Aspects of Piping Resistance to Seepage in Clayey Soils

Aspects de la Résistance du Piping à la Percolation dans les Sols Argileux

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SYNOPSIS In this paper practical aspects of internal erosion or piping in soils, particularly in embankment dams built of clay soils are examined. The need to control seepage path or to provide filter layers to protect against piping was early recognized. During the past decades various investigators proposed criteria dealing mostly with filters to protect the non cohesive material which are summarized on Table 1. Sound theoretical approach to define interaction between seepage forces, type of material, and erosion of soil particles or clay flocks is either deficient or difficult to apply in practice. It is felt that the mechanism of piping and the existing filter criteria should be reviewed. Ideally the guide lines for protective filters should be based on a sound theoretical basis, be proven by laboratory testing and should be consistent with the available experience. A list of earth dams where piping was observed is given on Table 2 and a list of references on the subject is added.

INTRODUCTION

Internal erosion or piping in soils constitutes a serious problem in geotechnical engineering and especially in embankment dams. The different aspects of interaction between soil caracteristics, seepage forces, the process of eroding soil particles, and washing of soil through filter voids are difficult to assess for engineering purposes. Well known criteria on the length of seepage path under spillways built on sand or silt,were proposed By Bligh (1910) and are given on Table 1, equation 1. The need to prevent piping action by covering the base material with transition or filter layers was also recognized. Terzaghi (1922) and other investigators introduced guide lines based on laboratory testing suggesting protective filters of specific grain sizes to prevent piping. These guide lines are assembled for convenience on Table 1 and are discussed further on. Other investigators made theoretical formulation of piping mechanism in cohesionless as well as in cohesive soils.

FILTER CRITERIA

The present filter criteria is based on laboratory mechanical experimentation of interaction between base and filter material under seepage flow. A summary of criteria is presented on Table 1. Terzaghi postulated equation (5), to prevent washing of fines through the filter and equation (6) to ensure filter permeability. Following Professors Terzaghi's and Arthur Casagrande's guidance, Bertram (1939) and other investigators deduced filter criteria working mostly on non cohesive natural or artificial materials.

Using uniform Ottawa sand and crushed quartz with over 50 percent relative density, Bertram found Terzaghi's equations (5) and (6) quite conservative. During subsequent years, a number of investigators conducted research along Terzaghi's early ideas. The U.S. Army Corps of Engineers (USACE) conducted testing and recommended filter criteria such as equations (11) to (21), see Table 1. In 1955 the USACE recommended equations (17), (18) and (19) as filter criteria to protect clay soils.

It follows that for medium to high plastic clays equation (17) may be discarded and $D_{15}F=0,4$ mm used instead,provided the coefficient of uniformity Cu of the filter is less than 20.

Karpoff (1955) experimentally derived filter criteria given by equations (22) to (26), which are recommended by the U.S. Bureau of Reclamation (USBR) in the "Earth Manual" (1974). Karpoff worked with natural subrounded filter.

Examination of numerous criteria on Table 1 shows that even to protect a none cohesive base material the existing filter criteria are far from being uniform or consistent.

In recent years it has become evident that the above mentioned criteria do not provide sufficient guidance for the design of filters to protect cohesive soils for both intact and fissured conditions. Recently Vaughan (1978) proposed to use what is known as a "perfect filter" which would prevent passage of the finest particles through a sustained crack in a clay core or prevent movement of fines in internally unstable broadly graded coarse soil. Laboratory experiments indicated that additon of non plastic fines, finer than mesh 200, to sand filter would effectively prevent washing through of fine colloidal clay particles or clay flocks. Several British zoned embankments were built with such filters after experience with Balderhead dam where cracking and erosion of clay core was observed, Vaughan (1970).

PIPING THEORIES

At present there seems to be no generally accepted theoretical formulation of piping mechanism in soils. Davidenkoff (1955) using simplified assumptions of exhit gradients and cohesion proposed to define the factor of safety agains piping in cohesive soils. He related the cohesion to the average gradient and the size of filter material, he did not provide sufficient experimental evidence to support it.

