Model Tests on the Seepage Erosion in the Silty Clay Core of an Earth Dam

Essais sur modèles d'érosion par infiltration dans les noyaux argileux des barrages en terre

W. WOLSKI, *University of Agriculture, Warsaw, Poland*

SUMMARY

The author explains the nature of the seepage erosion in the impervious core of an earth dam by means of model tests performed on silty clay samples. Seepage erosion phenomena have been tested by the following methods: x-raying the model samples, before and after seepage; pore water pressure measurements to obtain the changes in the porosity; direct visual observations of the soil sample. The experiments performed have proved that the seepage erosion occurs in two stages and depends upon the hydraulic gradient as well as upon the duration of time.

SOMMAIRE

C'est pour étudier les phénomènes d'érosion par infiltration dans le noyau étanche d'un barrage en terre, que furent effectués des essais sur modèles. Le phénomène d'érosion a été étudié au moyen des méthodes suivantes: la radiographie aux rayons X des échantillons avant et après la filtration; les mesures des pressions interstitielles pour déterminer les changements de la porosité; les observations directes des échantillons du sol. Les essais effectués sur les modèles ont démontré que l'érosion par infiltration a lieu en deux phases, et qu'elle dépend du gradient hydraulique ainsi que de la durée du phénomène.

THE CLAY CORE OF AN EARTH OR ROCKFILL DAM is subjected to seepage forces exerted on it by water percolating under high hydrostatic head. To protect the core material against the development of dangerous seepage erosion caused by the seepage forces, the core is flanked by multi-layer filters usually made of sandy soils. Owing to seepage erosion, piping is likely to develop in the dam core. The increased seepage flow caused by the piping may result in dam failure.

The multi-layer filters are expensive and their construction is difficult; therefore, there is a tendency to simplify their construction by using the non-graded (natural) coarse grain soils. The application of these soils depends upon the magnitude of seepage erosion in the dam core.

In this paper the author has attempted to analyse the effect of seepage erosion in silty clay in hopes of contributing to the establishment of definite criteria for designing impervious cores and filters in earth and rockfill dams.

FORMER OPINIONS CONCERNING THE EFFECT OF SEEPAGE EROSION

Very few of the reports published to date on the effect of seepage erosion in cohesive soils have attempted to determine the conditions for piping occurrence. The influence of the hydraulic gradient has been analysed as well as the influence of the soil type and its consistency, but not enough attention has been paid to the nature of seepage erosion. The most thorough works on this subject (Davidenkoff, 1955; Istomina, 1957) were based on the assumption that the development of piping in a soil sample is rapid and that the effect of seepage erosion depends on the phenomena occurring at places in which the seeping water emerges from the soil. These authors have published many practical suggestions concerning the protection of cohesive soils against the erosive effect of seepage, but have not examined the nature of seepage erosion.

MODEL TESTS OF SEEPAGE EROSION IN SILTY CLAY

To examine the nature of seepage erosion, 30 tests have been made on soil models, representing the contact parts of a dam core and its filter. The tests have been carried out on the models placed in cylindrical containers 20 cm in diameter, or cubic containers of 15 cm side length, made of steel or plexiglass.

The core model has been made of the silty clay which often occurs in the river valleys situated at the foot of the Carpathian mountains. Some characteristic properties of this soil are: particle size: sand (2–0.05 mm), 12 per cent; silt (0.05–0.002 mm), 72 per cent; clay (<0.002 mm), 16 per cent. Specific gravity (G), 2.71 grams/cu cm; liquid limit (w_L), 36.3 per cent; plastic limit (w_P), 19.7 per cent.

The tests have been divided into three groups, differing one from the other in the method of testing the seepage erosion as well as in the construction of the model itself.

X-ray Method Tests

In this group of tests, a membrane made of sheet iron with a circular hole, 50 or 10 mm in diameter, was used as a filter, the hole representing the pore of the coarse grain soil.

The seepage erosion occurring in the soil material placed in the container was tested by the X-rays. This radiographic method was applied for testing seepage erosion inside the silty clay model, without disturbing the sample. For this purpose, a number of pipe-like small channels were made in the soil which was placed in the container and which was compacted with the energy equal to that used for the Proctor test. These channels were made perpendicular to the direction of the percolating water and were filled with X-ray resistant red lead (Pb_3O_4). Each container with the soil model was X-rayed using the power of 5 mA at 140 kV, with an exposure time of 2 min. The radiographic test installation is presented in Fig. 1. The container with the soil model was exposed then to percolating water, the hydraulic gradient

