Analysis of Filter Requirements for Compacted Clays

Analyse des critères de filtre pour les argiles compactées

G. KASSIFF, *Senior Lecturer, Faculty of Civil Engineering, Technion—Israel Institute of Technology, Haifa, Israel*

D. ZASLAVSKY, *Senior Lecturer, Faculty of Civil Engineering, Technion—Israel Institute of Technology, Haifa, Israel*

J. G. ZEITLEN, *Professor of Soil Engineering, Faculty of Civil Engineering, Technion—Israel Institute of Technology, Haifa, Israel*

SUMMARY

It is recognized that conventional filter design criteria based on grain size, when applied to cohesive soils, may result in uneconomical design.

Theoretical and experimental studies on the selection of suitable filter materials for fat clay have been conducted in Israel during the last decade. The paper reports recent studies made on models of compacted clay placed in contact with actual filter material, as well as with bases with holes simulating filter material, and subjected to controlled flow of water. Testing conditions included variation of pressure on the clay, and of the size of holes within the bases and gradients. When failure took place the gradient was noted and the shear strength of the clay was determined. The experimental results show that a fat clay may be protected by a fairly coarse filter material. Relatively high average gradients were required to cause failure even when the clay was allowed to swell under zero pressure. A fairly reasonable agreement was found between the experimental results and a theory correlating the size of clay aggregate washed out, the exit gradients, and the tensile strength of the clay at failure.

SOMMAIRE

On sait que le critère de calcul d'un filtre conventionel, basé sur les dimensions des grains, s'il est appliqué aux sols cohérents, peut avoir comme conséquence des projets non économiques.

Des études théoriques et expérimentales, concernant la sélection des matériaux de filtre convenables pour l'argile grasse, ont été exécutées en Israël pendant les dernières années. L'article contient les résultats des études récemment exécutées sur des modèles d'argile compactée mise en contact soit avec le matériel de filtre même, soit avec des supports troués simulant le matériel de filtre et exposés à l'action d'un courant d'eau contrôlé. Les variables durant les essais furent la pression sur l'argile, les dimensions des trous dans les supports et les gradients. Au moment de la rupture, le gradient a été noté et la résistance au cisaillement de l'argile a été déterminée. Les résultats expérimentaux démontrent qu'une argile grasse peut être protégée par un matériel de filtre assez grossier. Pour arriver à la rupture, des gradients moyens relativement élevés étaient nécessaires, même quand l'argile se gonflait sous une pression nulle. On a établi qu'il y a une corrélation raisonnable entre les résultats expérimentaux et la théorie, laquelle établit une relation entre les dimensions de l'agrégat lavé, les gradients à la sortie et la résistance à la traction de l'argile au moment de la rupture.

VARIOUS ENGINEERING STRUCTURES, built within clay environments and subjected to flow of water, pose problems of seepage control and filter requirements for drainage. Pervious materials are used as filters to dissipate hydrostatic pressures, remove water quickly, and eliminate washing out of soil particles when danger of piping exists. It is generally recognized that the conventional filter design criteria based on grain size, when used for cohesive soils, ignore basic factors such as the resistance to piping owing to cohesive forces, soil structure, and the actual exit gradients developing in the soil-filter interface. As a result, the use of conventional criteria for cohesive soils may lead to uneconomical design of filters. It seems that more economical design criteria may be developed through rational analysis and experimental procedures. This is particularly important in areas lacking natural deposits of granular soils and where the only source of filter materials is crushed stone, processed in quarries and hauled over long distances.

As compared with cohesionless soils, cohesive materials offer far larger resistance to separation and washing out of particles by drag forces. In addition, clays require a smaller hydraulic conductivity for a filter, as the flux required for drainage is smaller. Hence, design criteria may be less severe and the range of possible filter materials wider.

In recognition of the considerations involved, several investigators have developed new approaches treating the problem both theoretically and experimentally. Davidenkoff (1955) made an important contribution in this field by developing a formula relating the cohesion of the base soil to the size of the protecting filter material and the hydraulic gradient. This was possible by using over-simplified assumptions both as to the cohesive strength of the base soil and as to the critical gradient. Zweck and Davidenkoff (1957) showed experimentally that with increasing fineness of the base soil the ratio of the 50 per cent sizes suggested by the U.S. Bureau of Reclamation for uniform filters may be increased. They also showed that this ratio is dependent on the seepage gradient. They did not investigate, however, base soils with materials finer than 0.01 mm. Zaslavsky and Kassiff (1965) presented a theoretical analysis of piping mechanism in cohesive soils, taking into consideration the actual exit gradients developing in the soil. The application of the theory for filter design will be attempted in this paper.

