CRUSHED ROCK FILTERS AND LEAKAGE CONTROL IN EMBANKMENT DAMS

By

Khor Chai Huat
Consulting Engineers
Angkasa-GHD Engineers Sdn Bhd
No. 8-3, Jalan Ipoh Kecil, 50350 Kuala Lumpur

ABSTRACT

A laboratory simulation of concentrated leak due to hydraulic fracturing and deformation cracking in dam core is performed. The ability of graded filters to seal concentrated leak is assessed. The filter criteria $\frac{D_{15}}{D^*_{85}} < 12$ is applicable for broadly graded impervious soils.

A comparison is made of behaviours of plastic clays verses cohesionless sandy silts when subject to concentrated leak. There are pros and cons for both type of materials for use in impervious section of dam. Laboratory tests show that concentrated leak occurring in both type of soils can be sealed with downstream filter and both materials remain intact even under condition of cracking and hydraulic fracturing. Low plasticity soils are susceptable to hydraulic separation. The ability of graded filters to seal hydraulic separation is sensitive to the coarse limit of the filter grading.

INTRODUCTION

At the present time, laboratory simulation of concentrated leak occurring in dam core and discharging into a downstream filter, uses high water pressure and concentrating the flow through preformed leakage channel in the impervious core specimen, e.g. 'non-erosion test' (Sherard, 1985) and 'pin-hole filter test' (Khor, etal, 1989). In such tests, preformed hole in core specimen was used to model leakage channel and leakage due to cracks or hydraulic fracturing was not induced in the core specimen during the tests. There are still doubts that the filter criteria derived from such tests are reliable for design of protective filter to control and seal concentrated leakage occurring in dam core due to hydraulic fracturing and deformation cracking.

In the practice of earth dam engineering, there are difference in opinion regarding suitability of low cohesion sandy/clayey silts for the construction of impervious core of embankment dams. Such doubt is reflected in cases where clay were hauled from great distances at considerable cost although uniform deposits of cohesionless silty sand or sandy silt were available at dam site.

A laboratory tests which simulate concentrated leak through dam core by inducing hydraulic fracturing in impervious core specimen during the test and the leak discharging into a downstream filter under high pressure gradient were performed to improve understanding of the behaviour of silty material under action of concentrated leak due to deformation cracking and hydraulic fracturing and to assess its suitability as dam core material.

Issues related to the practice and opinions regarding design measures for leakage control in embankment dams are discussed.

DESIGN OF FILTER FOR LEAKAGE CONTROL IN EMBANKMENT DAM

Concentrated leaks occurring in the impervious sections of embankment dams may be caused by: (Sherard, 1973)

(a) deformation cracking from differential settlement,

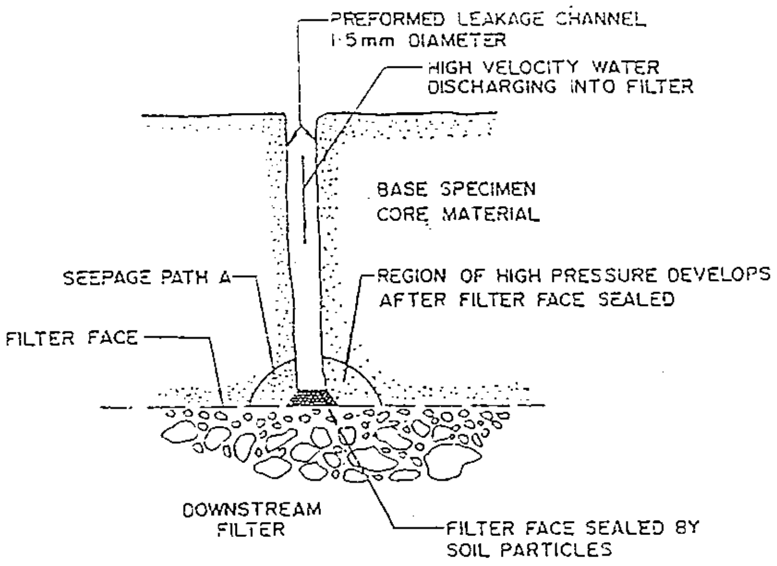

FIGURE 1: LABORATORY TEST SIMULATING CONCENTRATED LEAK THROUGH DAM CORE

(b) preferential seepage along lines of imperfections created during construction; e.g. inadequately compacted layers, fissures or fractures formed by deformation under wheels of construction equipment, and the process of drying and wetting during construction,

(c) separation of contact between earth core-rock foundation surface or earth-concrete interface caused by hydraulic pressure,

(d) hydraulic fracturing, a process of creation and propagation of thin physical separation through the dam core due to hydraulic pressure. Such process is caused by existence of strain or low stress areas in the compacted dam core through which water pressure can act to develop tensile stresses and separation of soil by the wedging action of hydraulic pressure (Sherard, 1985).

