EXPERIMENTAL STUDIES ON PROTECTIVE FILTER

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Synopsis This paper presents the experimental results of studies on protective filter for the purpose of securing durable and stable function of relief well system.

Factors influencing the durability of filter are; stable grading of filter material, repeating seepage pressure on and into filter system, and the relation of void ratios between filter and base materials.

The author had conducted the experimental studies of these factors and investigated the essential characteristics of long durable and stable filter.

Introduction

A word, "Protective Filter" is generally used to express drainage systems such as sand-gravel backfill around perforated pipes with open joints mainly used for side ditches and subsurface drains, and pervious sand-gravel drains at the toe of earth dam or levee to relieve seepage pressure, to prevent boiling, and to lower seepage plane across the dam or levee.

There are two main requirements for a good protective filter (hereinafter referred to as "filter") : First, it should be more pervious than the base material to be protected; and second, it should so well graded as to prevent penetration and washing of base material.

In early 1920, Karl von Terzaghi used for the first time a weighted filter. Then, in 1939, G. E. Bertram[1] of Harvard University, in 1941, U. S. Bureau of Reclamation[2], and in 1949, U. S. Waterways Experiment Station[3] had successively developed the study of filter design in field and laboratory, in order to keep pace with the necessity of extensive informations regarding filter design for Flood Control Program of the U. S. in Japan also, Kawakami and Esashi[4] of Tohoku University conducted much useful experiments in 1961, of which results are now being applied to wide range grading of base material.

Thus, filter design has been developed practically applicable to various fields of work.

Relief well is generally driven through various foundation strata to collect and relieve groundwater and one single type filter will not necessarily be satisfactory for every different staratum. In order to secure effective and durable function of such relief well system, some experimental studies of filter around a well have been carried out and reported in this paper. Then, the author will suggest a few considerations in designing stable filter under various kinds of factors such as grading of filter material, effect of repeating seepage pressure and the relations of void ratios between filter and base materials.

Sample, Equipment and Experimental Procedure

(1) Samples

Grain size distributions of base material used for filter test are shown in Fig. 1 (a).

Natural Sand No. 1; Bank-run sand in the upstream of Kamanashi river.
Natural Sand No. 2; } Bank-run sand of Kamanashi
Natural Sand No. 3; } river near Shingen Bridge.
Sand No. 4; Slag from Takara Mine.

Grain size distributions of filter material are shown in Fig. 1 (b). Filter materials were prepared by sieving bank-run sand of Kamanashi river in accordance with the requirements of JIS A 1204 (Method of Test for Grain-Size Analysis of Soils) and combining into specific proportions. All filter materials were subject to

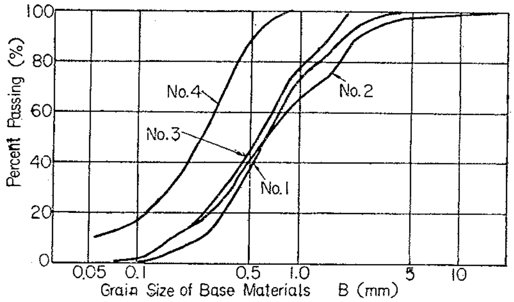

Fig. 1 (a)

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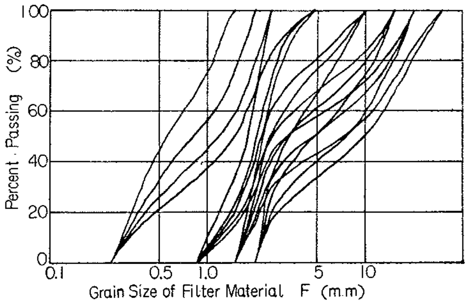

Fig. 1 (b)

double applications of yellow lacquer in order to make it possible to identify filter material after base material has penetrated thereinto.

(2) Equipment and Experimental Procedure

The equipment as shown in Fig. 2 was used for the test. It is substantially similar to Bertram's equipment, except several modifications by the author. The equipment consists of two major parts, one—to produce de-aired water necessary for filter test, and the other—to make filter test itself.

