SEEPAGE FORCES AND CONFINING PRESSURE EFFECTS ON PIPING EROSION

by

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ABSTRACT

An experimental study of piping erosion is presented. Various artificial granular filter and soil combinations are tested in a permeameter under variable confining pressures to determine the critical gradient where soil erodes through the filter.

Previous research concentrated on establishing a grain size ratio criteria, typically D_{15f}/D_{85s} <4, which separates stable from unstable filters. These works often ignored filtration formation phenomena and did not document the influence of variabilities such as confining pressure, filter thickness, and gradient flux.

To adequately control all variables required a new permeameter and careful attention to sample preparation. Artificial glass beads were water pluviated to permit consistent samples. By monitoring head, settlement, confining pressure, amount of eroded soil, and water outflow the onset of piping can be determined.

It is shown that grain size ratio is the most important parameter in piping. A soil/filter system with $D_{15f}/D_{85s} < 8$ will not fail, whereas a $D_{15f}/D_{85s} > 12$ will not retain soil. For $8 < D_{15f}/D_{85s} < 12$, piping will only occur if the critical gradient is reached. The critical gradient is lowered if the head is rapidly increased, as a filtration zone is inhibited from forming. A very thin filter has a similar effect. Stability is slightly inversely related to confining pressure for small grain size ratios.

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CHAPTER 1 INTRODUCTION

Seepage forces exist whenever there is a gradient of head in a permeable unit that allows water movement. The ability to prevent a cohesionless soil from migrating (eroding) under this hydraulic influence is of practical interest in many geotechnical engineering applications. The most significant of these applications has to do with earth dams, the failure of which due to soil erosion can have catastrophic consequences. Despite the established use of earth dams even before civil engineering existed as a practice, soil erosion continues to be a plague, as recently demonstrated by the appearance of sinkholes at the W.A.C. Bennett Dam in British Columbia. Research to understand soil migration due to hydraulic forces has been undertaken since the 1920s, and continues today.

To control the movement of soil particles, filters are used. Granular filters are comprised of cohesionless natural materials coarser grained than the soil to be protected from erosion. By placing the filter material down gradient from the soil base it is hoped that piping will be prevented. The term piping is used here as the free movement of soil base particles through a granular filter resulting in the formation of an open channel in the soil. This definition encompasses the movement of some soil particles, both into and through the filter. Movement of some soil through the filter is not only acceptable but often necessary for the filter to perform as designed. However, the formation of an open channel would allow continuous progressive erosion of the soil, which may lead to failure of the earth structure. Whether erosion will occur or not depends on a balance between stabilizing and erosional forces.

The most important factor controlling erosion is some effective grain size ratio between the filter and the soil needing filter protection. For a filter (whose diameter is referred to as D_f) that is comprised of uniformly sized spheres that are densely packed, it is a simple geometric exercise to determine the interstitial pore size. If the soil is also comprised of uniforly sized spheres of diameter D_s then the maximum diameter of the soil particle that can pass through the filter can be shown to be 0.155 D_f. Thus for uniform spheres, if the grain size ratio $D_f/D_s < 6.5$, then it is impossible for the soil particles to move through the filter openings.

While natural materials may approximate spheres, they always have some size gradation, and some effective diameter must be used to represent the filter and soil grain sizes. Conservatively, the largest filter particle size (i.e. the size by which 100% by weight of the filter particles are smaller than, or D_{100f}) would result in the largest interstitial spaces, while the smallest soil particle size (D_{0s}) is the size most likely to travel through the filter. However, the grain size ratio D_{100f}/D_{0s} ignores such stabilizing phenomena as the formation of filtration zones and bridging. These processes allows small soil particles to be retained by relatively large filter particles. A more realistic grain size ratio to serve as an index whether erosion will occur has been suggested as D_{15f}/D_{85s} (Cedergren, 1977).

The level of confining pressure (σ') may also influence stability against erosion. If a filter is placed in a loose state, the interstitial spaces will be larger than if it was well packed. Under increasing confining pressure the filter particles will tend to consolidate into a denser state. However, confining pressure may also act as a destabilizing phenomenon. Under low stress conditions interparticle friction may cause small soil particles to form arching bridges across interstital voids, decreasing the propensity for erosion. Large confining pressures increase stresses on these bridges, which may overcome the friction, causing particles to dislodge and arches to fail.

There are several other factors which can promote piping erosion. One of the reasons the grain size ratio D_{15f}/D_{85s} is used rather than D_{100f}/D_{0s} is the formation of a filtration zone (Honjo and Veneziano, 1989, Okita and Nishigaki, 1993). As soil migrates into the filter, the coarser fraction of the soil gets lodged in the pore spaces and the smaller fraction forms bridges. These processes will reduce the effective pore size within the filter, allowing smaller particles to become trapped. Eventually the effective pore size will be less than the smallest soil particle (D_{0s}), effectively blocking any further migration. This process is dependent on random particles juxtaposing in a specific geometry, and requires a certain minimum length of the filter to be effective. If the filter is too thin there will not be sufficient distance for the particles to form their interlocking pattern, and piping may occur.

The underlying principle of piping in a granular filter is that seepage forces are sufficient to mobilize the soil particles, but not so large that the inertia of the filter particles is overcome. Recognizing that seepage forces are dependent on the velocity of the water (Kenney et al, 1985) and that, for a given permeability, velocity is a function of gradient (from Darcy's law), the gradient can control the hydraulic forces acting to move the soil. The critical gradient is that gradient which allows piping to develop. A disruptive gradient is where the critical gradient forms by a concentration of seepage forces in a zone that has had the fines washed away. Sowers (1979) states that "Little information is available on disruptive gradients. Generally, they are well above 10...".

This thesis presents an experimental study of the influence of grain size ratio, the level of confining pressure, filter thickness, magnitude of gradient, and the rate of gradient increase on piping erosion in granular filters. The study was designed to ensure consistent and repeatable results. This necessitated careful attention to materials selection and soil/filter placement techniques to ensure full saturation. Narrowly graded glass beads ensure the samples are uniform while water pluviation allows saturated samples to be placed at consistent and repeatable densities. A custom designed permeameter allowed control of both confining pressure and applied hydraulic gradient, so that the influence of these parameters on piping can be determined. By a continuous monitoring of the settlement of the soil filter unit and hydraulic head the onset of piping could be clearly identified.

CHAPTER 2 LITERATURE REVIEW

2.1 GENERAL

Piping erosion can occur in many geotechnical situations. The relatively recent introduction of geosynthetic materials has led to many investigations as to their suitability as soil filters. In traditional piping problems, granular soils have been used for the filter material. The base soil to be retained may vary from clays to gravels. For cohesionless soils, the gradation may range from uniform to well graded and gap graded. For the latter two cases, piping may also occur within the soil (as opposed to between the soil and filter); these soils are referred to as internally unstable or suffosive.

There has been an extensive discussion on piping erosion in the literature. This review will be confined to the assessment of theoretical and experimental work on granular filters. Uniform graded soils are usually used in experiments, although some well graded, gap-graded, and suffosive soils are examined, as they relate to piping in general. The main areas reviewed are those concerned with this thesis: experimental aspects (testing apparatus, material tested, testing procedure) and soil/filter behaviour (onset of piping and effects of grain size ratio, confining pressure, filter thickness, and gradient).

2.2 TESTING APPARATUS

In previous experiments, the permeameter was generally a cylinder into which the soil and filter were placed and water was introduced at one end and alowed to escape from the other. The cylinder was made of lucite or other clear materials to aid observation during the experiment (Bertram, 1940). The size of the permeameter varied widely, and in research using sequential zoned gravel filters tended to be larger (Karpoff, 1955, USBR, 1955). Bertram (1940), who used sands, obtained similar results with permeameters that were 5 and 10 cm in diameter.

Most apparti were orientated with the soil overlying the filter. Bertram (1940) carried out experiments with flow both upwards and downwards and reported orientation had no significant affect on a soils' potential to erode through a filter.

2.3 MATERIAL TESTED

As mentioned in the introduction, most of the research reviewed used material in the silt to fine gravel size range. Composition included natural sands, crushed rock, fly ash, and glass beads (ballotini). For example, Bertram (1940) ran a series of experiments using natural (heterogeneous) sand, then Ottawa sand, and finally crushed quartz. The use of natural sand was abandoned after it was observed that the permeability decreased with time by a factor of five; it was feared that segregation was occurring during sample preparation in the heterogeneous sand. The more uniform Ottawa sand showed constant permeabilities during the tests. Crushed (angular) quartz was used to determine that the grain shape was not a factor (versus the subrounded sands) in potential for erosion.

2.4 TESTING PROCEDURE

This is one aspect of research which is unfortunately poorly documented. Experiments conducted by Schuler (1996) varied widely when a well graded filter was placed homogenously versus in a segregated manner. When described, most researchers placed the soil in a dry or moist state, followed by some method of compaction. Other tests were carried by depositing soil as a slurry. In either case, well graded material are likely to segregate during sample preparation. The use of uniform material can minimize this segregation, as there are no fines to separate out (Bertram, 1940).

Once the soil/filter system was ready, water was allowed to flow through the soil towards the filter. An exception was Kenney et al (1985), who carried out three different procedures. One set of tests was carried out in the traditional manner but with simultaneous tapping on the side of the permeameter. Another set of tests was carried out to investigate the minimum constriction size in the filter. In this case a very large gradient was applied to a filter and the soil was introduced in a fine suspension. The third procedure was to conduct dry vibration test. Here, the sample was prepared and subject to vibration. These test were not as conservative as the traditional tests (i.e. for a given filter size larger soil particles could be eroded hydraulically than under dry vibration). In their experiments on internal stability of granular filters, Kenney and Lau (1985) vibrated the sample lightly, and noted in replying to discussions (1986) that the duration of vibration had a significant effect as to whether the sample was stable or not. Sherard et al (1984) also used a shaking table, but in conjunction with applying a hydraulic gradient. Although the results of vibrating tests are conservative and therefore include a factor of safety, this is an unrealistic condition in real applications.