When a concentrated leak occurs in a dam core, the materials at the walls of leak can slake and dislodge by the shear stress induced by the eroding fluid. The eroded soils may be broken down into finer particles and segregated. The finer particles can be carried in suspension by the leak toward the downstream filter. If the eroded particles are arrested and filter face sealed, high pressure gradient will develop at the base filter interface around the leakage channel as illustrated in Figure 1. A downstream filter must be stable under action of the eroding fluid with high pressure gradient and capable of controlling the leak to prevent loss of dam core material.

FRACTURING FILTER TEST

Details of the laboratory test set-up are shown in Figure 2. The test procedures are similar to the 'pin-hole filter test' (Khor and etal, 1989) but with modifications of the procedure for the preparation of base specimen as follows:-

(a) placing a filter with surface rises slightly at the centre,

(b) compacting the base soil with a moisture content slightly lower than its optimum, e.g. minus 3% of Proctor's optimum to form a more brittle specimen, and

(c) applying additional compaction along the cylinder wall after the metal pin is withdrawn from the base specimen to cause differential stress.

As the soil is not elastic, differential stress applied during compaction of base specimen induces tensile deformation at the centre of base specimen which causes hydraulic fracture lines to develop radially from the pin-hole when hydraulic stress is applied during the test.

To start the test, the water valve is opened abruptly applying a full pressure of 4 Kg/cm^2 to the top of the specimen. This caused water to flow through the pin-hole and hydraulic fractured lines in the base soil at a pressure gradient of about 1600 to be discharged into the filter.

Water emerged almost instantly through the holes in the end plate. Observation of the flow was made for 10 minutes which included measuring the quantity of the water discharged and examine its turbidity. Finally the water valve was shut-off and the apparatus dismantled and the test specimen was examined for signs of erosion.

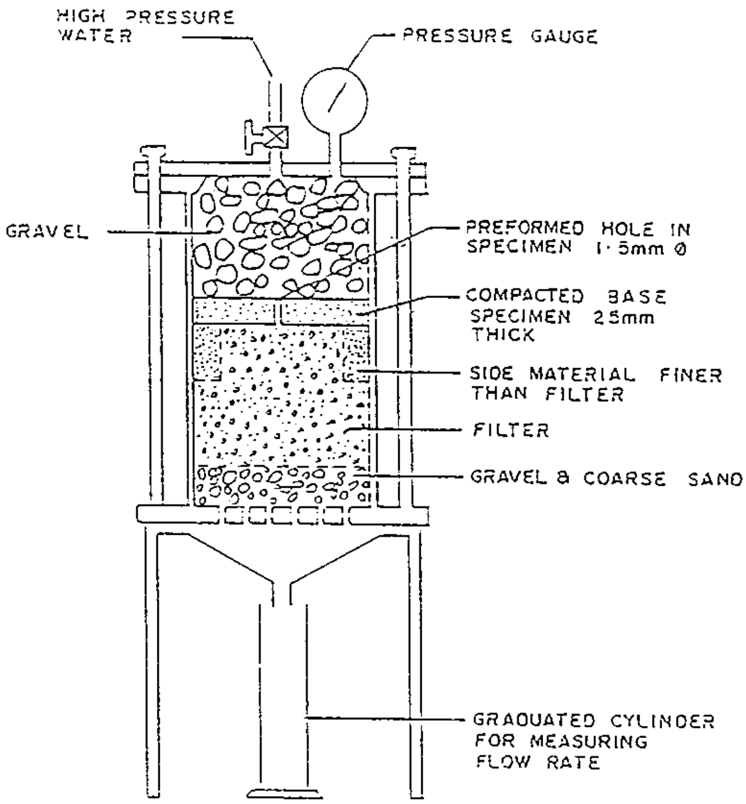

FIGURE 2: FILTER TEST DETAILS (SCHEMATIC)

For each base soil, a series of tests was carried out using fabricated filters with gradually decreasing coarseness as shown in Figure 3, finding for each the 'filter boundary' D_{15b}. For filters finer than this boundary, the tests were successful with initial discharge of faint colour of base soil which eventually become clear with no visible sign of erosion of the base specimen. For tests coarser than D_{15b}, the tests were unsuccessful with discharge of dirty water containing base soil particles.

At the end of the test when the apparatus was dismantled for examination, two to four fractured lined radial from the pin hole about 3 cm in length could be observed. It is believed that tensile deformation caused by differential stress applied during compaction might have caused fracturing of the base specimen although it was not visible in most cases. When high water pressure was applied the fractured surfaces were cracked open wider and extend longer in length causing new fractures which were not in existence before thus hydraulic fracturing was induced in the base specimen during the test.