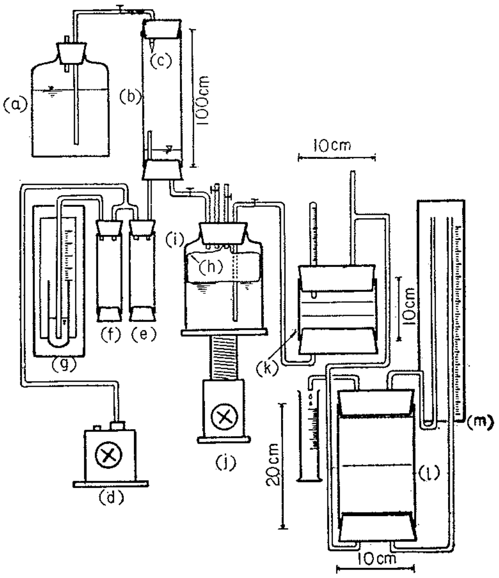

Fig. 2

(a)	20 *l*. Water Storage Carboy	(h)	Lucite Balloon
(b)	Lucite De-Airing Column	(i)	20 *l*. Water Storage Carboy
(c)	Spray Nozzle	(j)	Oil Jack
(d)	Vacuum Pump	(k)	Lucite Air-filter Cylinder
(e)	Water Trap	(l)	Lucite Filter Test Cylinder
(f)	Mercury Trap	(m)	Manometer
(g)	Scale Graduated Mercury Manometer		

De-Airing Water

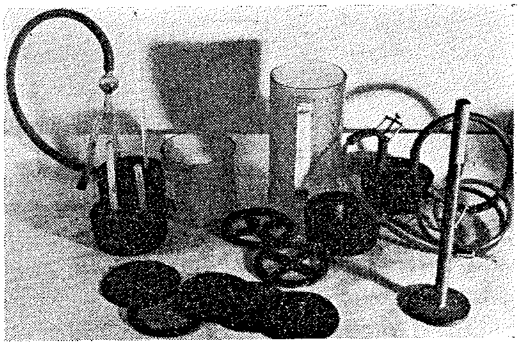

Photo. Equipment for Filter Test.

(1) Water about 10 degrees Centigrade warmer than the room temperature is poured in the 20 liter storage carboy (a).

(2) A clean lucite cylinder (b), 5 cm in diameter and 100 cm in length, and 20 liter storage carboy (i) are sucked by the vacuum pump down to about 550 mm Hg. For this operation, only one pinchcock connecting (b) and (i) is opened among four pinchcocks of the tubes on the rubber plug of carboy (i), and the other three are closed.

(3) Then the pinchcock on the tube connecting (a) and (b) is opened to permit free suction of water into the de-airing column (b). Water is vaporized and sprayed by spray nozzle (c) and de-aired in the column (b). During de-airing operations, internal air pressure of the column (b) is maintained at about 550 mm Hg. by vacuum pump. Top end of suction pipe is set 10 cm above the base of column to allow delay of water comming into carboy (i). Thus, the storage carboy (i) is filled with de-aired water.

(4) A thin lucite balloon (h) is sucked by vacuum pump down to 550 mm Hg. before de-airing operations and suspended in carboy (i). The balloon will take air and expand as water moves from (i) to (k) through siphon tube. This is a means for maintaining water in its de-aired condition during storage and test.

Filter Test

(1) A rubber plug with a glass tube is put on lower end of a clean dry lucite cylinder and the cylinder is placed on a wooden stand. Then, a rubber packing having a diameter epual to the inside diameter of the cylinder is placed on the rubber plug, and a 100 mesh brass screen

is placed on this packing.

(2) Base material is placed in the cylinder and compacted to 6 cm thickness with a tamper. Base material is weighted within an accuracy of 0.1 gr., and the volume is calculated by averaging four thickness measurements around the cylinder. Then, the void ratio of base material is determined.

(3) A 6 mesh brass screen which will little disturb penetration of base material is placed on the base material. Then filter material is placed and compacted in the same manner as is used in the preceding paragraph (2), and the void ratio determined. The screen shall be so arranged as to separate base and filter material after filter test.

(4) A 40 mesh screen is placed on the top of filter layer and a rubber packing of 5 mm thickness is placed thereon. Top end of the cylinder is plugged by a rubber plug with a short rubber tube pinchcock attached.