2.5 ONSET OF PIPING

When discussing material behaviour, the primary aspect of interest is under what conditions did piping occur i.e. did the filter fail to retain the soil. However, defining soil retention is somewhat subjective. Lafleur et al (1989) stated "The quantity of tolerable particle loss appears therefore very subjective and debatable. However, it is generally agreed that minor losses of the base are necessary to develop a state of equilibrium at the filter interface. Unfortunately, no data have yet been published to support the accurate prediction of these losses.". And Witt noted (1993) that for graded soils more particles will erode through the filter if there is only a small percentage of soil particles of suitable size to cause clogging in the filter.

Sensing the onset of piping was accomplished by various methods. Commonly, visual observation of the movement of soil particles into the filter (through a permeameter constructed of transparent material) was used. Examples of this technique include Bertram (1940), Karpoff (1955), and USBR (1955). A sophisticated and quantitative variation of this was employed by Okita and Nishigaki (1993). They used a γ-ray densiometer to measure movement of fine particles into the filter on the principle that the soil would infill the pore and void spaces of the filter, increasing the measured density.

As mentioned previously, observing particle movement may be misleading, as some soil migration into the filter may not indicate piping was occurring, but that only the very smallest size fraction was being eroded or that a filtration zone was forming. Sherard et al (1984) criticized the USBR (1955) tests on this basis. They go on to say that all of the USBR tests labelled as failure (due to particle movement) were successful because there is a linear correlation between increasing head and flow rate. If the soil had truly eroded (piped) then the flow rates should increase disproportionately because of the open channels formed in the soil, causing a large increase in permeability. What this criticism does not take into consideration is that erosion failure may be occurring but the open channels have not developed. For the USBR results to be called succesful it must be shown that particle movement eventually stopped, which was not stated in the USBR report.

A less subjective determination of piping may be made by measuring the amount of eroded soil. This was done by Bertram (1940). Unfortunately, the amount of soil eroding through the filter was measured at the end of the experiment rather than continuously, so it can only be concluded that piping had occurred, but not precisely when. Most previous work did not do testing under dynamic conditions, so it was sufficient to merely note that there had been piping at some point during the test. Monitoring the permeability of system was yet another technique used by Bertram (1940), assuming a large increase in permeability signified piping has occurred and a free flowing channel has been developed. Sugii et al (1996) also used a decrease in the permeability of the filter to indicate clogging.

Some research looked into other aspects of the soil/filter system beyond stability of the soil. Bertram (1940) was concerned that the filter did not impede the permeability of the system. If the permeability was adversely affected, the test was deemed a failure, even though the filter retained the soil successfully.

2.6 EFFECT OF GRAIN SIZE RATIO

Most previous work has concentrated on examining the geometrical requirements to obtain a stable soil/filter system. There are two aspects to the geometry: what grain size ratio to use and establishing the criteria. As previously discussed, the grain size ratio is used to represent the soil and filter materials. Honjo and Veneziano (1989) used the analogy of a screen aperatures to represent the filter opening size. By modelling the movement of a graded soil through the screen, it was determined that movement stopped when all of the aperatures were blocked by the coarse fraction D_{80s}-D_{90s} coming to rest against the screen. This is perhaps accurate for the pore voids, but does not reflect the narrower interconnecting channels. Kenney et al (1985) described this as the controlling constriction size. Lafleur et al (1993) used the concept of retention ratio (R_R), as expressed in the following equation:

$$R_R = \frac{O_F}{d_I}$$

where O_F is the opening size of the filter and d_I is the indicative grain size of the soil. Using these grain size ratios, there are three possibilities:

(i) $R_R >> 1$, erosion will occur causing piping,

(ii) $R_R \approx 1$, bridging will occur where arches form to catch finer particles, and

(iii) $R_R << 1$, blinding will occur where finer particles are caught and accumulate.

Table 1 below summarizes the grain size ratio criteria reviewed in the literature. Holtz (1985), in discussing the USBR (1955) report, stated that the use of ratio D_{50f}/D_{50s} represented the mean particle size for uniform sands and allowed for both satisfactory stability and permeability, the latter a problem associated with drainage canals that the USBR experiments were designed to study. Sherard et al (1984) defended the grain size ratio of D_{15f}/D_{85s} and criticized the use of D_{50f}/D_{50s} and D_{15f}/D_{15s} because D_{50f} does not control the pore channel size while D_{15s} does not have the properties important for filtration. Fischer and Holtz (1996) noted that while D_{85s} represents 85% of the soil particles by weight, it represents 99% of the particles by number. Most recent authors support the D_{15f}/D_{85s} grain size ratio.

Table 1 Comparison of grain size ratio criteria..

Reference	Basis and conditions	Grain size ratio	Criteria for filter*
Terzaghi, 1937	emperical	D_{15f}/D_{85s}	≤4 stable
Bertram, 1939	experimental	D_{15f}/D_{85s} D_{15f}/D_{15s}	8.7 - 11.5 stable 10.7 - 15.0 stable
Karpoff, 1955 & USBR, 1955	experimental, uniform, subround	D_{50f}/D_{50s}	5 - 10 stable
	experimental, graded, subround	D_{50f}/D_{50s}	12 - 58 stable
	experimental, graded, subround	D_{15f}/D_{15s}	12 - 40 stable
	experimental, angular	D_{50f}/D_{50s}	9 - 30 stable
	experimental, angular	D_{15f}/D_{15s}	6 - 18 stable
Myogahara et al, 1993	experimental	D_{15f}/D_{85s}	≤3 stable
	experimental, varying gradient	D_{15f}/D_{85s}	3 - 12
	experimental	D_{15f}/D_{85s}	≥ 12 failure
Okita and Nishigaki, 1993	experimental	D_{15f}/D_{85s}	≤7 stable
	experimental	D_{15f}/D_{85s}	7 - 10
	experimental	D_{15f}/D_{85s}	≥ 10 failure
Sherard et al, 1984	experimental	D_{15f}/D_{85s}	≤10 stable
	experimental	D_{15f}/D_{85s}	10 - 12 borderline
	experimental	D_{15f}/D_{85s}	≥ 12 failure
Sugii et al (1996)	experimental, sand sized particles	D_{15f}/D_{85s}	1.4, 1.7 no clogging
	experimental, sand sized particles	D_{15f}/D_{85s}	3.7 clogging

* Note that criteria may include permeability as well as stability considerations.

2.7 EFFECT OF THE LEVEL OF CONFINING PRESSURE

The effect of confining pressure on erosion potential was rarely discussed in the literature. When it was mentioned, the only purpose stated was to apply some positive pressure to hold the sample in place. Kenney et al (1985) were typical and maintained a positive stress through a spring loaded top perforated platten. When using a similar apparatus to measure internal stability of widely graded and gap-graded granular filters, the spring applied a constant confining pressure of 10 kPa. Lafleur (1984) used a confining pressure of 100 kPa to ensure the filter made contact with a membrane lining the permeameter.

2.8 EFFECT OF FILTER THICKNESS

The thicker the filter the more opportunities a migrating soil particle will encounter the minimum constriction channel (Schuler, 1996). Koenders (1996) notes that if the soil migration is blocked at the filter interface, then the filter is geometrically impenetrable. However, if soil particles penetrate into the filter some depth before they are arrested then the filter is geometrically safe with the designed thickness. Similarly, Schuler and Brauns (1993) stated that the filter must be of some thickness to have a characteristic size that can capture and stabilize the migrating soil. Bhatia et al (1996) used filters 2 cm thick in their experiments based on Kenney et al's (1985) work. This latter reference showed analytically that the minimum filter constriction does not improve significantly when the number of unit layers in the filter, m, is greater than 10. But, this is only valid for uniform filters.

2.9 EFFECT OF GRADIENT

There are three aspects to gradient of concern: magnitude, duration, and rate of increase. Gradients encountered in real world applications are generally low, long lasting, and gradually applied. There are significant exceptions, however, particularly concerning the magnitude. Singh and Varshney (1995) determined gradients of up to 9 on some dams by dividing the head by the core thickness. However, it is conceivable that gradients much higher could be experienced if the core were to be imperfect and allow free drainage partially through. McAlexander and Engemoen (1985) found exit gradients of 4.0 at the Calamus Dam, while Penman (1987) reported gradients of up to 33 across the grout cap of the Teton Dam. And there are examples of high gradients in applications other than earth dams. Giroud (1996) states that gradients of 10 are typical in shoreline protection. The gradient applied by different researchers usually reflected conditions typically encountered in geotechnical applications.

Large gradients may cause excess pore pressures to develop in the filter, reducing the effective stress which decreases interparticle friction, preventing the self filtration zone to develop (Schulz, 1993). Bertram (1940) justified large gradients as compensating for the short time scale of the laboratory experiments relative to the life over which a filter is expected to perform, but he noted no difference in stability when using gradients as high as 18-20 as opposed to 6-8. Kenny et al (1985) actively deterred arching from forming by applying large gradients and vibrating the sample. Sherard and Dunnigan (1986) in discussing Kenney and Lau (1985) noted that 20 times more sand migrated into the filter at a gradient of 45 than did at 3. Unfortunately, no mention was made if this was a linear correlation or if sand migration rapidly increased once a threshold gradient had been reached. Myogahara et al (1993) found that tests with:

(i) $D_{15f}/D_{85s} \leq 3$ never failed even with a gradient of up to 80,

(ii) $3 < D_{15f}/D_{85s} < 12$ failure depended on applied gradient with a general inverse correlation between grain size ratio and gradient to cause failure, and,

(iii) $D_{15f}/D_{85s} \geq 12$ failed spontaneously (0 gradient).