Experimental studies on the selection of suitable filter materials for fat clay have been conducted in Israel during the last decade in connection with the design of various hydraulic structures founded on and built of this material (Bar-Shany, *et al.*, 1957; Aisenstein, *et al.*, 1961). The present paper includes the experimental results obtained in the past, as well as those of recent model studies of piping in fat clays. A reasonable correlation was found between the experiments, the results of the model studies, and the theoretical approach to piping in cohesive soils.

THEORETICAL CONSIDERATIONS

A theoretical analysis of piping in cohesive soils (Zaslavsky and Kassiff, 1965) has shown that for a compacted clay the factor of safety, F, against piping may be approximately expressed as follows:

$$F = b\sigma_t/\gamma_w jd, \quad (1)$$

in which σ_t is the tensile strength of the clay, estimated from a drained triaxial test; j is the actual exit gradient (different from measured average gradient, i); d is the mean size of aggregates separated from the clay surface; and b is a dimensionless soil constant of the order of unity, dependent on the mean size and geometry of the aggregates washed out.

The engineering problem of protecting a compacted clay from washing out is to utilize a filter material with pore sizes smaller than the size of washable aggregates associated with the design gradients. This requirement combined with Equation 1 is schematically illustrated in Fig. 1, in which

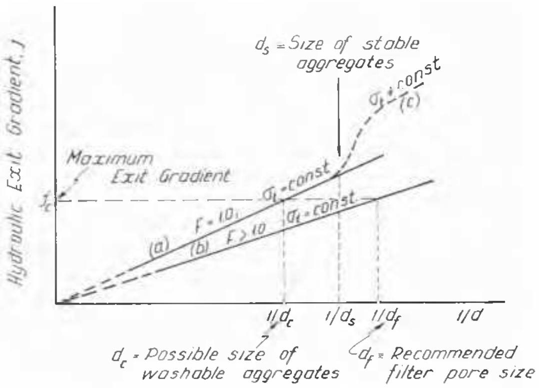

FIG. 1. Determination of pore size of filter material required to protect clay soil from washing out.

the exit gradient, j, is plotted against $1/d$ for a particular clay. Assuming σ_t = constant for a certain range of washable sizes, straight lines are obtained for various safety factors (line (a) for $F = 1.0$; line (b) for $F > 1$). Using a given hydraulic gradient, j_c, the critical size $1/d_c$ may be determined from Fig. 1. Under this gradient, particles to the left of $1/d_c$ are unsafe. The pore size of the filter material should be selected to the right of $1/d_c$, so that the aggregates of the clay would have a factor of safety, $F > 1$. Pore size may be used as a design criterion by taking into account the grain size, shape, and porosity of the filter material.

It may be noted that the lines (a) and (b) in Fig. 1 would tend to curve upward, as σ_t increases with decreasing stable aggregates size (line (c)). This occurs because the bond between individual particles is stronger than that between aggregates. The firmer the clay soil, and the higher the tensile strength, the steeper will be the lines shown in Fig. 1, indicating larger resistance to separation, resulting in coarser filter material. It should be pointed out, however, that the present analysis is limited to relatively small pore sizes, say 5–10 mm, because it is questionable whether the compacted state of the clay would be maintained after saturation in the vicinity of larger voids.

DESCRIPTION OF BASE SOILS INVESTIGATED

The soils studied represent typical clays in Israel utilized for the blanketing of reservoirs, for earth dam and canal construction, etc. They are very plastic (w_L = 60–80; I_p = 38–55; w_S = 8.5–11) and exhibit high swelling properties. The soils belong to the CH group (Unified Soil Classification), with 55–65 per cent of the particles smaller than 5 microns. The dominant clay mineral is montmorillonite (smectite). They have free swell of 100–110 per cent.