Zaslavsky and Kassiff (1965) introduced the following factor of safety against piping, relating resistance to piping exhibited by the tensile strength of clay to the driving forces produced by the seepage flow:

$$F_s = \frac{b\ \sigma_t}{\gamma_w \cdot j \cdot d} \qquad (30)$$

where:

F_s = the factor of safety

b = adimensional coefficient related to the geometry of particles (for a sphere b=1,0)

TABLE I

SUMMARY OF FILTER DESIGN CRITERIA

A - Earlier Ideas and Criteria to Prevent Piping or Heave by Observing Structures Built on Soil Foundation

AUTHOR	CRITERIA DEVELOPED		REMARKS
Sterns (1) (1900)	Ideas to provide filter protection to prevent washing out of fines by seepage		(1) Trans. ASCE, Vol. 48 P. 267.
Bligh (1910)	$C_c = \frac{L}{hcr}$ C_c = creep ratio L = percolation path hcr = maximum permissible head i = hydraulic gradient	(1)	Recommended C_c Values: Type of material — C_c — i - Silt & sand (slightly comp.) — 18 — 0,06 - Fine micaceous, sand — 15 — 0,07 - Coarse sand — 12 — 0,08 - Boulders, gravel, sand mixtures — 5-9 — 0,2 to 0,11
Lane (1935)	$C_w = \frac{\frac{1}{3} B + t}{hcr}$ C_w = weighted creep ratio B = length of percolation in horizontal direction t = length of percolation in vertical direction i = hydraulic gradient	(2)	Recommended C_w Values: Type of material — C_w — i Very fine sand or silt — 8,5 — 0,12 Fine sand — 7,0 — 0,14 Medium sand — 6,0 — 0,17 Coarse sand — 5,0 — 0,20 Gravel, fine — 4,0 — 0,25 Medium, gravel — 3,5 — 0,285 Coarse gravel — 3,0 — 0,33 Boulders, stone, gravel — 2,5 — 0,40
Harza (1935)	$i_f = \frac{h}{L} (I - P) (S - 1)$ i_f = flotation gradient h = difference in head L = lenght of path P = porosity S = specific gravity	(3)	For S = 2,65 Porosity (P) — Critical i_f 0,30 — 1,15 0,35 — 1,07 0,40 — 0,99 0,50 — 0,825
Creager, Justin Hinds (1945)	$\frac{h}{L} > 8$ or 10 h = difference in head L = length of path	(3A)	for highly pervious foundations, without cutoff provisions or filter protection
Cedergren (1973)	$G_s = \frac{\sigma_v}{u}$ G_s = factor of safety with respect to "blowup" or "bulk heave" σ_v = the total vertical stress at any point u = corresponding pore pressure	(4)	if weighted filter is provided, $G_s \geq 1,5$

B - Filter Design Criteria Based on Laboration Testing

AUTHOR	BASE MATERIAL (B)	FILTER MATERIAL (F)	CRITERIA DEVELOPED		REMARKS
Terzaghi (1922)	Criteria probably based on experience and reasoning		$\frac{D_{15} F}{D_{85} B} \leq 4$	(5)	Subscripts 15 and 85 refer to the percentage finer by weight than grain size D. F and B indicate Filter and Base material respectively
			$\frac{D_{15} F}{D_{15} B} \geq 4$	(6)	$C_u = \frac{D_{60}}{D_{10}}$ = (coefficient of uniformity)

Table I (Continued)