In the tests with successful filters, the initial discharged water shows faint colour of base soil particles. The flow rate is in the order 500 to 800 ml/min. The discharged water becomes clearer with time and eventually become clear during the test. A possible explanation for these observations is that the fractured surface left with loose soil particles which are readily carried in suspension by the eroding fluid. The clay aggregates breakdown into smaller sized flocs during the process of passing through the filter voids channel. It is believed that the smaller sized flocs below 15 micrometre cannot be retained in the filter initially. The coarser sized soil particles in the order of 30 to 60 micrometer are retained in the voids of filter interface with the base soil. As more soil particles are arrested at the filter face, the leak is eventually sealed and the water discharged become clear indicating that the erosion of base soil has ceased.

For tests with unsuccessful filters slightly coarser than the filter boundary D_{15b}, an initial discharge of dirty water containing base particles were observed. It become progressively clearer with time and usually become clear with 5 minutes. This indicates that erosion of base soil has occurred, but eventually the leak was sealed.

For tests with unsuccessful filters much coarser then D_{15b}, the flow rate increased and the discharged of coloured water become dirtier with time. Observation of base specimen after the test shows sign of erosion of base soil at the wall of fractures.

BASE SOIL AND CRUSHED ROCK PROPERTIES

Nine base soils of sandy (and gravely) clays and silts ranging from non-plastic silt to plastic clays were tested. Figure 4 shows the particle size gradings of the base soils which consist of fine fractions with

40% to 85% passing the 75 micron sieve. All soils tested are tropical residual soils. (Townsand, 1985) Figure 7 shows the graph of Atterberg Limit and Liquid Limit of the base soils. Soils S3, S4, S7 and S8 are actual materials used for the impervious core of Sg. Malut Dam. Figure 5 shows a cross-section of the dam, which is a zoned earth and rockfill embankment dam of 45 m high. The filter zone is constructed of processed crushed rock of granite. At the time of design, very little published data were available on the design of crushed rock filters for tropical residual soils.