The clays were placed at dry densities varying from 1.41 to 1.50 grams/cu cm with corresponding moisture contents of 29 to 23 per cent. Under these conditions the hydraulic conductivity of the clay varied between 10^{-8} and 10^{-9} cm/sec.

EXPERIMENTS WITH FILTER MATERIALS

Characteristics of Filter Materials

In Israel, the use of beach sands for filters in large hydraulic structures, usually located inland, is uneconomical because of long hauling distances. Therefore, initial studies were concentrated on the determination of the suitability of crushed aggregates as filter materials in contact with the clay. The aggregates originated from limestone rocks of variable hardness. The quarry waste was not considered suitable, owing to the presence of a large percentage of fines which rendered the material impervious when wet. Two uniformly graded aggregates, fine and medium crushed, were studied. Table I presents typical grain size characteristics of the aggregates.

TABLE I. TYPICAL GRAIN SIZE CHARACTERISTICS OF FILTER MATERIALS

Type of aggregate	Uniformity Coeff. D_{60}/D_{10}	Grain size (mm) Maximum size	D_{85}	D_{50}	D_{15}
Fine crushed stone	2.5	10	8.5	4	2.2
Medium crushed stone	2.5	20	10	7	4.0

Testing Programme, Experimental Set-Up, and Results

The study was carried out in two stages and consisted of seepage tests on compacted clay, 2.5 cm thick, placed in

FIG. 2. Photo showing clay, after free swelling, in contact with coarse filter material.

contact with the crushed aggregate within transparent permeameters. In the first stage the clay was completely confined in the permeameters, simulating a condition in which the clay was not allowed to swell under a relatively large surcharge. The second stage consisted of a detailed testing of the same system, but under more severe conditions, namely after the clay had been allowed to swell freely while in contact only with the coarser of the two materials (Fig. 2). In both series the maximum average gradients reached 50. After two months of observation none of the experimental combinations showed failure, either partial or complete. In spite of the high average gradients under which the clay was tested no clay particles were washed out into the filter materials. This behaviour was attributed to the relatively high resistance of the clay to separation by the drag forces, owing to its cohesive strength.

It may be noted that ever since the study was completed (1955) the fine crushed aggregate has been extensively used in various structures in Israel as a filter material in contact with expansive clays. Prototype results for some years now show satisfactory performance of the drainage provisions. On the other hand, some cases of complete failure have been observed when large-size gravel or stones were in contact with the clay, possibly owing to a lack of compaction of the clay mass as well as the large pore size.

RECENT STUDIES OF FLOW-THROUGH LAYERED SYSTEMS

In recent years the problem of flow-through layered systems has been investigated in Israel from various viewpoints, both theoretical and experimental, using laboratory and field models. The results of these investigations also shed light on the factors involved in filter requirements for clay soils. Kisch (1959) has shown that when a clay blanket is placed on a pervious soil and subjected to a downward flow of water, unsaturated flow may take place, resulting in a negative pore pressure head (suction), η, at the interface between the two materials. By models of impervious soils placed on sands varying in coarseness, he showed that the suction decreased with the increase of the size of the pervious material. Globinsky (1964) verified these results and extended the study to models of clay supported by a crushed gravel with a maximum size of 32 mm.

Zaslavsky (1962) defined theoretically the conditions for saturated and unsaturated flow in layered systems. He pointed out that, in order for saturated flow to occur, relatively high heads are required to operate on the clay blanket. He also showed how η may be calculated.

It may be stated, thus, that in cases where unsaturated flow occurs the effective pressure in the clay at the interface between the two materials is increased as follows:

$$\sigma' = \sigma + \beta u = \sigma + \beta\eta\gamma_w, \qquad (2)$$

where β is a numerical factor equal to or less than unity (Jennings, 1961). Therefore, in order to separate particles of the clay from the interface during unsaturated flow with high suction values, extremely large drag forces are required and the danger of clogging of the filter material is relatively low. A direct application of these concepts to engineering practice may be in the field of drainage for highways and runways. The flow that takes place under the pavement or the shoulders is usually unsaturated, because of the relatively low heads operating and their short duration. Hence, relatively large gravel may be used in drainage systems for these types of structure.