Bertram (1940) noted that (for a constant gradient) most soil movement occurred in the first 3 to 5 minutes in experiments that lasted up to 240 minutes. Sherard et al (1984) stated that if the movement occurred within the first 1 minute, then most of the soil would erode out at a constant rate. Clearly it was implied that not all tests were monitored until complete erosion occurred, as the test duration was generally 5 to 10 minutes.

Jones (1985) noted that if a large gradient is applied to a dry soil for a short time then saturation will not be very high. This is significant as an increase in saturation by 10% can increase permeability by up to 70%. A sudden large increase in the gradient may also have effects similar to a dynamic application of gradient. A dynamic application of gradient, such as in pulsating flow, would collapse any soil bridge network that was developing, destabilizing the system (Fischer and Holtz, 1996).

2.10 RESEARCH NEEDS

From a review of the literature, it is apparent that most research on filters has concentrated on determining criteria for stable soil/filter systems based on the grain size ratio. There are several aspects which have not been adequately addressed. The testing apparati are generally limited in their ability to control and monitor test parameters, such as confining stress, gradient, rate of gradient increase, and amount of soil eroded with time. The test materials and test procedures used do not allow for saturated, consistent, and repeatable reconstitution of soil/filter systems. Detecting the onset of piping has been poorly defined. And the sensitivity of grain size ratio criteria to confining pressure, filter thickness, and gradient have not been investigated fully. This thesis will address some of these aspects.

CHAPTER 3 EXPERIMENTAL ASPECTS

3.1 THE PERMEAMETER

Permeameters are used to test the propensity of a soil to erode through a filter. There is, unfortunately, no standard permeameter design which has been used by the different experimenters. As described in Chapter 2, each has designed a custom apparatus. All of the permeameters have similarities, such as the soil and the filter material within a cylinder, with water entering the cylinder at the soil end and exiting through the filter end. The only variable controlled in a permeameter of this type is the soil/filter size ratios.

The permeameter used in the work reported herein was of a newly developed design that allows complete control of all variables that may influence piping erosion phenomenon. The soil/filter specimen is still laterally confined within a cylindrical container, but a controlled vertical stress can be applied by a top loading platten on the soil, and the water flow is regulated to maintain a desired constant differential head through the soil/filter system. The soil, if eroded through the underlying filter, is captured in a collector at the bottom. Confining pressure, surface settlement, and differential water head are continuously measured whereas the flow rate and amount of eroded soil are measured over discrete time spans.

3.2 DESCRIPTION OF TESTING APPARATUS

3.2.1 The Permeameter

The permeameter was custom designed and fabricated at the civil engineering workshop of the University of British Columbia. A schematic diagram of the overall layout is illustrated in Figure 1 and that of the permeameter is shown in Figure 2. The soil/filter specimen is contained within a 10 cm inside diameter by 10 cm high cylinder of 7 mm thick polished stainless steel. The top loading platten has 5 mm holes and transmits confining pressure to the top of the soil. The loading ram is threaded to this platten and is sealed and vertically guided by an O-ring and set of linear ball bushings. The base of the pedestal also has 5 mm holes and is covered with a 1.5 mm mesh for retaining the soil/filter system. The mesh allows soil eroded by the downward seepage to pass through the pedestal and drop into one of two collectors which are positioned in place by a revolving plexiglass holder. The collectors consist of plexiglass dishes lined with aluminum foil. The loose seal between the collectors and the bottom pedestal does not impede the water flow, but the eroded soil particles are are captured by the collectors. The entire apparatus is submerged in a large water bath constructed of clear plexiglass with an overflow spigot for maintaining a constant water level on the outflow side.

3.2.2 Vertical Loading System

The desired vertical confining pressure is applied by a precision pressure regulator that feeds air to a single acting air piston mounted to a loading frame. The vertical stress applied to the system remains constant due to the high pressure set resolution of the regulator (with ± 5 mm head of water). A load cell rated at 400 kg and accurate to 0.1 %

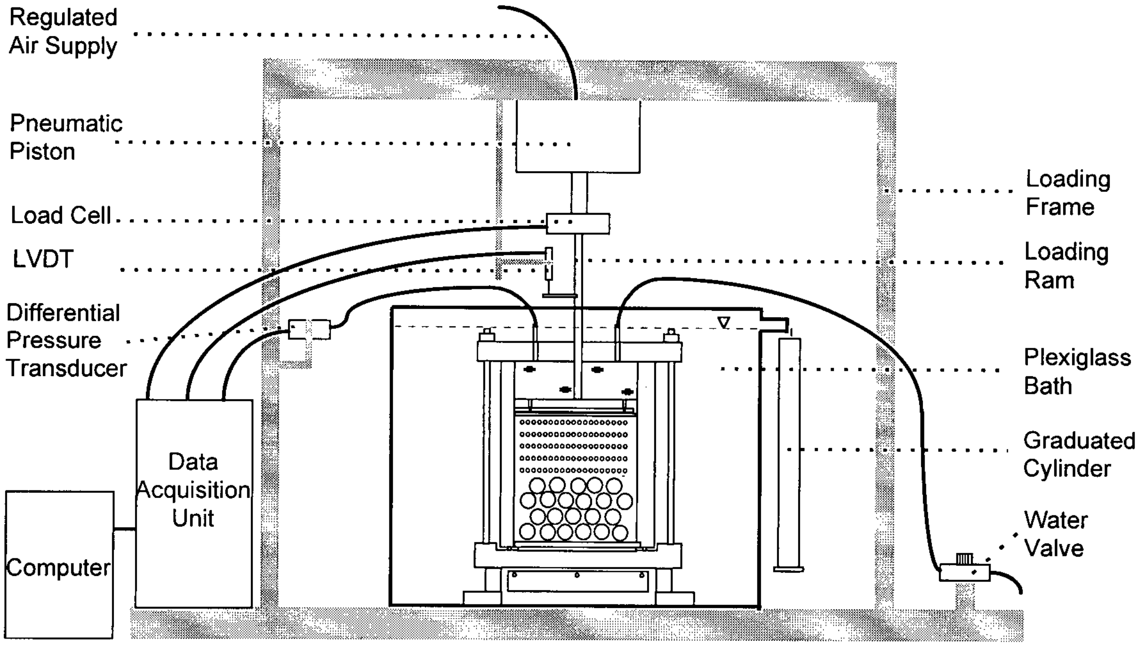

Figure 1 Schematic diagram of testing apparatus.

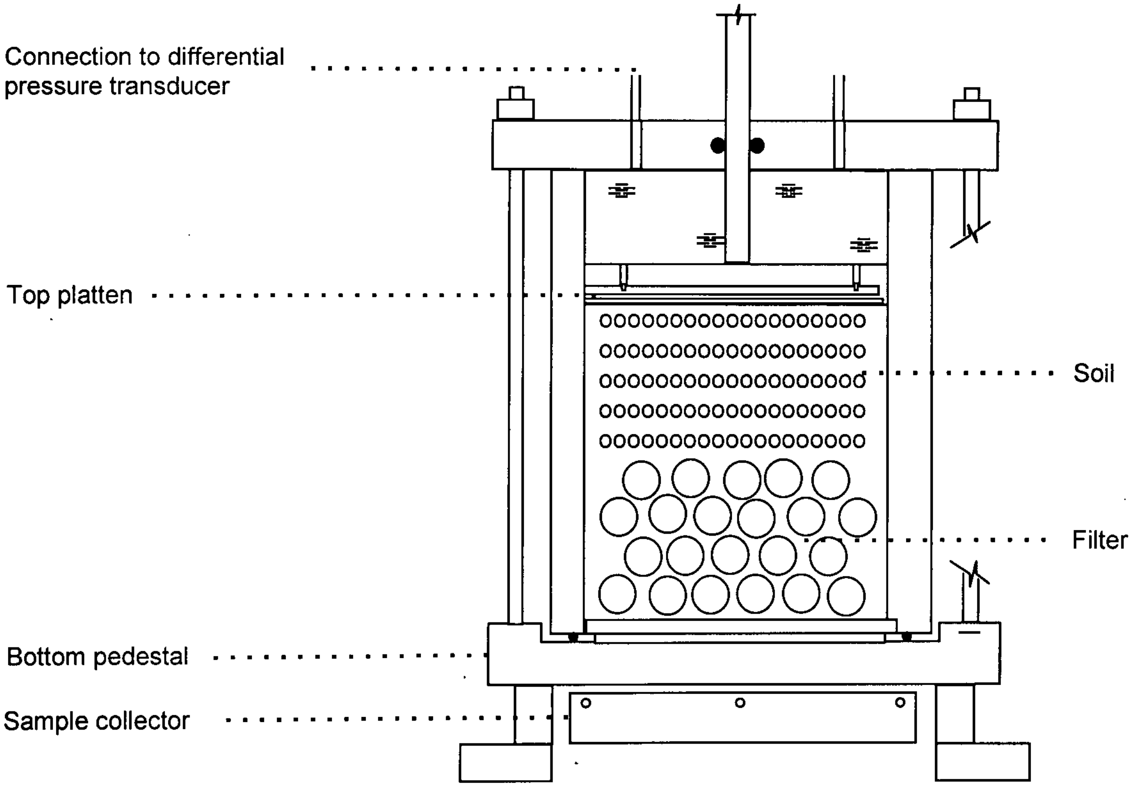

Figure 2 Schematic diagram of permeameter apparatus.

measures the applied force. A displacement transducer (LVDT) is attached to the loading frame and monitors the vertical displacement of the soil/filter system through a bracket attached to the platten rod.