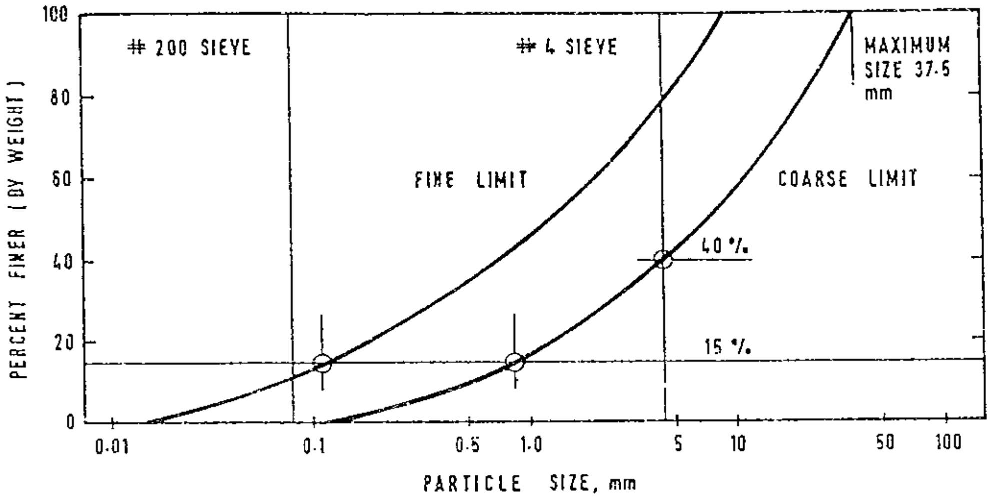

FIGURE 3: COARSE AND FINE LIMITS OF GRADATIONS OF CRUSHED ROCK FILTERS USED IN TEST

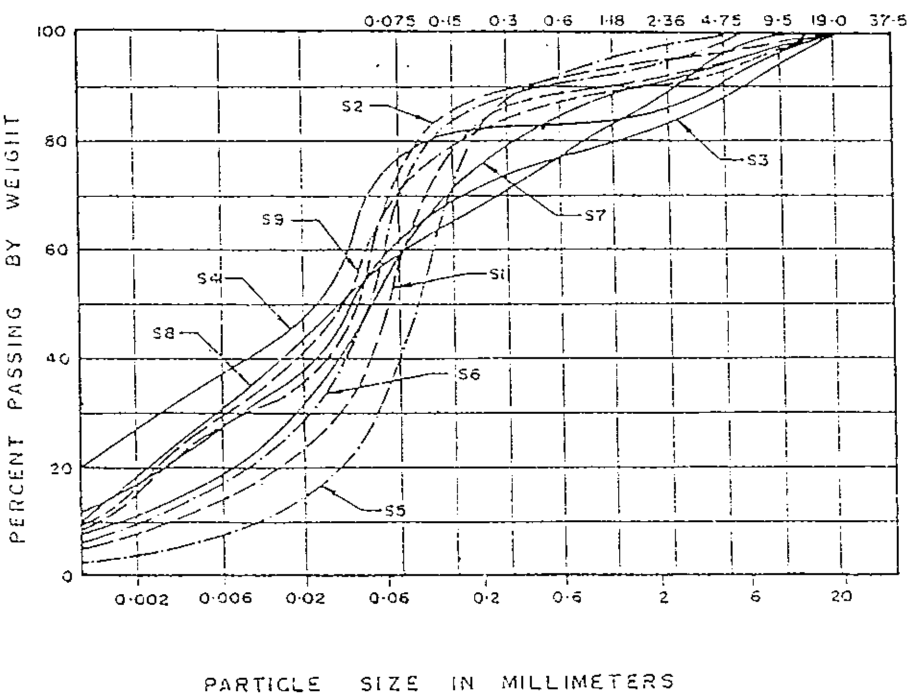

FIGURE 4: GRADINGS OF BASE SOILS

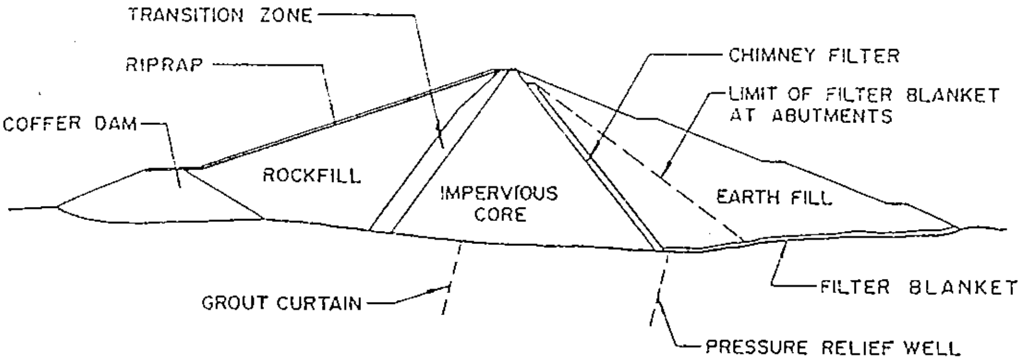

FIGURE 5: CROSS-SECTION OF SG. MALUT DAM

TEST RESULTS AND ANALYSIS

1. Table 1 shows the results of the filter boundary D_{15b} for the sandy impervious soils tested. It was observed that base soils with the same order of percentage passing the 75 microns sieve but with different grading of the sand and gravel fraction have the same order of filter boundary D_{15b}. The fine fraction dominates the test results.

   The conditions of the test (e.g. seepage velocity, pressure and hydraulic gradient) are so severe that all base soils tested are erodible. The soil particles or aggregates will be dislodged from the walls of the fractures. These eroded particles carried in suspension in the high velocity water were broken down into finer particles during the process of entering and passing through the filter. The fine silts and clay sized particles in the range 15 to 30 micron, tend to wash through the filter voids at the beginning of leakage. If the filter size is sufficiently fine, the medium to coarse silt-sized particles in the range 30 to 60 microns will be trapped in the filter voids and eventually sealed the filter face.

TABLE 1: SUMMARY OF BASE SOIL PROPERTIES AND FILTER TEST RESULTS

(1) Base. Soil No.	Base Soil Properties						Filter		
	(2) LL %	(3) PI %	(4) d_{85} (mm)	(5) d_{50} (mm)	(6) % Passing 0.075 mm	(7) d^*_{85} (mm)	(8) C_u	(9) D_{15b} (mm)	(10) $\frac{D_{15b}}{d_{85}}$
S1	30.4	8.8	0.24	0.058	58.4	0.062	19.2	0.79	12.7
S2	40.2	13.8	0.13	0.042	74.7	0.061	15.1	0.76	12.4
S3	40.5	14.6	2.91	0.047	59.8	0.052	13.5	0.85	16.4
S4	55.5	24.5	1.39	0.026	76.6	0.054	18.6	0.67	12.4
S5	19.4	0	0.24	0.092	41.1	0.063	14.4	0.77	12.2
S6	27.0	5.4	0.12	0.039	72.5	0.059	13.2	0.78	13.2
S7	36.5	13.0	0.58	0.05	59.1	0.054	17.2	0.70	12.9
S8	46.0	17.0	1.23	0.036	59.4	0.039	15.4	0.65	16.6
S9	43.4	16.9	0.27	0.035	71.6	0.055	12.5	0.67	12.1