In certain hydraulic structures, however, it is conceivable that saturated flow would occur. In a study of clay blanketing Aisenstein, *et al.* (1961) have shown that owing to swelling of the top portion of the blanket non-uniform distribution of hydraulic conductivity was obtained. The result was a non-uniform distribution of gradients, with actual exit gradients much higher than the average. In this case the danger of piping in the clay is great and a careful design of the filter is required.

It should be pointed out in this context that even a small overburden decreases swelling in the top layer of the clay, thus lowering its hydraulic conductivity which results in a

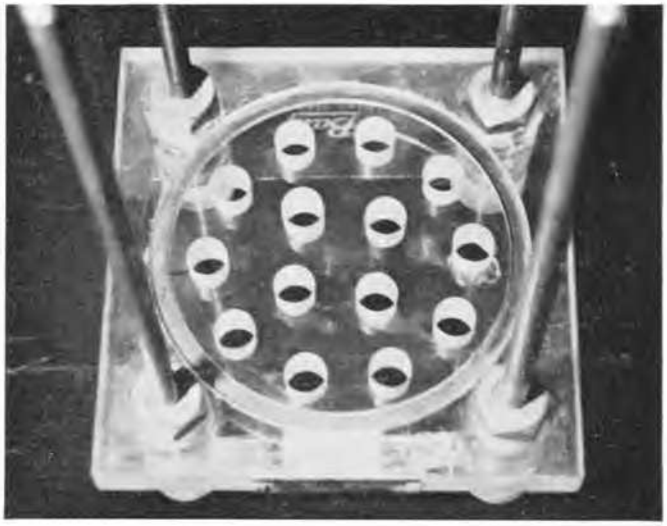

FIG. 3. Perforated base with 15-mm holes used for model studies of piping in compacted clay.

FIG. 4. Photo showing over-all set-up used for model studies of piping in compacted clay.

TABLE II. SUMMARY OF SEEPAGE MEASUREMENTS IN THE PERMEAMETERS CLOSE TO FAILURE BY PIPING

Test no.	Diameter of holes D (cm)	D^2 (cm²)	Number of holes, n	Total discharge measured, q_t, prior to failure (cu.cm./sec)	Critical discharge, $q_{cr} = q_t/n$ (cu.cm./sec)	Measured-average critical gradient, i_c	Calculated critical gradient, j_c*
			Surcharge = 0 kg/sq.cm.; Assumed $K = 10^{-6}$ cm/sec				
1	0.2	0.04	250	No failure at	about	100	
2	0.5	0.25	100	1.03×10^{-2}	0.103×10^{-3}	60	262
3	1.5	2.25	14	1.30×10^{-2}	0.930×10^{-3}	20	222
4	3.0	9.00	4	1.42×10^{-2}	3.56×10^{-3}	10	252
			Surcharge = 0.1 kg/sq.cm.; Assumed $K = 5 \times 10^{-7}$ cm/sec				
5	0.2	0.04	250	No failure at	about	1000	
6	0.5	0.25	100	3.0×10^{-2}	0.30×10^{-3}	935	1530
7	1.5	2.25	14	3.3×10^{-2}	2.36×10^{-3}	686	1340
8	3.0	9.00	4	4.1×10^{-2}	10.25×10^{-3}	555	1456

*The critical exit gradient causing failure was computed from: $j_c = 2q_{cr}/\pi D^2 K$ (Zaslavsky and Kassiff, 1965)

more evenly distributed gradient and less dangerous conditions at the exit.

MODEL STUDIES OF PIPING IN CLAY

Experimental Set-Up and Procedure

The experiments included model testing of a clay layer, 3.0 cm thick, compacted to a predetermined density within lucite permeameters. The layer was supported by various perforated lucite bases, with circular holes, varying in size from a maximum diameter of 30 mm to a minimum of 2 mm. Each base has uniform size holes. Fig. 3 shows one of the perforated bases, with 15-mm holes. The clay layer was saturated first and allowed to swell under surcharges varying from 0 to 0.2 kg/sq.cm, simulating various overburden pressures. The pressures were applied by a spring set-up (Fig. 4). The permeameters were then subjected to a gradual increase of a head of water and continuous measurements of discharge were taken during flow until piping occurred. The gradient was increased in increments of 10 and was kept at the same value for two weeks. The time required for failure varied accordingly from several weeks to nearly eight months, depending on the surcharge.