(5) Following the preparation of the filter test cylinder, an air-filter cylinder is prepared to filtrate remaining air bubbles in the de-aired water. A short lucite cylinder is prepared with a rubber plug on lower end of the cylinder and placed on a wooden stand. In this cylinder, a 40 mesh brass screen, a compacted layer of natural sand 2 cm thick, a 100 mesh brass screen, a compacted layer of base material 1 cm thick, another 100 mesh brass screen, a second layer of natural sand 2 cm thick, and then finally a 40 mesh brass screen are placed.

(6) Air is sucked from the air-filter (k) through top tube by a vacuum pump and the de-aired water is introduced from the bottom tube of the air filter. Then, in the same manner, de-aired water is introduced into the filter test cylinder (1) and the test is conducted.

Results and Discussions

(1) Relation between Filter Grading and Stability:

In previously published reports, the particle size corresponding to passing percent of 15 or 10 of filter material has been the only factor required in designing filter. For example, the requirement of U. S. Waterways Experiment Station which have been generally applied is;

$$5\times B_{15}<F_{15}<5\times B_{85}$$

where F_{15}; Particle size of filter material corresponding to passing percent of 15.

B_{15}, B_{85}; Particle sizes of base material corresponding to passing percents of 15 and 85 respectively.

It may be expected that if the particle size of filter corresponding to passing percent of 85 (F_{85}) or smaller particle sizes should constitute suitable filter components, filter would be stable, no matter how large the particle size of filter corresponding to passing percent of 85 (F_{85}) is. But is it true in all cases? The author tried to solve this question whether it is necessary to specify the particle size of filter corresponding to passing percent of 85 or not in designing filter.

According to the particle size relations shown in Fig. 3, filter layer will never cause failure if the particle size relations are within the minimum critical ratio of U. S. Waterways Experiment Station, but filter layer will not necessarily be free from failure even though fairly free from failure or unstable condition if the particle size relations are within the minimum critical ratio of Bertram. In this figure, the straight line from the origin 45 degrees declined to the ordinrte means,

$$\frac{C_{u\cdot f}}{C_{u\cdot b}}=1$$

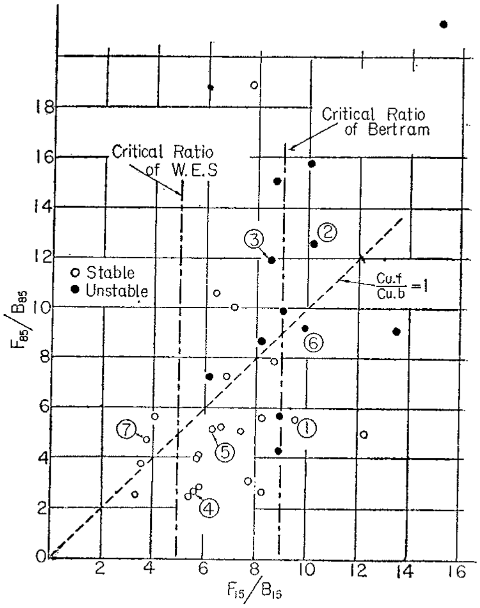

Fig. 3

where $C_{u \cdot f}$ and $C_{u \cdot b}$ Coefficients of uniformity of filter and base materials respectively.

In other words, grading curves of filter and base materials of which particle size relations are on this line would be parallel. The results shown in Fig. 3 lead to conclude that the filter layers of which particle size relations are in the area above this line ($C_{u \cdot f}/C_{u \cdot b}=1$) would tend to become twice as frequently "unstable" as those below this line. Therefore, the results justify the requirement of particle size corresponding to passing percent of 85. The filter material of which particle size relations are beyond the minimum critical ratio of U. S. Waterways Experiment Station should have higher coefficient of uniformity than that of base material to secure "stable" condition. The terms, "Stable" and "Unstable" are defined as judged in the following procedures.

(1) Upon completion of filter test, filter layer is carefully pushed out of the cylinder and oven-dried. Base material penetrated into the filter is selected and accurately weighed. Filter is defined "stable" if the penetration of base material is less than 0.3 gr., degree of accuracy of measurement, and "unstable" if the penetration is more than 0.3 gr. Filter is defined "failing" if the base material causes boiling and mixes with filter material during filter test.