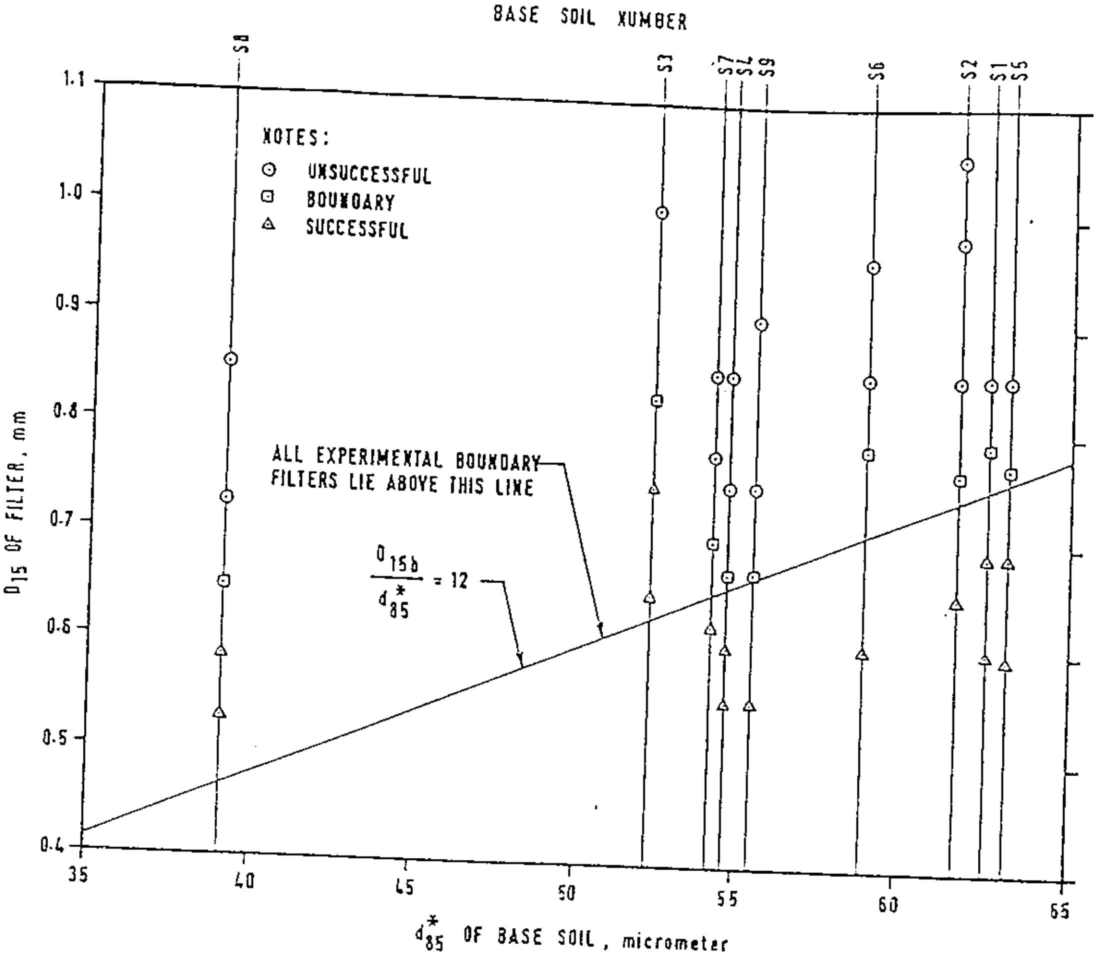

FIGURE 6: SUMMARY OF TEST RESULTS FOR WELL GRADED FILTERS

The sand-size particles in the soil matrix if eroded may be segregated and left behind in the leakage channel and may not contribute to the sealing of the filter. In order to control any base soils from erosion and piping, the fine fraction must be prevented from movement at the base filter interface.

It has been shown in the 'pin-hole filter test' that the parameter d_{85} size of the base soil passing the 75 micron sieve, is an appropriate measure of the base size for the purpose of determining the filter criteria for the sandy impervious soils. The results of 'Fracturing Filter Test' described above further support the deduction made previously.

2. Columns 9 and 10 of Table 1 show the filter boundary D_{15b} and the ratio respectively derived from the 'Fracturing Filter Test'. Comparing the results with that obtained from the 'Pin-hole Filter Test' it is observed that the boundary filter derived from the later test is finer. This is because the test condition of the 'Fracturing Filter Test' is more severe in that wider area of the base soil is subject to erosion which means a higher probability of failure as compared with the pin-hole test. As shown in Figure 6, all the values of D_{15b} plotted on the graph of D_{15b} verses d^*_{85} lie above the line described by the relationship $\frac{D_{15b}}{D_{85}} < 12$ derived.

This shows that the filter criteria, i.e. $\frac{D_{15b}}{D^*_{85}} < 12$ derived from the 'pin-hole filter test' is valied for design of downstream filter to protect the dam core against piping.