After failure the permeameters were dismantled and the clay was tested for strength by a laboratory vane. In addition, the strength of the clay was measured in the triaxial shear apparatus, with pore-pressure measurements, by quick shearing after consolidation. From the strength data, the tensile strength, σ_t, was evaluated.

Test Results

Observations of the mechanism of piping of the clay showed that piping started at the perimeter of the holes, forming cavities at this zone. This phenomenon was observed by Davidenkoff (1955) and explained by Zaslavsky and Kassiff (1965). As the gradients over the hole tended to become even, and as the soil at the centre of the hole lost support, the cavitations progressed towards the centre, assuming a dome-like shape. Further increase of hydraulic gradients brought about complete failure of the layer in the form of a tapered hole with a base of the size of the hole. It was also observed that the material washed out from the hole during the process was in the form of visible aggregates rather than in that of individual particles. The size of aggregates washed was dependent on the structure of the clay and increased with the strength of the clay.

The measured average gradients required to cause failure through the holes increased with decreased size of holes. However, an estimate of the actual exit gradients, based on hydraulic considerations of seepage through the dome-shaped

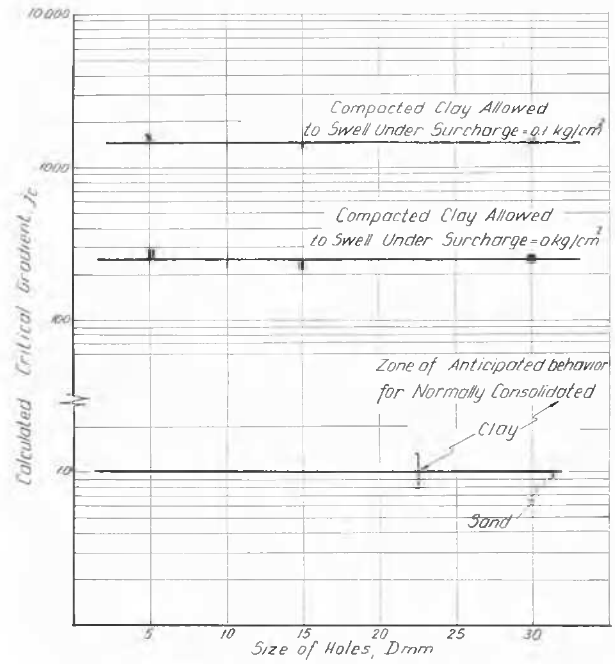

FIG. 5. Lines of critical gradients for various soils.

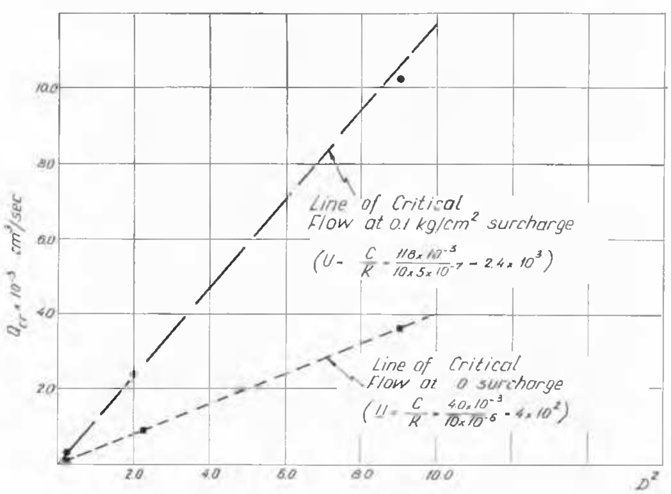

FIG. 6. Critical flow against the square of hole size for determination of U.