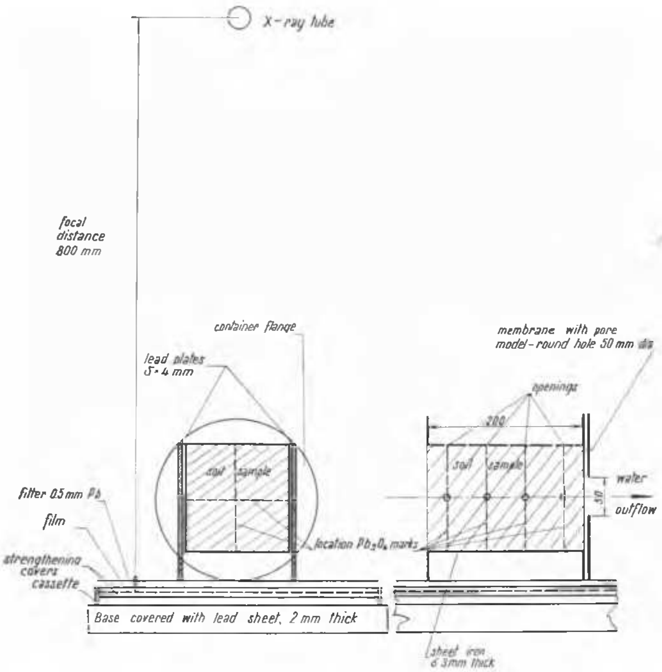

FIG. 1. Scheme of X-ray test.

FIG. 2. Radiogram of the sample after water flow.

being successively increased until the test sample was destroyed. The soil sample was then X-rayed again.

The pipe-like small channels were clearly visible in the radiographs of the containers. They have been made perpendicularly cross-shaped in the four sections of the soil model. Photographs made in two directions allowed three-dimensional observation of seepage erosion in the tested soil. A comparison of radiographs made before and after exposing the soil model to the percolating water allowed determination of whether the red lead marks, and consequently the neighbouring soil, had been displaced. An example of the radiographic contact print made for one of the tests is presented in Fig. 2. The photographs made after exposing the soil to percolating water show displaced marks of red lead. The dotted lines drawn in Fig. 2 illustrate the previous location of the indicating marks (according to the photograph made before exposing the soil to percolating water).

Auxiliary tests, apart from X-ray ones, have also been employed in this group of experiments to define the soil consistency.

Pore-Pressure Method Tests

The test model applied in this group of experiments was the same as in the first group employing the X-ray method. The manner of testing the seepage erosion was different, however.

The changes occurring in the soil as a result of seepage have been determined according to the changes of water pressure in the soil pores. Pore pressure was measured by capillary piezometers. The following assumption was used here: that the decrease of pressure indicated by the piezometers in any point of the examined soil sample (in spite of seepage progressing with the mean gradient unchanged) proves that the consistency of the neighbouring soil has changed (porosity has increased). The course of pressure changes in the particular piezometers located in the model determined the seepage erosion process.

The scheme of test installation, including the location of the piezometers, is shown in Fig. 3. Pore pressure diagrams representing readings of the piezometers during seepage flow illustrate one of the experiments. From the time the gradient increases up to the value of $i = 15$, with a pressure $h = 300$ mm, the decrease of pressure in piezometers 2, 3 and 4 is clearly visible in the diagram, indicating the gradual increase of porosity in the neighbouring soil.

Tests Made on the Natural Coarse Grain Soil

The test model applied in this group of experiments was made of silty clay and coarse grain soil graded within the limits of 15 to 25 or 25 to 40 mm. This model was used in place of the sheet iron membrane in the previous experiments. It is to be emphasized that the consistency of the natural soil used in the test was almost the same as that in the proposed dam, and that the thickness of layers was sufficient to allow observation of the extent of the phenomena subject to analysis. Consequently, the test model may be considered as a part of the dam, representing to the scale of 1:1 both the dam core and its filter.

This group of tests was made to verify whether the seepage erosion effect observed on the membrane models is the same as that in cases where the dam core contacts the natural coarse grain soil.

The experiments were analysed on the basis of changes at the contact surface between the dam core and the coarse grain soil, observed through the transparent container wall.