3.2.3 Water Flow System

The water is fed through a port on the permeameter cap. The constant head on the inflow side is accomplished by throttling with a valve the water supply system line pressure and by holding constant water level at the outflow end with the overflow. Lafleur (1984) noted that while this downward flow may be opposite to some real life situations, it in fact accentuates the propensity for piping as gravity is assisting the soil grains in their potential for mobility. The water flow is controlled by two metering valves. A differential pressure transducer, with a maximum range of ± 35 kPa (up to 3.5 m of head) is connected to a second port on the permeameter cap. A differential water head up to 100 cm, the maximum water pressure the municipal system would allow, could be applied across the system. Water flow rates were monitored by manually measuring the volume of water exiting the water bath, and the amount of the eroded soil measured over discrete time spans of about 10 minutes.

3.2.4 Data Acquisition System

A Hewlett Packard 3497A data acquisition unit collected the data from three A/D input channels; one each from the load cell, LVDT, and differential pressure transducer. All transducers are excited by 5 v d.c. The 3497A then outputs the signals from these three channels to a microcomputer. This data was then converted from voltages to engineering units by a program, which was simultaneously saved and displayed on the monitor of the computer. The data from the three channels was input and displayed once every second, but recorded only once every 15 seconds.

3.2.5 Measurement Resolution

For the parameters measured continuously by transducers, the water head was recorded to an accuracy better than 0.3 mm and the settlement to 0.01 mm. The confining pressure was accurate to 0.1 kPa. For those parameters measured discretely by manual readings, the weight of eroded soil was accurate to 0.01 g and the outflow water volume to 1 %.

3.3 MATERIALS USED

3.3.1 Natural Materials

Most researchers have used natural sands and gravels in their erosion experiments. This allows the experiments to simulate soil/filter interactions from actual or potential applications. However, the main focus of the current research was to investigate the piping phenomenon in a more fundamental manner. In the experiments using natural materials, it has proven difficult to constitute consistent and repeatable samples and therefore the effect of a specific variable on susceptibility to erosion is difficult to isolate. This was evident in a series of experiments initially carried out on natural sand and gravel filter systems. The sands and gravels were alluvial, sub-angular, uniform materials. The size fractions of the sand were: D_{15} = 0.15 mm, D_{85} = 0.22 mm, and that of the gravel were: D_{15} = 2.0 mm, D_{85} = 3.7 mm. The soil was comprised of an equal mixture of sand and gravel, and the filter was composed of just the gravel.

Figure 3 demonstrates the inconsistencies encountered in results using apparently identical soil/filter systems of natural materials. Four samples were prepared using the natural materials described above. In each of the tests, the hydraulic head was increased until the sample failed (i.e. the piping occurred). As the samples were identical in composition and height and the reconstitution technique and testing conditions remained constant, it is expected that their performance should be similar. It can, however, be seen that the samples actually behaved quite differently. While two samples failed at a similar magnitude of system head of 79 and 82 cm, one sample failed much earlier at 60 cm, and the fourth did not fail until 113 cm.

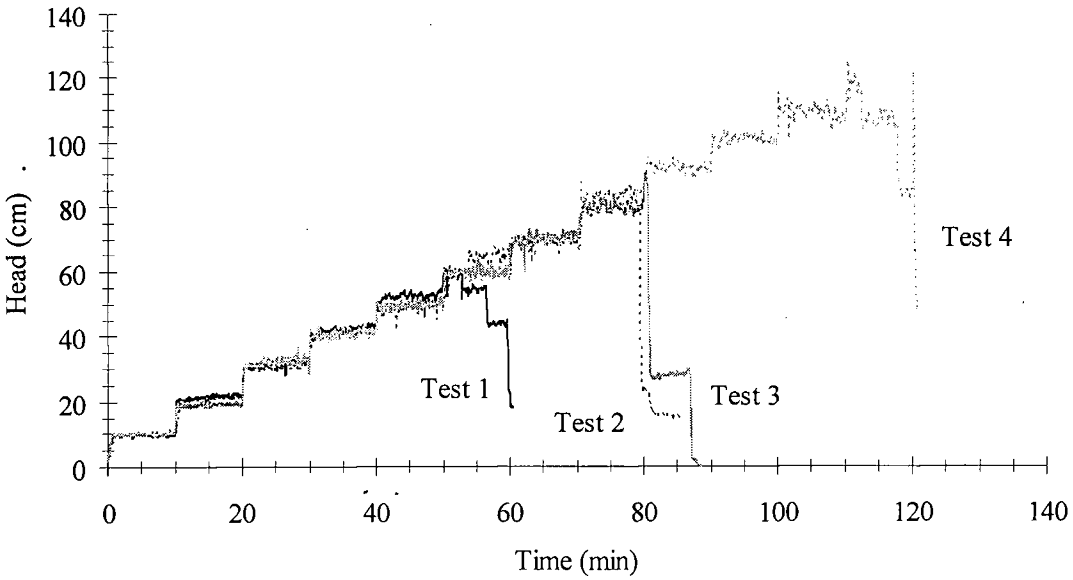

Figure 3 Inconsistencies in using natural materials.

This discrepancy is probably due in part to the inability to produce the same fabric consistently when placing the moist tamped filter and soil components. In small scale laboratory tests, a small inconsistency in the fabrics could allow a preferential channel to form which may induce premature piping.

3.3.2 Artificial Materials

To overcome some of the inconsistencies inherent in using natural materials, it was decided to use controlled materials with grains of known shape, surface texture, and uniform size. To promote consistency while still approximating natural situations (Kenney et al. 1985), idealized granular materials comprised of glass beads were used in the testing program. Spherical glass beads were used, with a minimum round fraction of 70 %. Their specific gravity is 2.5, which is very similar to quartz, a common constituent of natural sands and gravels. Filters were monosized beads of either 2 mm or 3mm diameter. Each soil was comprised of beads trapped between two consecutive sieve sizes. The mesh sizes (and equivalent opening sizes) used were: 40-45 (0.425-0.355 mm), 45-50 (0.355-0.300 mm), 50-60 (0.300-0.250 mm), 60-70 (0.250-0.212 mm), and 70-80 (0.212-0.180 mm). Figure 4 shows the size distributions of filters and soils used. From Hazen's equation it is known that the permeability of sands is related approximately to the square of D_{10}. Thus the ratio of filter to soil permeability was a minimum of:

$$\frac{\left(D_{10f}\right)^2}{\left(D_{10s}\right)^2} = \frac{(3)^2}{(0.362)^2} = 69$$

As the filter has a much greater permeability, the gradient in the filter will be negligible, and all head loss should occur through the soil until piping occurs.

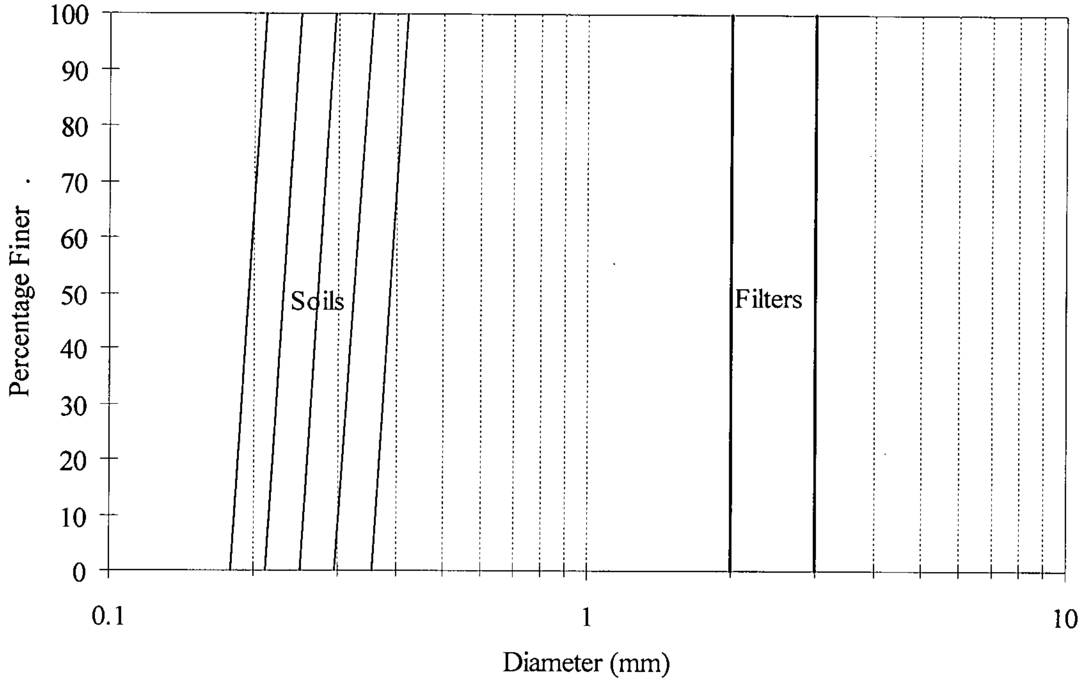

Figure 4 Size distribution of materials tested.

The use of narrowly graded, spherical particles of homogeneous composition may limit the applicability of these results to pratical considerations. Natural heterogenic sands of varying shapes that are well or gap graded will probably behave differently. But an examination of the fundamental behaviour of soil/filter systems requires the use of controlled graded materials. Only then the effect of variables other than the soil/filter size ratio can be assessed in isolation.

3.4 TEST PROCEDURE

3.4.1 Sample Preparation

Prior to placing the sample, the bottom pedestal, lower screen, and permeameter cylinder are assembled in the water bath. The bath was then allowed to sit for several hours to promote de-airing. The permeameter was then ready to receive the filter and soil.