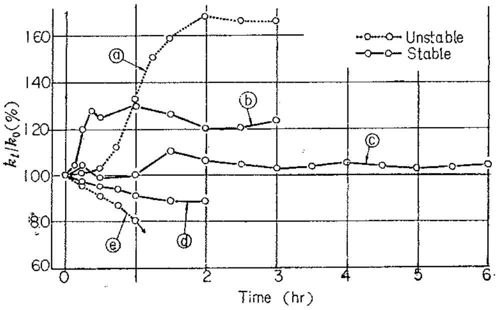

Fig. 4

Table Data of Filter Test

Test No.	Dia. of Filter (mm)	Dia. of Base (mm)	F_{50}/B_{50}	Hydraulic Gradient	Penetration (g)
a	1.5~2.5	0.075~0.11	22.5	4.0	2.4
b	2.5~4.8	0.25 ~0.40	11.3	2.5	0.17
c	0.85~1.5	0.075~0.11	12.3	4.0	0.23
d	1.5~2.5	0.15 ~0.25	10.2	6.5	0.17
e	2.5~4.8	0.15 ~0.25	17.9	5.5	Failure

(2) G. E. Bertram assumed that the filter material which maintains the constant coefficient of permeability over the test period will be "stable" and vice versa. However, the author could not necessarily get the similar results. As shown in Fig. 4, "Permeability Time Relations," no remarkable trend to verify Betram's assumption was noted.

Then the author assumed that the penetration of base material into the filter layer would be caused by more or less piping action[5] and the jumping of seepage discharge at a constant hydraulic gradient (critical hydraulic gradient) would be the basis of judgement. (see Fig. 5).

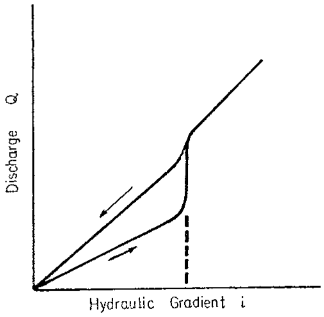

Fig. 5

However, the increase of seepage discharge was so gradual and slow in the test that the author could not find the seepage jumping (see Fig. 6). Therefore, the rate of change of permeability was then investigated as the basis of judgement.

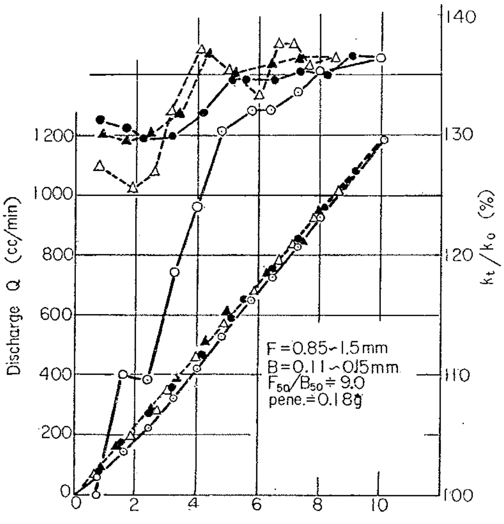

Fig. 6

In the first test, the rate of change of permeability increased as the hydraulic gradient increased, but after the second test, the rate of change of permeability was almost constant regardless of the increase of the hydraulic gradient (as the result of consolidation and/or rearrangement of sand layer). Filter layer which has relatively large difference in the rate of change of permeability between the first and second tests was judged "unstable" because of its piping action.

The final judgement on the stability of filter layer was based on the combination of abovementioned two methods, with the retest for the uncertain results.

The author compared the test results with the curve developed by Kawakami and Esashi (minimum critical ratio of filter) although the samples were within a limited range of grain size distributions. As shown in Fig. 7, the results show satisfactory agreement.

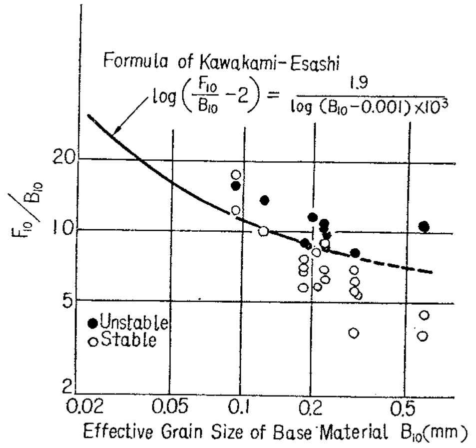

Fig. 7

(2) Void Ratios of Filter and Base Layers

Void ratios of filter and base layers have not been fully investigated although they are thought to influence the stability of filter.