3. In tests with low plasticity soils (e.g. soil No. 5 and 6) hydraulic fracturing is induced more readily during the test compare with the more plastic soils. Low plasticity soils are less deformable especially at lower moisture content. Tensile strain caused by differential stress applied during compaction might have induced tensile cracks in the soil specimen. The fractures were extended wider under action of hydraulic stress when high water pressure is applied during the test. The fractures occurring in low plasticity soils tend to be filled with mud for the successful tests.

As low plasticity soils have low unconfined compressive strength, the soil particles at walls of fractures tends to slake, soften and the walls collapse to fill up the fractures with mud.

In tests with more plastic soils (e.g. soil No. 3 and 4) hydraulic fractures is induced only when compacted with moisture content about 5% below O.M.C. The fractures tend to stay opens due to its higher unconfined compressive strength which cause arching over the cracks to keep them open.

4. It was observed that hydraulic fracturing did not occur for soil specimens compacted at moisture content higher than optimum. This may be due to the fact that the base soils compacted at higher moisture content are more deformable which allow stress redistribution when differential stress was applied during compaction. Consequently no or very low tensile strain was induced to enable hydraulic fracturing to develop.

5. The test results show that all the soils including the low plastic soils tested remain intact even under cracked condition caused by deformation cracking and hydraulic fracturing so long as the leak is discharging into a downstream filter fine enough to arrest the particles eroded. The test provides a conservative assessment of the ability of filter to seal concentrated leak.

6. Leaks in sandy silt is sealed more readily compared with the clayey soils. The boundary filter D_{15b} required for the sandy silt (Soil No. 2 and 6) is coarser compared with that for the sandy clay (Soil No. 7 and 8). The sandy silts contain a higher percentage of silt sized particle in range of 30 to 60 microns which if eroded can be trapped more readily in the filter voids. On the other hand, the sandy clays which contain higher percentage of fine particles below 30 microns, which if eroded are more difficult to be arrested by the filter voids. The test results show that filter size D_{15b} is governed by the size of d^*_{85} of the base soil.

7. For tests with soil samples prepared without applying differential stress during compaction, no fracturing was observed. It was deduced that under the conditions of the test, in order that hydraulic fracturing can develop in the base specimen, tensile strain must be induced prior to application of the water pressure. Under the conditions of the test, hydraulic fracturing is initiated by the presence of discontinuity in the base soil formed by pin-hole and the tensile strain around the pin-hole caused by differential stress applied during compaction of the base specimen.

8. Column 3 of Table 1 shows the plasticity index of base soils. There is no correlation between the filter boundary D_{15b} and the Plasticity Index of soils as shown in Figure 7. Plasticity Index of the soils have no influence on the filter criteria.

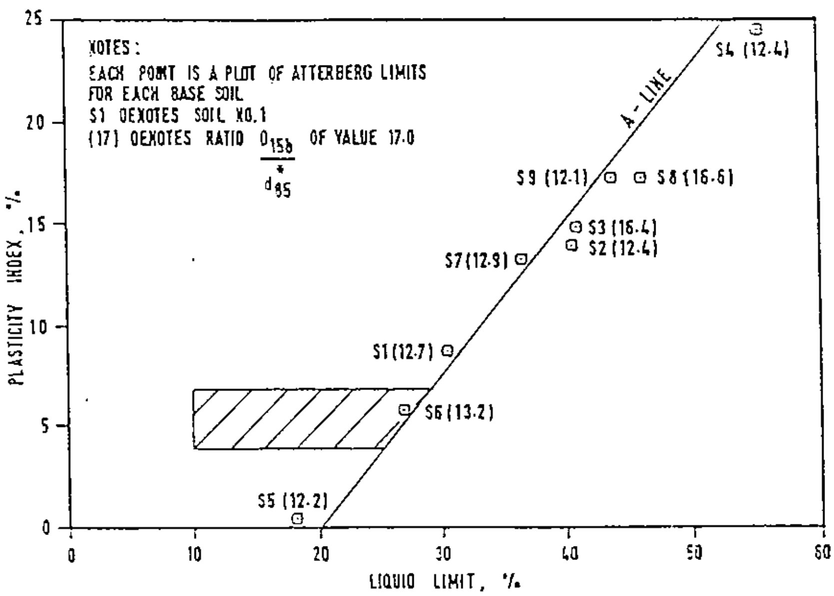

FIGURE 7: PLOT SHOWING NO CORRELATION BETWEEN ATTERBERG LIMIT AND FILTER CRITERIA

Base Soil No.	Base Soil d^*_{85} (mm)	Filter D_{15b} (mm)	Filter C_u	$\frac{D_{15b}}{d^*_{85}}$
S3	0.052	0.63	10.5	12.1
S4	0.054	0.67	11.2	12.4
S6	0.059	0.73	8.5	12.5
S8	0.039	0.51	12.5	13.3

TABLE 2: SUMMARY OF TEST RESULTS ON LEAKAGE DUE TO HYDRAULIC SEPARATION

9. In each series of tests performed on each soil, the extent of fractures varied in each test. This could be due to variations in the compositions, densities, water content or any combination of the three. (Jaworski etal, 1981). However, despite the variation in the extent of fracturing in the tests for each base soil, the test results i.e. filter boundary D_{15b} converges to a consistent minimum value when a sufficient number of tests were performed for each soil. The test result is reproducible under the condition of the test.