As described in Section 2.6, various researchers have previously shown that the size of filter voids relative to the soil grain size is important in controlling piping. Uno et al (1996) showed experimentally that the mean diameter of voids, d_e^*, is given approximately by

$$d_e^* = \frac{1}{2} e D_w$$

where e is void ratio and D_w is mean diameter of soil particles. Thus it is of prime importance to ensure that the specimen uniformity and void ratio is constant between tests to ensure repeatability. Another constraint is saturation. Section 2.9 noted that small changes in saturation can have a significant impact on permeability values and therefore seepage forces.

The most desirable method for preparing uniform saturated samples of consistent density is water pluviation (Vaid and Negussey, 1986). A weighed quantity of filter or soil, as listed in Table 2, was vigorously boiled for 10 minutes in a flask. The filter material was pluviated first, maintaining the flask top constantly approximately 5 mm from the surface, and spreading the material over the surface area in an uniform manner.

Once all the filter material had been deposited, the top platten was carefully lowered onto the filter to level the filter surface and the filter height recorded. The platten was then removed and the soil pluviated on top of the filter using the same technique. Once the sand was deposited and the top surface levelled, a fine wire mesh was placed on its surface. The mesh was intended to prevent any soil from working up through the water flow holes in the loading platten during consolidation. It also discouraged soil grains from lodging between the platten and the inside of the permeameter. The top platten was then gently lowered on top of the soil, levelled, and the soil height recorded. The permeameter was then assembled with its top cap and any loss through the filter during the system reconstitution process recorded. There was generally minimal soil loss during pluviation, particularly with low grain size ratios. The system was now ready for testing.

3.4.2 Application of Confining Stress

The first stage of the testing program was to apply the desired confining pressure and allow the soil to consolidate under no differential head (minor flow will occur due to excess pore pressure dissipation during consolidation). The confining pressure was applied gradually, taking several minutes to reach the target level. Once the confining pressure was set, it was monitored and could be adjusted if required in order to maintain the constant pressure in the loading piston, although adjustment was rarely necessary. The system was then left to consolidate for approximately one hour, or until settlement had ceased. Typical confining pressure, settlement versus time curves are shown in Figure 5. It can be seen that most settlement occurs during the application of the

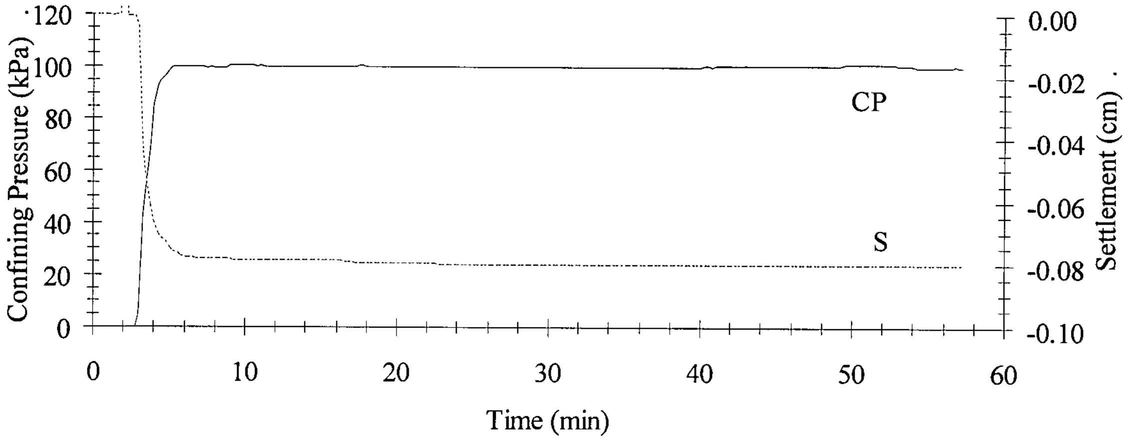

Figure 5 Typical confining stress and settlement vs time curves during consolidation.

confining pressure. As discussed later in Section 4.2, there was minor (usually < 1% by weight) soil loss during this confinement application stage. A new eroded soil sample holder was brought into position under the permeameter and the erosion phase of the experiment was started.

3.4.3 The Erosion Phase

Although there was some variation in the test procedure to determine the impact the rate of gradient increase had on soil stability, the procedure described below is the standard one used. After consolidation a small head was applied to the system. The head was increased slowly by manually opening the water inflow valve until a differential head of about 2 cm was being applied. Head as measured by the differential pressure transducer was displayed on the computer monitor every second, and was maintained constant for ten minutes by adjusting the inflow valve as required. During the early phases of the experiment little adjustment was required, but as the experiment progressed, an increasing amount of intervention was necessary to maintan a constant head. After five minutes from the commencement of flow, the outflow rate was measured in a graduated cylinder by intercepting the outflow for a specific time interval, typically one minute. Approximately eight minutes after starting flow under the ambient head, any eroded soil was recovered. This involved rotating a new eroded soil holder under the permeameter and removing the old one. The aluminum foil lining holding the eroded soil was then oven dried overnight at 110°C to yield mass of the eroded soil. At the end of ten minutes, the head was incremented by another 2 cm, and the monitoring, measuring, and the eroded soil collection procedure was repeated. The head was increased by 2 cm increments every time until the maximum head limit of the system was reached or the sample failed due to piping.

The procedure described above was somewhat altered to investigate the effect of rate of head increase on seepage erosion. In these tests the head was incremented more rapidly, by up to 23 cm in the first minute (rather than 2 cm). All other aspects of the procedures were unaltered.

3.5 TESTING PROGRAM

The two filter sizes and various soil gradations were matched to yield a range of D_{15f}/D_{85s} from 7.3 to 12.3, as shown in Table 2. All tests were carried out using a filter thickness of about 3.7 cm, except for two tests which examined the effect of a thinner filter on the susceptibility to erosion under otherwise identical conditions. Although it has not been shown what minimum filter thickness is acceptable, Humes (1996) suggested it may be as low as 0.79 cm. Initial soil thickness was about 3 cm except for those tests with D_{15f}/D_{85s} of 7.3, 8.2 or 8.7. At these low size ratios piping occurred at high gradients, and with a head limited to approximately 100 cm, a thin sample of < 2 cm was required. These relative filter and soil heights are very similar to those used by Sugii et al (1996) of 3.8 cm filter and 3.2 cm soil. It is not possible to calculate soil void ratios as some soil migrated into and through the filter during pluviation. However, for a given size and weight, soil heights are very similar, indicating pluviation allowed a consistent and repeatable sample preparation.

Table 2 Test parameters.

Test No.	Load (kPa)	Rate of Head Increase	Filter			Soil			D_{15f}/D_{85s}
			Size (mm)	D_{15f} (cm)	Weight (g)	Size (mesh)	D_{85s} (cm)	Weight (g)	
950104	100	gradual	3	0.3	200	40-45	0.0410	200	7.3
950123	100	gradual	2	0.2	400	60-70	0.0244	250	8.2
960106	100	gradual	3	0.3	400	45-50	0.0346	250	8.7
971121	100	rapid	3	0.3	400	45-50	0.0346	250	8.7
960211	300	gradual	3	0.3	400	45-50	0.0346	250	8.7
960203	400	gradual	3	0.3	400	45-50	0.0346	250	8.7
951006	50	gradual	2	0.2	400	70-80	0.0207	400	9.7
951005	100	gradual	2	0.2	400	70-80	0.0207	400	9.7
950901	100	gradual	2	0.2	250	70-80	0.0207	400	9.7
951003	200	gradual	2	0.2	400	70-80	0.0207	400	9.7
951007	300	gradual	2	0.2	400	70-80	0.0207	400	9.7
951029	400	gradual	2	0.2	400	70-80	0.0207	400	9.7
951004	400	gradual	2	0.2	400	70-80	0.0207	400	9.7
960101	100	gradual	3	0.3	400	50-60	0.0290	400	10.3
951024	200	gradual	3	0.3	400	50-60	0.0290	400	10.3
960210	300	gradual	3	0.3	400	50-60	0.0290	400	10.3
960224	100	gradual	3	0.3	400	60-70	0.0244	400	12.3

CHAPTER 4 TEST RESULTS

The test results of piping erosion potential are presented and discussed in this chapter. Calculations to determine basic parameters are first given. The main part of this chapter then deals with the series of experiments using artificial glass bead soil/filter systems, as outlined in Section 3.5. The aspects that will be examined include compression during application of the test confining stress, experiment repeatability, and the effects of D_{15f}/D_{85s}, the level of confining pressure, filter thickness, and rate of gradient increase on critical gradient at which piping occurred.

4.1 CALCULATIONS

The results are presented as either direct measurements or calculations from the direct measurements. Direct measurements that are made continuously are imposed head, confining pressure, and settlement; and direct measurements made at discrete intervals are the rate of outflow and the amount of eroded soil. Calculated from the direct measurements are the system gradient and permeability.

Gradient (i) is calculated by the following equation:

$$i = \frac{h}{l}$$

where h is imposed head and l is length of the soil. The gradient is calculated over the length of the soil rather than the length of the total specimen length (soil + filter) because the filter is much coarser grained than the soil and does not restrict the water flow (Sub-Section 3.3.2). This is also evident from the data plots where the permeability greatly increases after the soil layer has been eroded, as discussed in Section 4.6. As both the head and soil length (initial length - settlement) are continuous measurements, the gradient is calculated continuously.