TABLE III. PREDICTION OF MAXIMUM SIZE OF FILTER REQUIRED

Surcharge on clay, (kg/sq.cm.)	Actual critical exit gradient, j_c	Mean size of washable aggregate observed, d (cm)	Calculation of d*, assuming $b = 1$: Tensile strength, σ_t (kg/sq.cm.)	U†	d (cm)	Maximum filter size‡ predicted: From d computed (cm)	From d observed (cm)	Actual maximum filter size used§ (without failure) (cm)
0.0	250	0.2	0.12	4×10^2	0.4	2.0	1.0	2.0
0.1	1500	0.5	0.93	2.4×10^3	0.6	3.0	2.5	2.0

*The computation is made from $d = \pi b \sigma_t / 2\gamma_w U$ (Zaslavsky and Kassiff, 1965).
†From Fig. 6.
‡Maximum filter size is based on the assumption that, for uniform crushed stones, the size of pores is approximately 1/5 of the maximum size.
§From Table I.

cavitation (Zaslavsky and Kassiff, 1965), has shown that the exit gradients were a sole function of the clay properties and γ_w, independently of the size of holes. It means, actually, that the critical flow causing failure in the base soil was independent of the size of filter material, provided that washable soil aggregates were several times smaller than the filter pore size.

During this study, failure in the clay layers by piping occurred only under surcharges of 0 and 0.1 kg/sq.cm. No failures were obtained for tests under a surcharge of 0.2 kg/sq.cm., despite use of gradients of up to 1000. Table II summarizes the results obtained from the seepage measurements just prior to failure. The differences in magnitude between the average critical gradients measured and those calculated may be noted from Table II. Fig. 5 presents the experimental results for the clay tested in terms of the critical exit gradients against the size of holes in the base of the permeameters, from which it may be seen that the average calculated critical gradient, j_c, is about 250 for zero surcharge and 1500 for a surcharge of 0.1 kg/sq.cm., assuming hydraulic conductivities of 1×10^{-6} cm/sec and 5×10^{-7} cm/sec, respectively. For comparison, critical exit gradients for sand and for normally consolidated clay are also shown on the figure.

CORRELATION WITH THEORETICAL APPROACH

The results of the experiments with actual filter materials and with the models may be correlated now with the theoretical approach, as presented in Equation 1.

Table III presents values of the maximum grain size of filter materials required to protect the clay under the two surcharges, obtained by using the theoretical formula at failure conditions, i.e. $F = 1.0$. These values are also compared in the table with values of maximum filter size predicted from observation of aggregate size at failure, as well as with the tests with actual filter materials (Table I). The comparison shows that the theoretical approach would have predicted a maximum filter size of the same order as that which was actually tested without failure occurring.

CONCLUSIONS

The experimental results showed that a fat clay may be protected by a fairly coarse filter material, depending on the conditions of the clay, that is, on its strength after swelling. The surcharge on the clay, however small, plays a significant role in protecting it from washing out.

A reasonable correlation was found between a theoretical approach to piping on cohesive soils and experimental results with actual filter materials, indicating that additional work on the subject may lead to the establishment of filter design criteria for compacted clays.

ACKNOWLEDGMENT

The experimental work was carried out in the Soil Mechanics Laboratory of the Technion–Israel Institute of Technology and was sponsored by Swope Foundation.

REFERENCES

AISENSTEIN, B., E. DIAMANT, and I. SAIDOFF (1961). Fat clay as a blanketing material for leaky reservoirs. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2.

BAR-SHANY, M., G. KORLATH, and J. G. ZEITLEN (1957). The use of fat clay in dam construction in Israel. *Proc. Fourth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2.

DAVIDENKOFF, R. (1955). De la composition des filtres dans des barrages en terre. *Proc. Fifth Congress on Large Dams*, Vol. 1, Report 16.

GLOBINSKY, Z. (1964). A model study of suction, moisture and movement variations in clay shoulders of runways. M.Sc. thesis, Technion–Israel Institute of Technology.

JENNINGS, J. E. (1961). A comparison between laboratory prediction and field observations of heave of buildings on desiccated subsoils. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1.

KISCH, M. (1959). The theory of seepage from clay-blanketed reservoirs. *Géotechnique*, Vol. 9.

ZASLAVSKY, D. (1962). Reduction of water losses from small reservoirs and fish ponds. Report on Project No. 1107/60, Technion Research and Development Foundation, Haifa, Israel.

ZASLAVSKY, D., and G. KASSIFF (1965). Formulation of piping mechanism in cohesive soils. Publication N° 40, Faculty of Civil Engineering, Technion-Israel Institute of Technology, Haifa.

ZWECK, H., and R. DAVIDENKOFF (1957). Experiments on uniformly graded filters. *Proc. Fourth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2.