Assuming that the filter layer with large void ratio which is relatively porous would be easily penetrated by base material, stable and unstable combinations of filter and base materials were selected by Fig. 3 and the filter test was conducted by varying the void ratio of filter material while keeping the same void ratio for the base material. Penetration of base material did not necessarily increase in proportion to the increase of void ratio of filter material. Then, the void ratio of base material was also varied and the relation $r\,(r=e_b/e_f$, where e_b is the void ratio of base material and e_f is that of filter material) versus penetration was plotted in Fig. 8. Penetration of base material is in proportion to the ratio (r), for various combinations of base and filter materials.

The relation shown in Fig. 8 seems somewhat curious but the fact that the large void ratio of base material would tend to cause boiling and the small void ratio of filter material would tend to cause increase of flow velocity in the filter layer justifies the results.

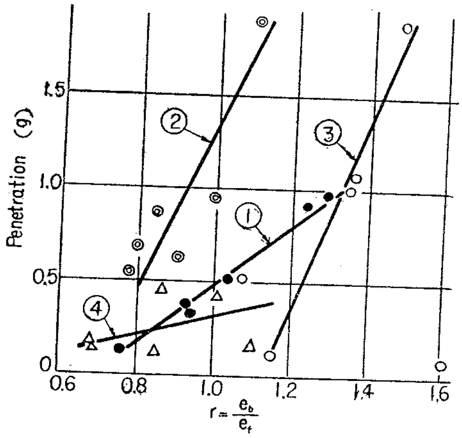

Fig. 8

Each straight lines in Fig. 8, corresponding to the numbering of points shown in Fig. 3, have steeper slope with the increase of ratio F_{15}/B_{15}. The closer to the critical ratio of stability the samples are, the more penetration has the base material for a small change of the ratio r.

(3) Effect of Repeating Seepage Pressure

Most structures with protective filter will be subject to the repetition of seepage pressure. Filter must be designed based on not a few repeating application of seepage pressure but a number of repetitions of seepage pressure to secure durability.

In filter test, hydraulic gradient was increased from 0 to 6 and returned back to 0 in one houre. This is defined as a cycle of filter test. Repetition of such seepage pressure was applied to the samples in 1 to 200 cycles and the pene-

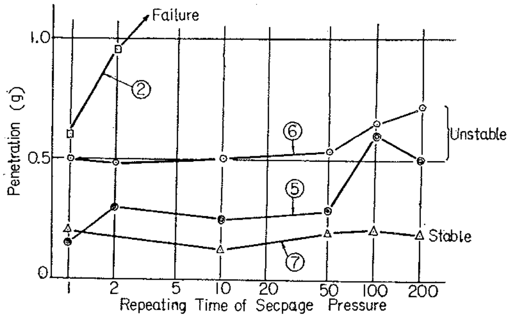

Fig. 9

tration of base material was measured for 1, 2, 5, 10, 50, 100 and 200 cycles of test. The results are plotted in Fig. 9 with the numbering corresponding to the points in Fig. 3.

The combination of filter and base layers in the right side of Bertram's critical ratio failed in boiling condition by at most a few cycles of seepage pressure. The combination of filter and base layers between the W. E. S.'s critical ratio and Bertram's showed a slight and gradual increase of penetration with the increase of cycle number, for example, 50% increase of penetration at 200 cycles compared to 1 cycle. The combination of filter and base layers in the left side of the W. E. S.'s critical ratio showed no increase of penetration with the increase of cycle number, indicating perfectly stable condition.

Conclusion

The filter test and the analysis of the results mentioned above will lead to the following conclusions :

(a) The stable combinations of filter and base layers are within the critical ratio of U. S. Waterways Experiment Station or the formula of Kawakami-Esashi. The critical ratio of W. E. S. is safe enough for up to 200 cycles of seepage pressure application.

(b) Generally speaking, it is desirable that the filter material has smaller coefficient of uniformity than that of base material.

(c) Void ratio of filter material (e_f) shall be decided based on the void ratio of base material (e_b). The ratio $r(=e_b/e_f)$ shall be as small as possible to minimize the penetration of base material.

Acknowledgement

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