filter layer above collapsed into the pipe, filling it with coarse particles. In the meantime the fine material washed through the pipe would be clogging the filter layer below and decreasing its permeability.

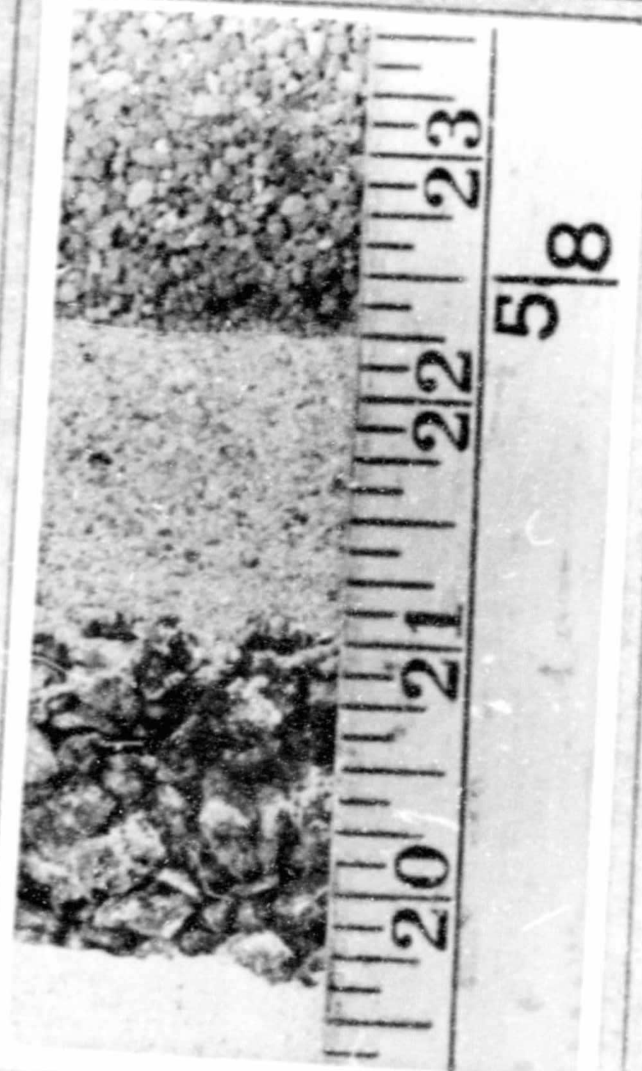
The collapse of the upper filter layer into the pipe invariably initiated a progressive failure by piping right up the height of the filter tank the process for each foundation layer being similar to that described. The system would then gradually stabilise itself until a new piping failure started.

Exactly the same phenomena were observed with the Series 2 tests. The photographs clearly show the form which the piping failure takes and they illustrate the action of a progressive piping failure and the clogging of filter layers by fine material washed through the pipes.

On emptying the filter tank, it was found in each case that piping failure had occurred right round the edges of the tank. An illustrating photograph shows how the originally plane surface of the top stone layer in the tank had become domed by the downward collapse of the outer edges of the filter beds as a result of piping.

Although those regions of the filter layers which had failed by piping were much more confused with the layers intermingled as the photographs show, the interior of the filter bed was completely undisturbed. Each layer was completely separate from its fellows and no washing through of fines from the foundation soils into the filter layers had occurred.

All the sand layers, regardless of their behaviour in the special filter tests had provided near perfect filtering action.



TESTS ON MODEL FILTERS — MECHANICS OF OPERATION AND FAILURE.

LEFT: PENETRATION OF FINES FROM FOUNDATION INTO FILTER LAYERS BELOW TO FORM ——

CENTRE: GRAIN STRUCTURE BRIDGES GIVING STABILITY AGAINST FURTHER PARTICLE MOVEMENT.

RIGHT: THE COMMONEST TYPE OF FAILURE — DESTRUCTION OF BRIDGES BY PIPING.

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FLOW MEASUREMENTS.

At intervals during both tests, measurements were taken of the time elapsed from the start of the test, the pressure drop across the filter tank and the rate of discharge through the filter. From these measurements mean permeabilities were calculated for the filter bed and graphs showing the variation of this permeability with time were prepared.

These permeability-time graphs give an excellent record of the changes occurring within the filter tank as time progressed.

Considering the graph for the first series of tests: The initial rapid increase in permeability accompanied the opening up of pipes and flow channels in the filter. The permeability then dropped off as material from the foundation layers was washed through the pipes and clogged the filter layers below. A second sudden increase in permeability occurred as a further piping failure developed.

Considering the graph for the second series of tests: The initial decrease in permeability indicates the compression of the filter bed with consequent reductions in the void spaces. The permeability then suddenly increased as piping started and progressed. After this the permeability decreased gradually as the fine material washed through the pipes and clogged the filter layers.

The cycles passed through by the two different filter beds, one ten times as permeable as the other, have very similar forms. This process of sudden failure by piping and subsequent re-stabilisation by movement of the filter sand would probably have been found to continue with a decreasing amplitude of the "permeability waves" and an increasing time between wave peaks had the tests been continued longer.

DISCUSSION AND CONCLUSIONS:

With hydraulic gradients of up to 34½, this series of filter tank tests must surely be among the most severe tests to which filters have ever been subjected. Conditions were probably at least 50 times more severe than those under which any normal drainage or protective filter would be required to operate.

The first series of filter tests showed that for the samples of sands which were tested it is not important whether a sand behaves as a filter within itself or not. Of the six sands tested, four underwent extensive changes of grading in the special filter test. Nevertheless, apart from piping failure, those four sands were retained just as well by the "single-sized" filter layers as were the other two which did not change significantly in grading. That is to say, from the point of view of suitability as filter materials, it does not matter if a sand does not behave as a filter within itself.

Within the filter a redistribution of the particles will take place and the grading will vary between the "entrance" and exit sides of the layer. At the boundaries of the layer intermingling and leaching out of the fines will occur to an insignificant extent until stable 'bridge' structures have been established.

Once equilibrium has been reached, however, the filter system will be stable and will function efficiently.

The second series of tests showed that the Terzaghi design criteria, although established by tests on single sized sands, do hold for graded sands. Also that a non-filter gives as good a protective filtering action as does a sand which behaves as a filter within itself.

An examination of the filter layers after the test showed that in each of the three cases, the fine slimes foundation material was perfectly retained where the layers were not disturbed by piping.

It is probable that no piping would have occurred had the hydraulic gradients been less severe. The experience gained in these tests shows the importance of having structurally uniform and strong filter layers if a filter is to operate as designed. Piping can be a most destructive and disruptive agent and every care must be taken to prevent it. For this reason, anything which might cause local concentrations of flow must be avoided. If a drainage pipe, outlet conduit or some other feature has unavoidably to cut through a filter layer in the direction of flow, cut-off collars should be provided to lengthen the flow paths and special care should be taken in compacting the filter material around the interrupting feature.

The last four chapters have all dealt with the action of water on the gradings of filter sands and with the extent to which the flow of water is responsible for the failure of filters. It now remains to consider changes of grading due to physical and chemical weathering of sand particles.