SUMMARY OF FILTER DESIGN CRITERIA

B - Filter Design Criteria Based on Laboration Testing

AUTHOR	BASE MATERIAL (B)	FILTER MATERIAL (F)	CRITERIA DEVELOPED		REMARKS
Bertram (1939)	Silt, fine sand (quartz, Ottawa Sand)	Uniform quartz & Ottawa Sand	$\frac{D_{15}F}{D_{85}B} \leq 6$	(7)	
			$\frac{D_{15}F}{D_{15}B} \leq 9$	(8)	
Newton & Hurley (1940)	Well graded gravely sand	Natural bank gravels, fairly uniform fines screened out	$\frac{D_{15}F}{D_{15}B} \leq 32$	(9)	- do not agree with Terzaghi's and Bertram's criteria.
			$\frac{D_{15}F}{D_{50}B} \leq 15$	(10)	
U.S. Army Corps of Engineers Waterways Experiment Station (USACE - WES) (1941/42/48/53)	Random material all types, fine to coarse uniform sand	Random type natural pit-run gravels	$\frac{D_{15}F}{D_{15}B} \geq 4$	(11)	- gradation of filters showld be aproximately parallel to base. Filter should be well graded
			$\frac{D_{15}F}{D_{15}B} \leq 20$	(12)	- To avoid movement of filter into drain pipe perforations or joints see equations (20) and (21)
			$\frac{D_{50}F}{D_{50}B} \leq 25$	(13)	
			$\frac{D_{15}F}{D_{85}B} \leq 5$	(14)	
			$\frac{D_{15}F}{D_{85}B} < 6$ (15); CuB < 1,5		
			$\frac{D_{15}F}{D_{15}B} < 40$ (16); CuB < 4,0		
1955	cohesive soils (all types)	concrete sand, coarse aggregate recommended	$\frac{D_{15}F}{D_{15}B} > 5$	(17)	For medium to high plastic clays discard equation (17) and use, $D_{15}F = 0,4$ mm, provided
			$\frac{D_{50}F}{D_{50}B} \leq 25$	(18)	$CuF \leq 20,0$
			$\frac{D_{15}F}{D_{85}B} \leq 5$	(19)	
			$\frac{D_{85}F}{\text{slot width}} \geq 1,2$	(20)	
			$\frac{D_{85}F}{\text{hole diam.}} > 1,0$	(21)	

Table I (Continued)

SUMMARY OF FILTER DESIGN CRITERIA

B - Filter Design Criteria Based on Laboratory Testing

AUTHOR	BASE MATERIAL (B)	FILTER MATERIAL (F)	CRITERIA DEVELOPED		REMARKS
USBR 1947/55/74	Artificial Blended materials of various ranges including uniform material	Artificial uniform filters	$5 < \frac{D_{50} F}{D_{50} B} < 10$ $12 < \frac{D_{50} F}{D_{50} B} < 58$ $12 < \frac{D_{15} F}{D_{15} B} < 40$ $9 < \frac{D_{50} F}{D_{50} B} < 30$ $6 < \frac{D_{15} F}{D_{15} B} < 18$ $\frac{D_{85} F}{\text{max. opening of pipe drain}} \geq 2$	(22) (23) (24) (25) (26) (27)	Other requeriments: 1. 100% passing 3 in. sieve 2. percent passing sieve # 200 < 5% 3. finer section of base and filter material should be approximately parallel 4. use eq. 22 for natural subrounded uniform material 5. for natural graded filters use eq. 23 and 24 6. for crushed rock filters use eq. 25 and 26 7. To avoid movement of filter into drain pipe opening use equation (27)
Sherard et al (1963)			$\frac{D_{15} F}{D_{15} B} \geq 5$ $\frac{D_{15} F}{D_{85} B} \leq 5$	(28) (29)	Other requirements: 1. 100% passing 3 inch sieve 2. percent passing sieve # 200 < 5% 3. grain curves approximately parellel 4. use base material passing 1 in. sieve
Vaughan (1978)	cohesive soils	non plastic silt, sand	"perfect filter" retaining clay in suspension or clay flocks		Testing recommended to establish criteria

σ_t = tensile strength of soil
γ_w = specific weight of water
j = exit gradient related to the geometry of failure
d = average particle size

It follows from formula (30) that the gradient j generally exceeds the average gradient i, and that the filter on one side protects the base material but, on the other side, increases the outlet gradient and therefore increases the chances of starting the erosional process.

Ranganathan and Zacharias (1968) came to the conclusion that the resistance to piping in clays increases with the increase in shearing and tensile strength of soils. Tests performed by these investigators indicated to a sudden increase in the coefficient of permeability as piping sets in. Folque (1977) confirmed this fenomena in his tests and suggests that this sudden increase in permeability of base material be taken as indication of piping failure. Wolski et al (1970) studied filter protection for core material in zoned embankment on the basis of reological behavior of extrusion of plastic core material into the adjacent filter layer. He found that actual maximum gradients in the core may exceed by as much as 2.5 to 60 times the average value estimated analytically.