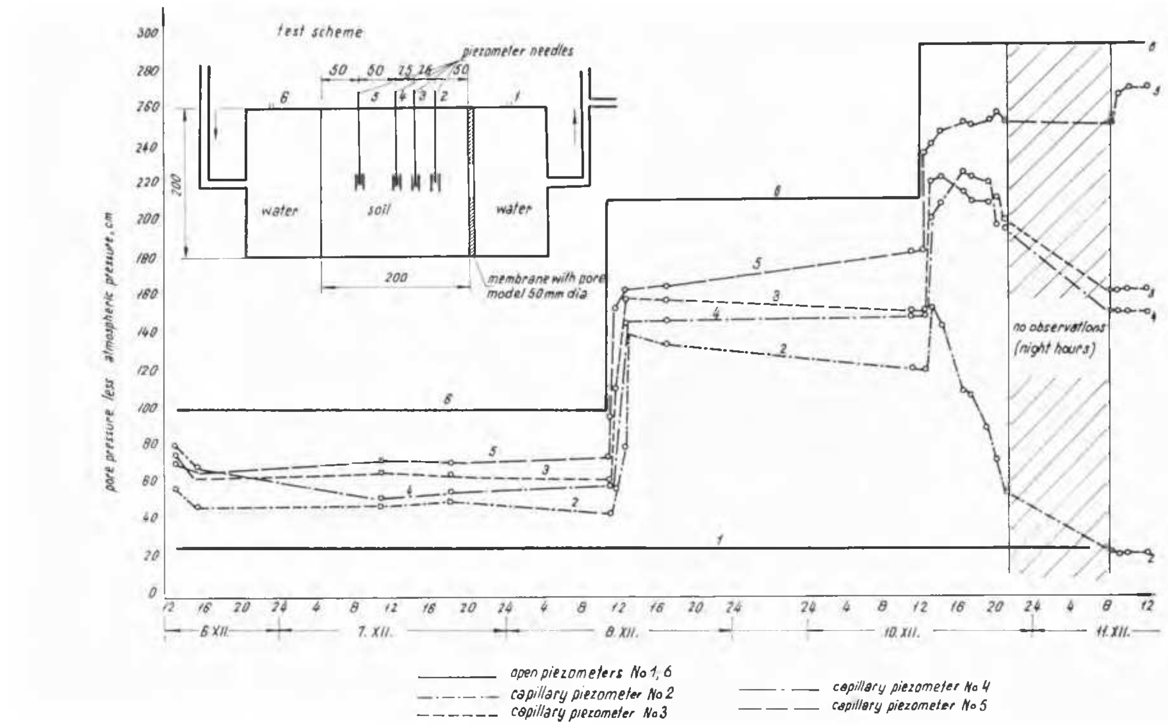

FIG. 3. Pore water pressure diagram.

The final results of tests were determined after seepage was completed. This determination was made both by visual and by "palpable" ways, which allowed the determination of the possible changes in consistency of the tested soil at the contact surface. Soil samples were also taken for laboratory evaluation. The moisture content, unit gravity, and consistency of the silty clay, as well as the grain size analysis of the coarse material filter were determined, to check the displacement of the clay aggregates.

Fig. 4 is the photograph of the contact surface of the cohesive soil, with cavities showing places of the seepage erosion. The deep hollow which can be seen in this photograph represents the piping channel. The liquid soil which filled up this channel has been removed for better visibility. The more important data on the tests are shown in Table I.

DISCUSSION OF RESULTS

The model tests enabled the general course of the seepage erosion effect occurring at the contact surface between the dam core and its filters to be determined. It was observed in both methods of the X-ray and pore-pressure tests that the seepage erosion failure of a soil sample occurs in two stages.

The first stage was observed at gradients less than 10, or at the beginning of seepage under higher gradients. The extent of the seepage erosion effect, which may be defined as the displacement of the small soil particles or shells, is limited in this phase to the zone where seeping water emerges from the soil. The depth of this zone was equal to one-half of the average dimension of the pores in the adjacent coarse grain soil. This limitation was caused by the dimensions of "arches" formed in the cohesive soil in the neighbourhood of the coarse grain soil (Fig. 5). The soil particles directly adjacent to the pores and not supported by the arches have been detached by the seepage forces.

The second stage began after passing the critical gradient, ranging from $i = 10$ to $i = 20$. The X-ray and pore-pressure methods have shown that in this phase the particles supported by the arches and located farther from the surface where seeping water emerges from the soil have been also subject to seepage erosion. It was the effect of soil loosening, proceeding progressively inside the sample model. This effect had the rheological form of a volume flow (Reiner, 1960), with the volume increase caused by the enlargement of pores. At the same time, the soil particles have been detached from the continuously existing arch surface. When the disturbed zone thus created (Fig. 5) extended as deep as ⅔ of the soil sample, piping occurred. The soil in the disturbed zone had then a porosity ranging from 44 to 48 per cent, and a moisture content close to the liquid limit. A general scheme of the seepage erosion occurring in a silty clay sample at the moment of piping is presented in Fig. 5.

The tests have proved the influence of time upon the course of experiments.