TEST ON HYDRAULIC SEPARATION

Tests were carried out to evaluate the criteria of crushed rock filters required to seal concentrated leak at boundary between impervious soils and dissimilar materials such as surface of concrete structure or rock foundation. For this purpose, a 1.5 mm diameter pin-hole is performed at the contact surface between soil and cylinder wall to simulate concentrated leak due to hydraulic separation. The same test procedure described earlier was used.

Table 2 shows the test results of filter boundary D_{15b} and coarse limit of filter for the sandy impervious soils tested. The tests show that the maximum size of filter grading has significant influence on the test results. The results also confirm that the filter criteria i.e. $\frac{D_{15b}}{d^*_{85}} < 12$ derived is acceptable criteria provided the coarse limit of filter grading is less than 15 mm.

It is expected that finer filter will be required to seal concentrated leak due to hydraulic separation. Due to less efficient packing of the angular particles in contact with the cylinder wall, the larger filter void channels along the cylinder wall is less effective in arresting the base soil particles eroded. The larger the maximum size of filter grading, the lower is the degree of packing of the particles and the higher is the tendency to segregate.

It was observed that hydraulic separation occurs more readily for low plasticity soils compared with the more plastic soils.

COMPARISON OF IMPERVIOUS SOILS FOR DAM CORE MATERIALS

From the observations of the Laboratory tests described in the earlier sections, the theoretical pros and cons of the silty soils compare with clayey soils for impervious dam core materials may be summaries below:-

Properties	Clayey Soils	Silty Soils
Resistance to erosion.	High plasticity soils have higher resistance to erosion cause by concentrated leak.	Low cohesion silty soils have no or poor resistance to erosion.
Susceptibility to hydraulic fracturing	Clayey soils are more deformable and more able to accommodate deferential stress. Higher tensile strength of clayey soils have better resistance to hydraulic fracturing.	Low tensile strength and less deformable. More susceptible to deformation cracking and hydraulic fracturing.

Properties	Clayey Soils	Silty Soils
Susceptibility to hydraulic separation between soils and adjacent dissimilar materials e.g. concrete surface or rock foundation.	Better adhesion between plastic soils and contact with surface of dissimilar materials. Generally have better resistance to hydraulic separation.	Low plasticity silts have no or low adhesion in contact with surface of dissimilar materials and are more suscepitible to hydraulic separation.
Healing of concentrated leak.	Cracks or fractures when develop can stay open due to higher unconfined compressive strength which cause arching over cracks. Eroded particles consist of fine clay aggregates can break down into fine clay flocs 10 to 15 microns which are more difficult to be arrested by down-stream filters.	Low cohesive strength materials at walls of cracks. tend to swell, soften and collapse. Cracks tend to fill up with mud. Silty soil content higher percentage of silt size particles of 30-60 microns which if eroded can be more readily arrested by filters.
Healing of Cracks develop during construction.	Cracks or fractures are less easily healed and can open again after construction under hydraulic stress or differential settlement.	Low cohesion soil are less likely to cause arching over cracks. Cracks can close up more readily under self weight of fill.
Susceptibility to deformation cracking.	High plasticity clay is more deformable and better able to follow imposed strains from differential settlement.	Low plasticity silt is more brittle and can fracture when subject to differential settlement.

The tough highly plastic clay will resist erosion of the walls of a leak in an open crack better than low plasticity silty soil. However all clays will erode under severe conditions. It is not reliable to depend on the feeble erosion resistance to provide defence against piping due to concentrated leak.

The higher unconfined compressive strength of clay core provides more likelihood that the embankment material can arch around the leakage channel and keep it open. In impervious embankments of cohesionless silty soil the walls of the initially open, water-filled cracks quickly become saturated, soften and tend to squeeze shut.

The high plasticity clays are more able to resist deformation cracking and hydraulic fracturing is considered not important. Concentrated leak due to deformation cracking and hydraulic fracturing can be sealed by effective filters. The primary function of dam core is to be impervious. The prevention of piping should rely on the filter. With increasing confidence in the use of protective filter to defence against piping, the preference for impervious cores of plastic clay may not be valid.

An exception to the general practice of using the least costly impervious materials available is the case of impervious core material directly in contact with hard rock foundations where there is no filter to prevent the erosion.