Nedriga et al (1974) recommends that conservative design practice would be to assume a hypothetical transverse cracking through the clay core and to determine then the seepage velocities through the sustained crack. He found that the critical or erosive velocity in such cracks would be 5 to 10 cm/s and 39 to 65 cm/s for silty and silty gravel respectively.

Terzaghi (1943), Cedergren (1973) made theorization and testing on the seepage effect in upward direction and bulk heave. Terzaghi's concept of critical hydraulic gradient is used to express the safety of the mass of soil submitted to the seepage force, the latter being the product of the critical gradient multiplied by the weight of water. When the seepage force exceeds the weight of soil mass, heaving action is initiated. Cedergren's equation 4 an Table 1 gives the equilibrium condition between the total vertical stress at any point and the corresponding pore pressure. A surcharge of granular material can effectively, prevent the bulk heave.

Kalin's investigations showed that simplifying conditions, such as assuming homogeneity of the mass of soil through which seepage takes place instead of layered non homogeneous soil in seepage flow computations may be significantly on the unsafe side.

Kjellman (1964) and Silveira (1965) offer a different theoretical approach to the problem of washing of fines through the filter. Kjellman argues that the conventional filter criteria do not take into account the thickness of the filter layer and that the base material should countain enough coarse grains so that they block all entrances to the pore channels in the adjacent filter of a certain required thickness. Silveira proposed a complex analyses to determine filter gradation based on "void size distribution curve" instead of grain size curve of the base and the filter material. He then uses the probabilistic analyses to determine possibility of washing of base material particles through filter voids to arrive at the required filter gradation.

TABLE 2

A LIST OF DAMS WHERE PIPING HAS DEVELOPED

Nº	YEAR		NAME OF THE DAM	TYPE OF DAM	HEIGHT m	OCCURENCE OR DEFECT	CAUSE
	CONSTRUCTION	OCCURENCE					
1	-	1890	Gunninson, Calif., USA	Homogeneous dam	6,60	Piping through dam	
2	1895	1895	Angels, USA	Homogeneous dam	17,40	Piping through dam	
3	-	1896	Bradford, England	Homogeneous dam	29,70	Piping through dam	
4	1899	1899	Lake Francis, Calif.	Homogeneous dam	25,40	Piping through dam	
5	1893	1904	Avalon, USA	Zoned dam	19,40	Piping through dam	
6	1901	1904	Greenlick, USA	Homogeneous dam	20,40	Piping through dam	
7	1907	1909	Blackrock, USA	Zoned dam	23,10	Piping through dam foundation	
8	1905	1910	Jalesburg, USA	Homogeneous dam	19,80	Piping through foundation	
9	1911	1913	Blackfoot, USA	Zoned dam	16,20	Piping through foundation	
10	1912	1914	Horse Creek, Col. USA	Homogeneous dam	18,20	Piping through foundation	
11	1913	1914	Hebron, USA	Homogeneous dam	18,20	Piping through foundation	
12	1913	1915	Lyman, USA	Homogeneous dam	21,50	Piping through foundation	
13	1902	1916	Lake Toxaway, USA	Homogeneous dam	20,50	Piping through dam	
14	1920	1921	Forsyt, USA	Homogeneous dam	21,50	Piping through foundation	
15	1920	1923	Apishapa, Col., USA	Homogeneous dam	37,00	Piping through dam	Cracking due to differential settlement
16	1927	1928	Lake Almanour, USA	Homogeneous dam	42,90	Piping through foundation	
17	1929	1929	Little Field USA	Homogeneous dam	41,30	Piping through dam	
18	1930	1930	Corpus Christi, USA	Homogeneous dam	20,20	Piping through foundation	
19	1903	1932	Desabia Forebay,Cal USA	Homogeneous dam	17,50	Piping through dam	
20	1899	1935	Lake Francis, USA	Homogeneous dam	25,40	Piping through dam	
21	1938	1939	Dry Creek, Mont. USA	Homogeneous dam	15,20	Piping through dam and foundation	
22	1946	1948	Wister, Oklahoma, USA	Homogeneous dam	16,00	Piping through dam	
23	1947	1948	Fred Burr, USA	Homogeneous dam	19,80	Piping through dam	
24	1949	1949	Wister, USA	Homogeneous dam	29,70	Piping through foundation	
25	1949	1950	Stockton, Calif., USA	Homogeneous dam	26,70	Piping through dam	Cracking due to differential Settlements
26	1940	1954	Pampulha, Brazil	Homogeneous dam with concrete slab on upstream face	11,50	Piping through dam (complete failure)	High gradients due to rapture of concrete plate and inadequate internal dranage
27	1899	1957	Mill Creek, USA	Homogeneous dam	22,10	Piping through foundation	
28	1959	1960	Penn Forest, USA	Homogeneous dam	49,50	Piping through dam	
29	1960	1960	Alamo Arroyo, Site 2	Homogeneous dam	22,50	Piping through foundation	
30	1959	1962	Cobb Creek nº 1	Homogeneous dam	24,80	Piping through foundation	
31	1951	1963	Baldwin Hills, USA	Homogeneous dam	86,50	Piping through dam	
32	1962	1963	Little Deer Creek, USA	Homogeneous dam	28,00	Piping through dam	
33	-	1963	Cougar, Oregon, USA	Rockfill dam with clay core	174	Piping through dam	Cracks due to differential settlement
34	1962	1963	Jennings Creek Watershed 3, USA	Homogeneous dam	22,80	Piping through foundation	
35	1960	1964	Jennings Creek Watershed 16, USA	Homogeneous dam	18,2	Piping through foundation	
36	1964	1964	Kedar Nala, India	Homogeneous dam	6,6	Piping through dam	
37	-	1964	Round Butte, Oregon USA	Rockfill dam with impervious core	147	Piping through dam	Transverse cracks due to irregular placemen of rockfill