The time factor was of a lesser importance in cases where the gradients were below the critical one, that is when only first-stage displacement took place. Even though the cavities in the contact surface were formed within a few hours, the posterior seepage of water through the sample sometimes lasted for a few months (in one case for one year) without causing any additional erosion. If the gradient was increased to a value exceeding the critical one, the second-stage erosion phenomena, lasting from 5 to 20 hours, ended in a piping effect.

This statement is of a special importance with respect to the establishment of ways of determining the critical gradients. In a case where the increase in hydraulic gradient is very rapid, the critical gradient may be overlooked and exceeded. It could happen, in case of the second-stage erosion that the gradient would be increased without waiting for the piping effect.

The experiments made on the models with natural coarse grain soil have confirmed the results of tests made on the

FIG. 4. Contact surface after test, with piping channel.

simplified models with a sheet iron membrane substituting for the soil. The values of seepage erosion have been similar in both groups of tests, both in the first stage, when gradients were smaller than the critical one, and in the second stage, when gradients were at critical or higher. This conclusion is verified by the values of critical gradients, shapes of the arch (stage 1) and the disturbed zone (stage 2), and the soil consistency in the disturbed zone (Table I).

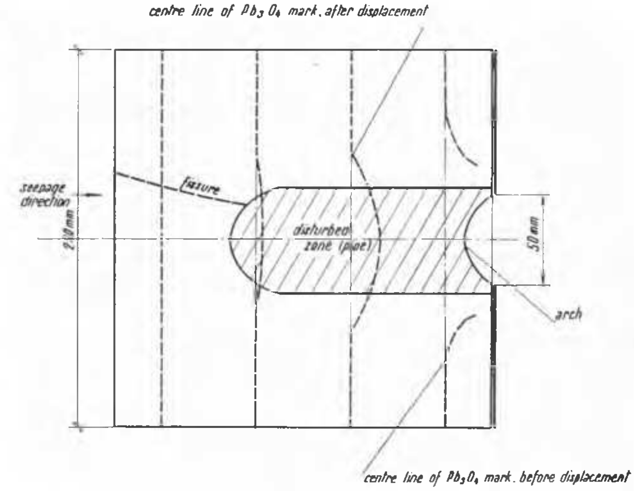

FIG. 5. Scheme of the seepage erosion in the silty clay sample at the moment of failure.

The phenomena observed during the experiments made on the membrane model and the conclusions presented in this paper are also valid for natural conditions occurring at the contact surface between the dam core and its filters.

CONCLUSIONS

The following conclusions may be drawn on the basis of the model tests reported.

1. The phenomenon of seepage erosion is composed of two stages. The first stage does not cause any destructive effect (shallow cavities are formed in the cohesive soil, in the neighbourhood of the coarse grain soil). The second stage is characterized by the loosening of soil behind some of these cavities. Soil zones with disturbed structure are formed; these later become piping channels. The second stage of seepage erosion causes failure of the soil sample.
2. The second stage of seepage erosion is a rheological phenomenon, which could be classified as a volume flow.
3. The second stage of seepage erosion is a slow process. The experimental determination of the critical gradients requires, therefore, a reasonably long period of time to carry out the tests successfully.

ACKNOWLEDGMENT

I wish to express my thanks to Professor R. Pietkowski for his help and suggestions.

TABLE I. EXPERIMENTAL DATA

		Duration of tests*			Soil properties*					
					γ_d (gram/cu. cm.)		n (per cent)		w (per cent)	
Test method	Number of tests	Complete test	At failure gradient	Failure* gradient i_{av}	Before test	After test†	Before test	After test†	Before test	After test†
Radiographic	17	2 hours to 120 days	6 to 20 hours	15 to 20	1.60 to 1.69	1.60 to 1.65 1.40 to 1.49	37 to 41	39 44 to 48	21.7 to 25.2	22.7 to 25.1 29.7 to 34.5
Pore pressure	4	5 to 12 days	15 to 20 hours	15 to 23	1.60 to 1.62	—	—	—	22 to 23	21 to 22 36 to 39
Direct observation	9	50 hours to 1 year	5 to 15 hours	10 to 40	1.54 to 1.66	1.54 to 1.70 1.40 to 1.52	35 to 43	35 to 36 42 to 44	16 to 26	20 to 26 24 to 31

*The limit values are given; data of individual experiments fall within limits presented.
†The values written above the line concern the undisturbed zone, below the line, disturbed zone.

REFERENCES

Davidenkoff, R. (1955). De la composition des filters dans barrages en terre. *Cinquième Congrès des Grands Barrages* (Paris).

Istomina, W. S. (1957). *Seepage resistance of soil.* Moscow.

Reiner, M. (1960). *Deformation, strain and flow.* London.