Permeability (k) is calculated from Darcy's law:

$$k = \frac{Q}{A \times i}$$

where Q is flow volume and A is area. The permeability is calculated at discrete intervals corresponding to when the flow volume was measured and is plotted at time corresponding to the mid point of measurement interval. The measurement interval was chosen such that the flow volume would fill the graduated cylinder at least half way (500 ml) to minimize reading errors, and this interval varied from two minutes to 15 seconds. While the permeability calculated was for the soil/filter system as a whole, it is essentially the permeability of the soil, as it is very much lower than that of the filter (as explained in Section 3.3.2).

4.2 CONSOLIDATION UNDER INITIAL CONFINEMENT

Although not intended to determine soil/filter relationships, parameter monitoring during the consolidation phase of the experiments revealed the influence of confining pressure. Two tests with identical D_{15f}/D_{85s} of 9.7 and similar soil and filter thicknesses were subjected to confining pressures of 50 and 400 kPa, applied at 5.5 and 4.25 minutes respectively. The settlement-time curves are shown in Figure 6. No gradient was applied and minimal settlement occurred prior to applying the confining pressure, so the settlement observed is a result of the stresses applied and not seepage or gravity forces. Table 3 below summarizes the results.

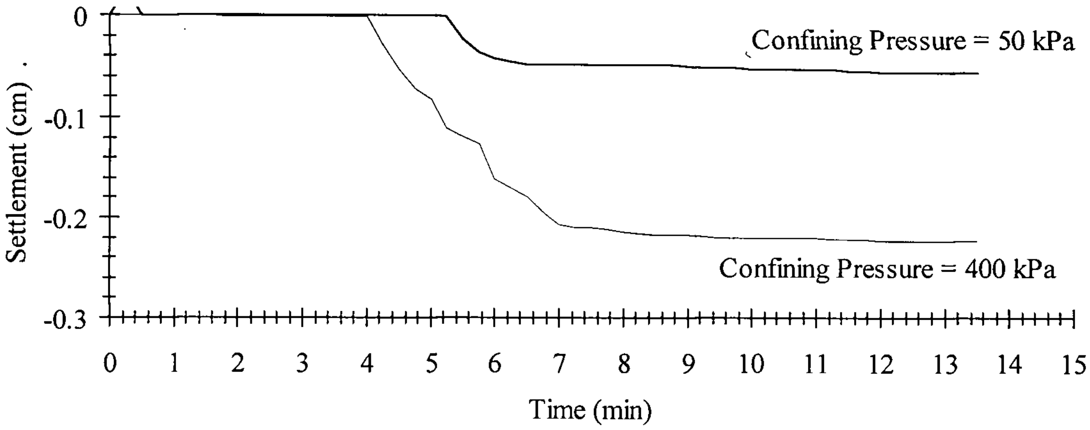

Figure 6 Settlement during consolidation (no gradient imposed).

Table 3 Results of consolidation.

Confining Pressure	50 kPa	400 kPa
Maximum Settlement	0.056 cm	0.223 cm
Eroded Soil	1.23 gm	11.40 gm
Eroded Soil (% of original)	0.3 %	2.9 %

The sample consolidated under the larger confining pressure had more settlement and eroded soil by a factor of four and eight, respectively. This non-linearity between settlement and eroded soil shows that the settlement caused by a confining pressure is not just due to the soil repacking into a denser state, but that the confining pressure is destabilizing the soil and forcing some of it into (and through) the filter. If the soil was merely densifying then there should be similar minor amounts of soil eroding through.

4.3 TEST REPEATABILITY

As mentioned previously, major considerations were made to the permeameter design, soil/filter material selection, and experimental procedures to ensure that the tests were repeatable. To demonstrate the test repeatability, tests were carried out on two identical soil/filter systems, which in principle should yield similar results. In each test, the soil and filter thicknesses as well as the size ratio D_{15f}/D_{85s} 9.7 were identical. Both samples were prepared using the standard methodology, and the confining pressure used was 400 kPa. Figure 7 shows a comparison of results from the two tests.

Figure 7a shows the hydraulic head and gradient with time. In both tests the head was incremented every 10 minutes by 2 cm. It is clear that one of the soil/filter systems has difficulty maintaining a maximum head of 22 cm, which subsequently drops off rapidly before stabilizing at 2 cm. The other soil/filter system has the head increase another two 2 cm increments to 26 cm before finally dropping off to 6 cm. The gradients in the two tests are initially proportional to the hydraulic head imposed until about 80 minutes (for the test that reached a maximum head of 22 cm) and 100 minutes (maximum head of 26 cm). From 80-100 and 100-110 minutes, respectively, the gradients are characterized by erratic and gradually increasing gradients disproportionate to the head. This is because minor erosion is decreasing the sample lengths. When piping ensues, the gradients start to increase rapidly and significantly , followed by a very dramatic drop off. The onset of the increase in gradient marks the critical gradient at which piping is triggered. For the two tests these gradients are essentially equal - 9.4 and 9.7 respectively.

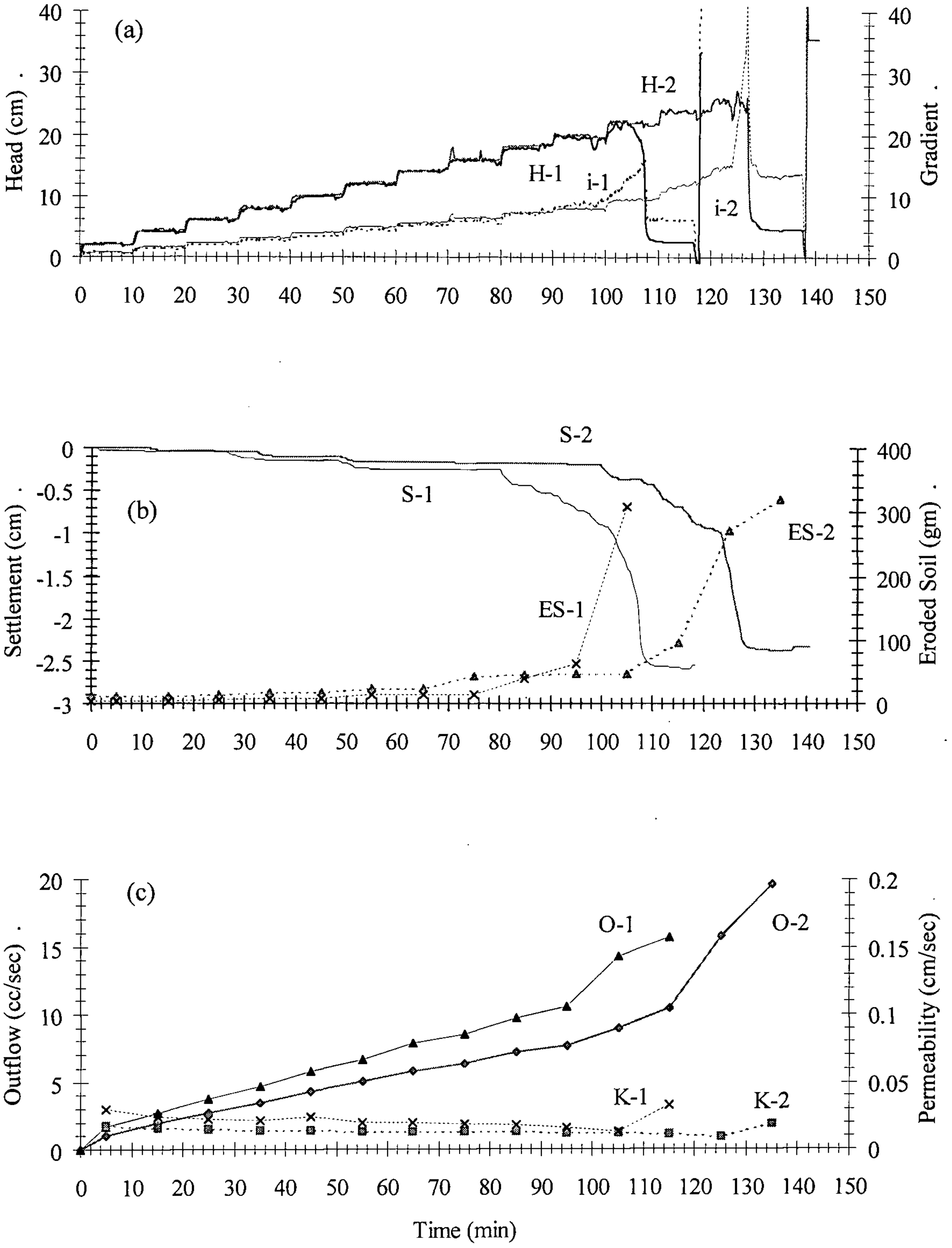

Figure 7 Test repeatability.

After piping, the gradient remains constant until it drops off to zero when the water flow is shut off at the cessation of the test.

It may be noted in Figure 7b that the settlement induced during flow is intermittent rather than continuous. For both tests, initially minor settlement occurs only when head increments are applied. Later on (80 minutes for one test and 100 for the other) both systems experience erosion in the interval between a head increment. Eventually (at 100 and 110 minutes) the erosion becomes continuous when piping is occurring. This instant is regarded herein as the commencement of piping erosion and the associated gradient as the critical gradient. Once all the soil has been eroded the settlement stops. The cummulative weight of eroded soil is also plotted in Figure 7b, and as expected generally reflects the trends in settlement curves.

Figure 7c shows rate of outflow and permeability variation with time. Outflow steadily increases with time as the head is increased. After piping has occurred, the next sampling intervals (at 105 and 125 minutes) show a significant increase in the outflow. Permeability values for both samples are very similar and gradually decrease with time until after piping has commenced. This will clearly be due to the process of soil migration into the filter which decreases system permeability.

The profiles of the various test parameters versus time are similar, differing by only a time offset, indicating the filtration/erosion process is the same. Despite one test reaching the critical gradient later than the other, the difference is within experimental error. This confirms the repeatability of the testing procedure adopted.