IMPERVIOUS CORE CONTACT MATERIAL

Hydraulic separation can occur at an interface between soil and an adjacent dissimilar material such as concrete or rock as soon as the water pressure reaches the same magnitude as the normal stress across the interface. Hydraulic separation is resisted by adhesion between the soil and material in contact. It was observed in the tests that hydraulic separation occurs more readily in low plasticity silts compare with plastic clays.

For dams core of fine, highly erodible soils, it is desirable to compact the foundation contact materials at a higher moisture content, say 5% above optimum moisture content. Besides being more deformable to facilitate the squeezing of soils into gaps of irregular rock surface, the soils compacted under high positive pore pressive can prevent formation of hydraulic fracturing as shown by Jaworksi (1985).

There is concern that cracks in dam foundation surface may not be adequately sealed by grouting and surface treatment and that sealed cracks may reopen again under load of dam embankment. There is always a possibility that eroded material from the dam core can be carried into cracks in the foundation rock where there is no filter to prevent erosion of the dam core. For these reasons, it is not suitable to place very erodible fine grained soils (e.g. cohesionless silts or dispersive clays) directly on rock foundation contact.

SUMMARY AND CONCLUSIONS

1. A "fracturing filter test" in which hydraulic fracturing is induced during the test using relatively high water pressure applied over a short length of core material produces results which measure the ability of downstream filter to seal a concentrated leak occurring in dam core.

2. The filter criteria i.e. $\frac{D_{15}}{d^*_{85}} < 12$ derive from the "pin-hole filter test" for crushed rock filters when apply to sandy impervious soils is verified valid under the "fracturing filter test".

3. The ability of graded filter to seal concentrated leak due to hydraulic separation is sensitive to the coarse limit of filter grading. the filter criteria i.e. $\frac{D_{15}}{d^*_{85}} < 12$ is acceptable provided the coarse limit of filter is less than 15mm.

4. Hydraulic fracturing and deformation cracking in low plasticity soils is induced more readily compared with higher plasticity soils.

5. All impervious soils including cohesionless sandy silts tested remain intact even under fractured condition caused by hydraulic fracturing and deformation cracking if the leak is discharging into a downstream filter fine enough to arrest the soil particles eroded.

6. Leaks in low plasticity soils can be sealed more readily compared with fine plastic clays. Fractures in clayey soils tend to stay open whereas in low plasticity soils the fractures tend to close and fill with mud.

7. A comparison of behaviours of plastic clays verse cohesionless sandy silts shows that there are pros and cons for both materials for use in impervious section of dam. Neither materials have clear advantage over the other.

8. Low plasticity soils are susceptible to hydraulic separation and are not suitable for use in impervious core contact material to be placed directly on rock foundation surface where there is no filter to prevent eroded core material from carried by leaks into cracks of rock foundation.

APPENDIX I : REFERENCES

1. Jaworksi, G.W., Duncan J.M. and Seed, H.B., "Laboratory Study of Hydraulic Fracturing", Journal of Geotechnical Engineering Division, ASCE, June 1981, pp. 713-731.

2. Khor, C.H. and Woo, H.K., "Investigation of Crushed Rock Filters for Dam Embankment", Journal of Geotechnical Engineering Division, ASCE, March 1989, pp. 399-412.

3. Kulhawy, F.H. and Gurtowsky, T.M., "Load Transfer and Hydraulic Fracturing in Zoned Dams", Journal, Geotechnical Division, A.S.C.E., September 1976, pp. 963-974, 1976.

4. Sherard, J.L., "Embankment Dam Cracking", Embankment Dam Engineering, John Wiley and Sons. New York, pp. 272-353, 1973.

5. Sherard, J.L., Dunnigan, L.P. (1985). "Filters and Leakage Control in Embankment Dams", proc. ASCE Symposium on Seepage and Leakage from Dams and Impoundments, Denver, CO, May 1985, pp. 1-30.

6. Townsend, F.C., "Geotechnical Characteristics of Residual Soils", Journal of Geotechnical Engineering Division, ASCE, Vol. III, No. 1, 1985.

APPENDIX II : NOTATION

The following Symbols were used in this paper:

C_u	=	Coefficient of uniformity of a filter = $\frac{D_{60}}{D_{10}}$
d_{85}	=	Particle size in base soil for which 85% by weight of particles are smaller (Similarly for d_{50}).
d^*_{85}	=	d_{85} size of base soil recalculated by excluding the fraction retained on the 75 microns sieve.
D_{15}	=	Particle size in filter for which 15% by weight of particles are smaller (similarly for d_{50}, d_{60} and d_{10}).
D_{15b}	=	D_{15} size of filter found to be boundary between successful and unsuccessful tests for any given base soil, using the filter test.
k	=	coefficient of permeability, cm/sec.
LL	=	Atterberg's liquid limit
PI	=	Plasticity Index
%	=	Percentage
O.M.C.	=	Optimum Moisture Content of Standard Proctor.