TABLE 2

Nº	YEAR		NAME OF THE DAM	TYPE OF DAM	HEIGHT m	OCCURENCE OR DEFECT	CAUSE
	CONSTRUCTION	OCCURENCE					
38	1961	1965	Balderhead, England	Rockfill dam with impervious core	52,4	Piping through dam	Poor filter grading and segregation
39	–	1965	Djatiluhur, Indonesia	Rockfill dam with clay core	124	Piping through dam	Horizontal fissures due to core consolidation
40	1964	1965	Hyttejuvet, Norwey	Rockfill dam with impermeable core	100	Piping through core of the dam	Hydraulic fissuring in core, segregation of filter
41	1963	1963	Yard's Creek Upper Reservoir, N. Y., USA	Rockfill dam with impermeable core	26,70	Piping through dam	Cracking in core and filter due to excessive fines in filter
42	1965	1966	Metahina, New Zealand	Rockfill dam with impermeable core	66,80	Piping through dam	Cracking in core and filter due to excessive fines in filter
43	1970	1971	Viddlalsvatn, Norwey	Rockfill dam with impermeable core	76,80	Piping through dam	Cracking in core and filter due to excessive fines in filter
44	1970	1971	Seitevare, Sweden	Rockfill dam	116,90	Piping through foundation	Concentration of high gradients due to discontinuities in foundation permeability
45	1970	1971	Bastusel, Sweden	Rockfill dam with impervious core	44,00	Piping through foundation	Discontinuity in foundation leading to seepage concentration
46	1970	1971	Flagstaff Gully, Tasmania, Australia	Rockfill dam with impervious core	44,00	Piping through dam	Open craks in rock, cracking in filter, erodible clay in core
47	1975	1976	Teton, Idaho, USA	Rockfill dam with impervious core	100	Piping through contact between core and foundation leading to total failure	Erodible material, open joints in rock. Inadequate filter gradation and low permeability
48	1975 - 1977	1978	Cofferdam in Amazon Region, Brazil	Rockfill dike and compacted clay	15	Piping and failure of a section through compacted clay core	High gradients, poor transition and filter leading to failure of a section
49	1970	1973	Tarbela, West Pakistan	Rockfill dam with clay core	147	Piping in upstream clay blanket	Piping of sand, clay through openwork boulder-gravel foundation

CONCLUSION

Piping erosion can be compared with cancer disease in a sense that once initiated it can rapidly develope beyond control. One way to keep out of trouble is to keep the exit gradients conservatively low following Bligh (1910) and Lane (1935).