4.4 EFFECT OF GRAIN SIZE RATIO ON EROSION POTENTIAL

As established by many previous works, the grain size ratio D_{15f}/D_{85s} is of critical importance in controlling if piping will occur. In a series of experiments the influence of D_{15f}/D_{85s} on when soil/filter system becomes unstable under incresing gradient, as established by the critical gradient, will be examined. The soil/filter systems were reconstituted and tests performed using standard procedures, but at various confining pressures. For easy comparisons the results are presented separately for each selected confining pressure: 50, 100, 200, 300, or 400 kPa. Thus any variance among any one suite of results is due to variations in the ratio D_{15f}/D_{85s} only.

4.4.1 Behaviour at σ' = 50 kPa

The performance of the soil/filter system at σ' = 50 kPa is presented in Figure 8. This test will be described in detail as being representative of the typical behaviour. The system head, Figure 8a, was increased at the standard rate of 2 cm increments over approximately 2 minutes every 10 minutes to a maximum of 52 cm when it rapidly dropped off and stabilized at 6 cm. This head loss is now clearly through the soil contaminated filter since most of the soil is already eroded. This rapid drop in head occurred despite attempts to maintain it at the desired level (52 cm) by increasing the water flow to the maximum. The head could be maintained as long as there was even a thin layer of soil remaining without a continual channel to restrict the flow, but the gradient clearly increased disproportionately as the soil length decreased with continuing erosion. The gradient profile shows three distinct stages: (i) steady state, (ii) piping, and (iii) post erosion. During stage (i) the gradient is proportional to the head until about 257

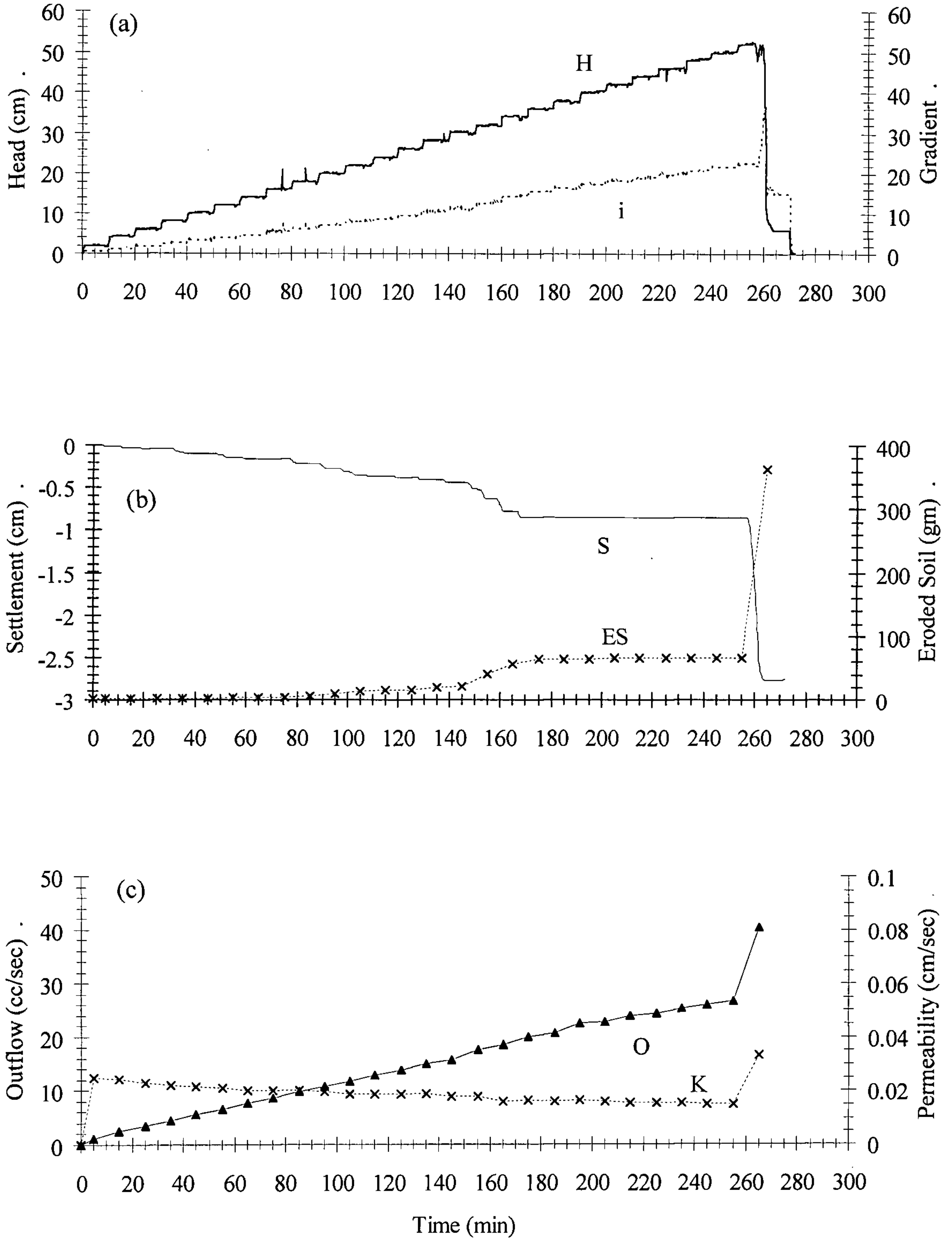

Figure 8 Soil/filter performance at σ' = 50 kPa.

minutes. Stage (ii), from 257 to 261 minutes, is characterized by rapidly increasing gradients disproportionate to the head (which is approximately constant at 52 cm). This was immediately followed by an abrupt drop in gradient. The onset of the increase, and not the maximum value, marks the critical gradient at which piping starts, i.e. 22.7. The large gradient increase is a result of the soil eroding away, decreasing the soil length, and a consequent raising of the gradient to a maximum of 37 (there is still a finite soil length). Once sufficient soil has eroded out, a channel develops through the soil, allowing water to freely flow past the soil. This causes an immediate drop in head, which makes the gradient drop from 37 to 15 in less than a minute. The gradient then remains constant at this level, stage (iii).

As piping is considered to initiate when large amounts of soil starts getting washed through the filter in a continuous manner, the onset of piping can be better assessed from the settlement-time plots, shown in Figure 8b. There are five stages to the settlement curve. Stage (i) occurs during the initial 140 minutes, with minor settlement associated with head increments. The unstable fine soil particles, particularly those near the soil/filter interface, are being washed through the filter. Stage (ii) lasts from 140 to 170 minutes when there is more significant erosion, even between head increments. This happens when a filtration zone may be forming, and if an arch or bridge fails, the particles that were trapped behind are released. The nature of the plot of settlement and cummulative eroded soil curves indicate that up to 170 minutes the self filtration zone continues to form. There is then a hiatus in the erosion and settlement, stage (iii), from 170 to 257 minutes, when the soil/filter system is stable. All of the metastable soil particles have been washed out and the filtration zone is retaining the remaining soil. Eventually, in stage (iv) the erosion commences again and becomes continuous (from 257 to 264), and this is when piping is occurring and the soil is freely washing through a channel. When this occurs, the critical gradient has been reached. Once the soil has all been eroded in stage (v) the settlement stops. The minor rebound at the end of the test is due to release of confining pressure.

It is apparent from the plots in Figure 8 that the duration of gradient is not influencial on stability, as erosion, if it occurred, commenced immediately after the application of an increase in gradient. Only the magnitude of gradient is important, as significant erosion did not occur until the critical gradient was reached. The cummulative weight of eroded soil is not proportional to settlement during stage (i) because some of the soil is migrating into the filter and becoming trapped, forming a filtration zone as described by Okita and Nishiaki (1993). There is more soil accumulating during stage (ii), and stage (iv) collects the remaining (majority) soil.

The flow rate and permeability are shown in Figure 8c. Outflow is initially proprtional to head, up to about 27 cc/sec. There is then a large increase in the flow rate up to 40 cc/sec. This is because while the head remains constant, the sample length is decreasing, and according to Darcy's law (with permeability and area remaining constant) the flow rate must have a corresponding increase. This was also predicted by Sherard et al (1984) in discussing the USBR work (see Section 2.5) and later experimentally observed by Skempton and Brogan (1984), as reflected by flow increasing disproportionately with gradient due to piping. Permeability gradually decreases from

0.025cm/sec to 0.015 cm/sec during the test as the soil forms a self filtration zone over time, as discussed by Okita and Nishigaki (1993). This self filtration zone decreases the permeability of the system as the smaller size fraction of the soil infills some filter voids (Kohler, 1993). The decrease in permeability is not very dramatic and is pratically constant from 170 to 257 minutes (corresponding to when the settlement and eroded soil indicate the system is stable) because the narrowly graded soil does not result in significant self filtration within the soil. After the piping has commenced, the permeability increases by a factor greater than two despite the drop in gradient as a consequence of a channel forming through the soil.

4.4.2 Behaviour at σ' = 100 kPa

The system performance to flow under σ' = 100 kPa and for D_{15f}/D_{85s} of 7.3, 8.2, 8.7, 9.7, 10.3 and 12.3 is illustrated in Figure 9. The results for the test with a grain size ratio of 7.3 are not plotted because this system did not fail (despite the use of a thin filter to represent a worse case). The results for size ratio 12.3 are not shown because it failed during sample preparation itself i.e. even under no steady flow.