Deficiency in the existing piping theories and filter criteria, especially in clay soils, is well recognized. Zaslavsky et al (1965); Silva (1973); Mello V.F.B. (1977), 17th Rankine Lecture, Geotecnique, September; Wilson, Marsal (1979) and others called attention to this fact and suggested improvements. Ideally such theory should consider the seepage forces acting on the base material, the resisting forces such as cohesion and tensile strength, and the mechanical blocking of soil particles by filter.

Folque (1977), investigating piping resistance in clays of medium plasticity, presents an example determining analytically the critical gradients which will induce piping. Following Zaslavsky's (1965) and Wolski's (1970) theories, he found the average and maximum critical exhit gradients to be 24 and 120 respectively. He found that there was no piping effect on clay in his laboratory testing even for gradients above 50.

Of the series of filter criteria summarised on Table I USBR equations 22 to 27 appear to be more appropriate for non cohesive soil.

Filter protection criteria for cohesive soils is lacking. There is a tendency to protect clay cores and erodible or dispersive clays with transition filter "perfect filters" see Vaughan (1978), Bello et al (1979). At Guri dam, Venezuela, Kilian de Fries proposed to use filter adding 3 percent of non plastic rock flour to the sand filter in order to retain clay flocks of medium plasticity.

At present disputes often arise between the designer and the contractor as to the filter requirements. Therefore, a review of the theory and the filter criteria appears to be urgent in order to rationalize the design and to reduce the costs, using, whenever possible, available materials and instalations. Table 2 lists 49 dams where piping has developed of which only 3 or 4 have failed. One possible reason for such a small number of failures is that the filter criteria as used in the most cases may have been quite conservative. The other possible explantion may be that a number of low embankments built in haphazard way for agricultural purposes have failed due to piping but were never reported.

REFERENCES

Aitchison, GD, Wood, CC (1965). Some interactions of compaction, permeability and post-construction deflocuation affecting the probability of piping failure in small earth dams. Proc. 6th ICSMFE (2) 442-446,Montreal.

ASTM (1977). Dispersive clays, related piping, and erosion in geotechnical projects.

Bazant, A (1949). Measuring soil deformation caused by the pressure of the seepage. 17th Int. Navig. Congr., Lisbon, 195-198.

Bello, JIB, Shu FALL (1979). Filtros protectores en presas de tierra. Thesis, submitted to Catholic University, Caracas.

Bertram, GE (1940). An experimental investigation of protective filters. Publ. nº 267, Harvard Series.

Bjerrum, L, Nash JK, Kennard, RM, Gibson RE (1972). Hydraulic fracturing in field permeability testing - Geotecnique (22), 2, 319-332.

Bligh, WG (1910). The practical design of irrigation works (2nd Edition), D. Van Nostrand Co.

Casagrande, A (1940). Seepage through dams - Journal New Eng. Water Works Assoc. Vol. 51 June 1937. Reprinted Boston Society of C.E. 1940.

Casagrande, A (1961). Control of seepage through foundations and abutments of dams. Geotecnique 3, 161.

Cedergren, HR (1960). Seepage requirements of filters and pervious bases. Proc. ASCE 86, SM5, 15.

Cedergren, HR (1967). Seepage, drainage and flow nets. New York, John Wiley & Sons.

Cedergren, HR (1973). Seepage control in earth dams. Embankment Dam Engineering, Casagrande Volume.

Charles, JA (1977). Discussion of load transfer and hydraulic fracture in zoned dams, ASCE, Vol. 103, GT6, June.

Creager, WP, Justin, JD (1945). Engineering for Dams, Vol. III. John Wiley and Sons.

Davidenkoff, R (1955). De la composition des barragens em terra. 5th ICOLD, Paris.

Davidson, LW (1978). Hydraulic fracture in embankment dams, USBR, Denver, Colorado, Presented at ASCE annual meeting, Chicago.

Folque, José (1977). Erosão interna em solos coesivos. Filtros de proteção, Journal Geotecnia,Portugal, June-July.

Folque, José (1961). Reologia de solos não saturados.

Hsu, SJC (1963). Resudual clay earth dams constructed by Rio Light 2nd PACSMFE, Recife.

Hsu, SJC (1974). Aspectos de Erosão Interna ou Piping em Solos Argilosos, 6th Braz. CSMFE, Rio de Janeiro.

Independent Panel Review of Teton Dam Failure (1976). Report to USBR & State of Idaho on Failure of Teton Dam Dec..

Infanti, N, Kanji MA (1974). Preliminary considerations of geochemical factors affecting the safety of earth dams 2nd Int. Congr. of Eng. Geology, Rio de Janeiro.

Kalin, M (1977). Hydraulic piping, theoretical and experimental findings. Canadian Geothechnical Journal, Vol. 14 nº 1, February 1977.

Karpoff, KP (1955). The use of laboratory tests to develope protective filters, Proc. ASTM, (55), 1183.

Kassif G, Zaslavsky D, Zeitlen N (1965). Analysis of filter requirements for clays, 6th ICSMFE, Montreal.

Kjaernsli, B, Torblaa (1968). Leakage through horizontal cracks in the core of Hyttejuvet dam, NGI. Publ. nº 80.

Kjellman, W (1964). Unorthodox thoughts on filter criteria, Swedish Geotechnical Institute.

Kovacs et al (1973). Changes in the materials of earth dams and their influence on permeability. Research of Institute for Water Resources development. Publ. nº 7, Budapest.

Kulhawy, FH, Gurtowski, TM (1976). Load transfer and hydraulic fracturing in zoned dams, ASCE. Vol. (102) Paper 12400, Sept.

Lane, EW (1935). Security from under-seepage, Masonry Dams on Earth Foundations transactions ASCE, 1935. Vol. 100.

Leach, RE (1977). Hydraulic fracturing in soils - A Literature Review, Paper S-77-6, USACE,WES, March.

Lehr, H, Stanescu, E (1967). Investigation of safeguard aganinst piping in earth dams - III Asian Region. Conf. on S.M., Haifa.

Lenzberg, H, Nogueira, G (1975). Fracturacion hidraulica em Preso Futalenfu 5th Panam CSMFE, Buenos Aires, (2).

Leonards, GA, Naran, J (1963). Flexibility of clay and cracking of earth dams. Journal ASCE, March.

Leps, TM (1975). Notes in Hydraulic Fracturing in embankment dam core zones. Lecture on Recent Developments in Design, Construction, and Performance of Embankment Dams, Berkley, Cal. June.

Lowe, J, III (1970). Recent development in the design and construction of earth and rockfill dams. 10th ICOLD Congress, Montreal (5), 19.

Marsland, A (1935). Model experiments to study the influence of seepage on the stability of a sheeted excavation in sand. Geotechnique,3, pp. 223-241.

Massarsch, KR (1978). New aspects of soil fracturing in clays. Journal ASCE GT8, (104) Paper 13961, August.

Middlebrooks, TA, Jervis WH (1947). Relief wells for dams and levees, Trans. ASCE,(112), 1321-38.

Nawaz, KS & Nagvi, SA (1970). Foundation treatment for under seepage control at Tarbela Dam Project 10th ICOLD, Montreal.

Nedriga, VP, Maleshev, MP (1974). Method to estimate percolation throught fissured core in high earthrockfill dam. Hydrotechnical Construction - December.

Nobary, ES, Lee KL, Duncan, JM (1973). Hydraulic fracturing in zoned earth and rockfill dams, Report nº TE-73-1.

Peele, TC (1937). The effect of lime and organic matter on the erodibility of Cecil clay: Soil Sci. Amer. Proc. Vol. 2, pp.79-84.

Penman, ADM (1977). Hydraulic fracture specialty session nº 8. 9th ICSMFE, Tokyo.

Peter, P (1970). Computation of the degree of filtration stability 10th - ICOLD, Montreal (2), 191.

Ranganatham, BV, Zacharias, G (1968). Interaction of density, soil type and time on piping resistance of cohesive soils, 3rd Budapest Conf. on Soil Mech., Budapest.

Seed, HB, et al (1976). Hydraulic fracturing and its possible role in the Teton Dam, Failure, Appendix D of Independend Panel Review. On Teton dam Failure.

Sherard, JL(1953). Influence of soil properties and construction methods on the performance of homogeneous earth dams, Technical Memorandum nº 645, January, (Thesis).

Sherard, JL (1959). Discussion on tractive resistance of cohesive soils, Journal of ASCE SMFE.

Sherard, JL, et al (1963). Earth and Earth - Rock Dams. John Wiley and Sons.

Sherard, JL (1971). Study of piping failure and erosion damage from rain in clay dams in Oklahoma and Mississipi (Preliminary Report for SCS US Dept. of Agriculture) July.

Sherard, JL, Decker, RS, Ryker, NL (1972). Piping in earth dams of dispersive clay proc. conf. on the performance of earth and earth supported structures, ASCE, June.

Sherard, JL (1973). Embankment Dams Cracking. Casagrande Volume.

Sherard, JL, et al (1976). Identification and nature of dispersive soils, Jnl. Am. Soc.Civ. Engr. GT4, 286.

Sherard et al (1976). Dispersive clays,related piping, and erosion in Geotecnical Projects. Symposium ASTM, Chicago.

Sherard, JL (1978). Current trends for evaluation of soil properties for the impervious material in central core of the embankment dams. Lecture at ASCE Annual Convention, Chicago, October.

Silva, FP (1973). Considerações sobre filtros de proteção. IPT, Publ. nº 990.

Silveira, A (1965). An Analisys of the problem of washing through in protective filters. Proc. 6th ICSMFE, Montreal (2), 551.

Silveira, A (1966). Considerações sobre distribuição dos vazios em solos granulares. Proc. 3rd Brazilian CSMFE, Belo Horizonte.

Silveira, A and Peixoto Jr, TL (1975). On permeability of granular soils. Proc. 5th Panam. CSMFE, Buenos Aires (2), 161.

Shidhran, A et al (1971). Pore size distribution studies. Proc. ASCE (97), SM5, 771.

Terzaghi, K, Peck, RB (1967). Soil Mechanics in Engineering Practice 2nd Edition, Wiley, New York.

Terzaghi, K (1943). Theoretical Soil Mechanics, Wiley, New York, 510.

Terzaghi, K (1949). First Memorandum Concerning Design and Construction of Vigário Dike, Brazil, September, (not published).

Thanikachalam, V and Sakthivadivel, R (1973). Design of filter thickness based on application of Queneing Theory. Proc. 8th CSMFE, Moscow, (4) 3, 174.

Turnbull, WS, Mansur CI (1961). Investigation of underseepage Mississippi River Levees, Trans. ASCE, (126) part 4, 1429-1539.

USBR (1974). Earth Manual, 2nd Edition, Water Resources Technical Publication (USBR).

USCE, WES (1941). Investigation of filter requiriments for underdrains, Techn. Memo nº 183-1. Vicksburg.

USCE, WES (1953). Filter experiments and design criteria. Technical Memo nº 3-360, Vicksburg, Miss.

Vargas, M et al (1955). A ruptura da Barragem de Pampulha, Publ. 529 IPT, São Paulo.

Vargas, M and Hsu, SJC (1970). The use of vertical core dams in Brazilian Earth Dams, 10th ICOLD, Canada.

Vargas, M (1973). Structurally unstable soils in Southern Brazil, 8th ICSMFE, Moscow.

Vaughan, PR et al (1970). Cracking and erosion of the rolled clay core of Balderhead dam and remedial works adapted for its repair 10th ICOLD, Montreal.

Vaughan, PR (1976). Cracking of embankment dam cores and the design of filters for their protection. Lecture given to Spanish Society of Soil Mech. Madrid.

Vaughan, PR (1978). Design of filters for the protection of cracked dam cores against internal erosion. "Preprint of paper presented at Session 25. ASCE Annual convention, Chicago, October.

Wilson, DSD, Marsal, RS (1979). Current trends in design and construction of embankment dams, prepared for ICOLD International Comission and ASCE Geotechnical Division.

Wolski, W et al (1970). Protection against piping of dams cores of Plusch origin cohesive soils, 10th ICOLD, Montreal.

Zaslavsky, D and Kassiff, G (1965). Theoretical formulation of piping mechanism in cohesive soils, Geotecnique, September.

Zweck, II, Davidenkoff, R (1957). Experiment on uniformly graded filters, Proc. 4th CSMFE, London (2).