Figure 9a shows head versus time. The heads all increase similarly for each size ratio until each test fails. It can be seen that there is an inverse relationship between the maximum head reached prior to failure and D_{15f}/D_{85s}. The corresponding gradients, Figure 9b, also show this trend, implying that the critical gradients increase with grain size ratio. In tests with D_{15f}/D_{85s} = 8.2 and 8.7, shorter soil lengths (approximately 1.9 cm) were used than in the other tests (approximately 3 cm) to enable higher gradients to be applied with the head not exceeding 100 cm (the maximum obtainable from the

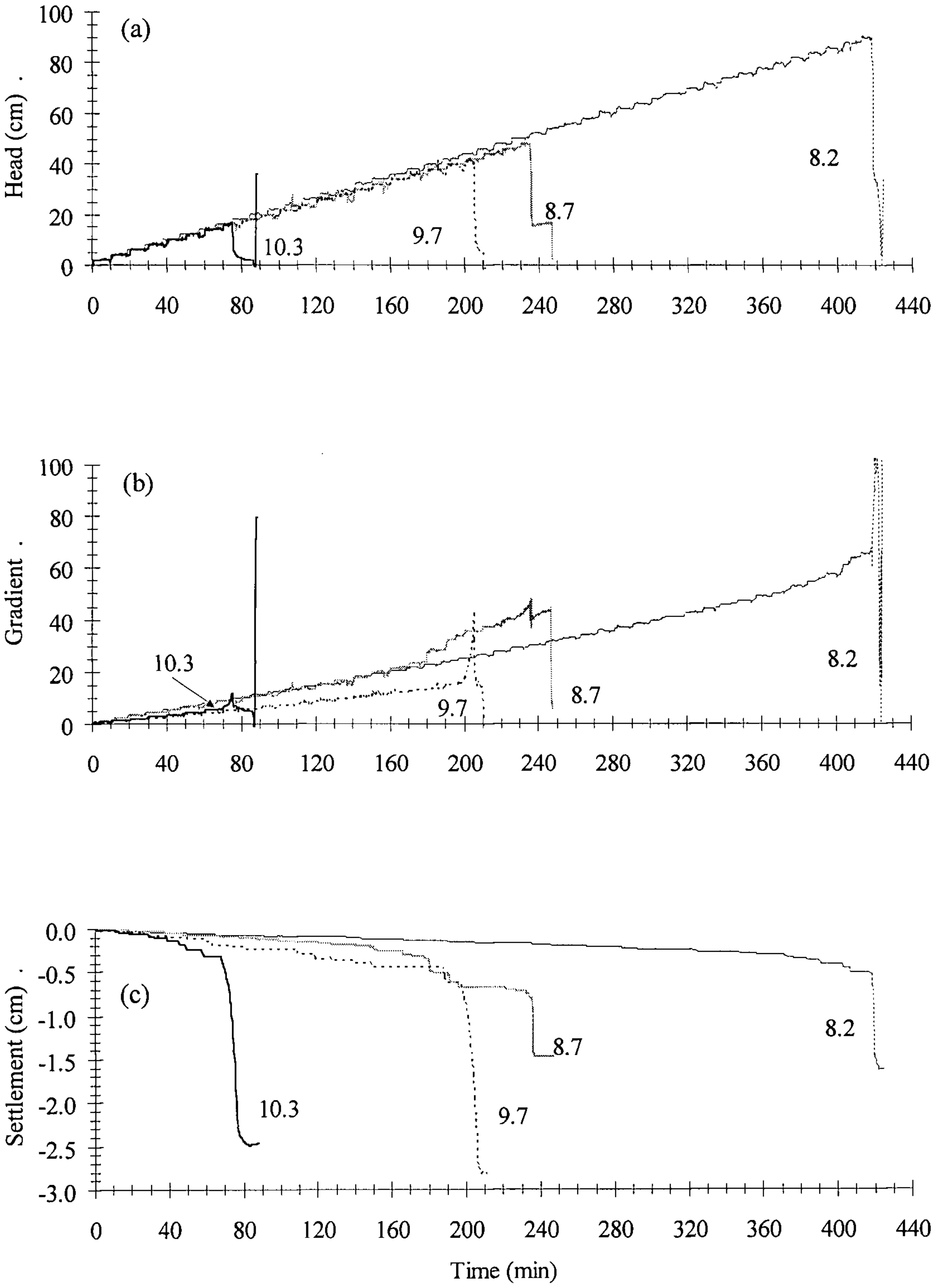

Figure 9 Soil/filter performance at σ' = 100 kPa.

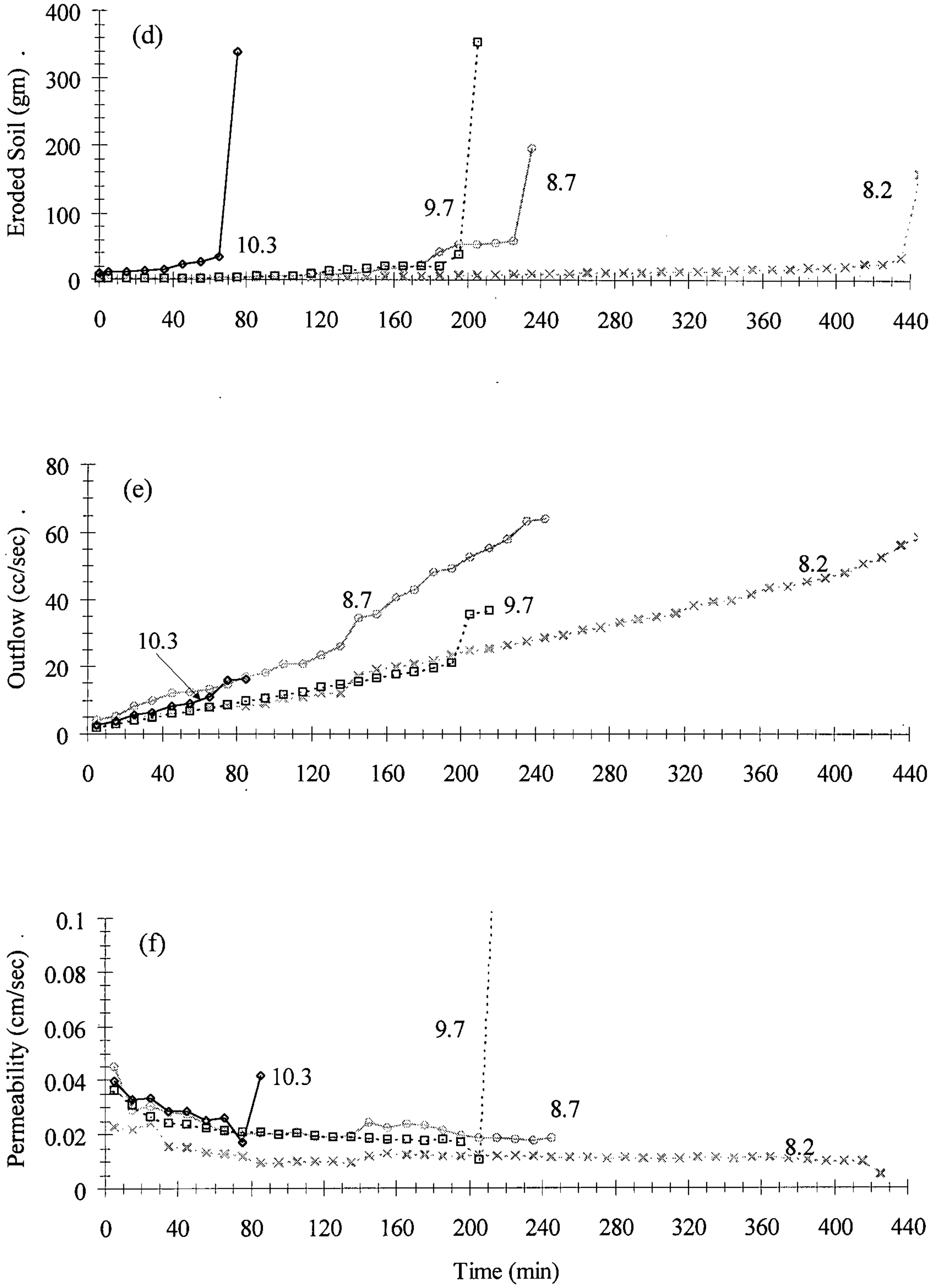

Figure 9 Soil/filter performance at σ' = 100 kPa (continued).

municipal supply). This accounts for the steeper gradient curves for these two tests.

In Figure 9c, the tests with larger grain size ratios not only suffer large settlement earlier, but it occurs more rapidly. This is also reflected in the cummulative eroded soil plots, Figure 9d. The outflow rates, Figure 9e, are similar to each other, with the exception of the test with D_{15f}/D_{85s} = 8.7. This test has a significantly steeper curve because it had a shorter initial soil length and experienced significant erosion, further decreasing the soil length. This reduction in length requires a consumate increase in flow rate (from Darcy's law), as area, permeability, and head are similar to the other tests. The permeabilities in Figure 9f are not that different because the soils are not too different in grain size. All grain size ratios showed somewhat decreasing permeability with time trend. In two tests outflow rates were measured after piping had occurred, and their last readings reflect the decrease in permeability due to the open channel formation. In particular, the rate measurement with D_{15f}/D_{85s} = 9.7 was done well after the soil had eroded away, and the permeability increased greatly from 0.01 to 0.15 cm/sec. This higher permeability reflects that of the filtration zone within the filter, which would have a much coarser average grain size than the soil itself.

4.4.3 Behaviour at σ' = 200 kPa

Two tests with different grain size ratios, D_{15f}/D_{85s} = 9.7 and 10.3, were carried out with a confining pressure of 200 kPa. The results are presented in Figure 10. Only a few 2 cm increments of head were needed for the test with a grain size ratio of 10.3 causing failure in only 48 minutes, whereas the test with 9.7 did not fail until 278 minutes. The critical gradients, Figure 10b, were 4.1 and 23.3, respectively. The grain

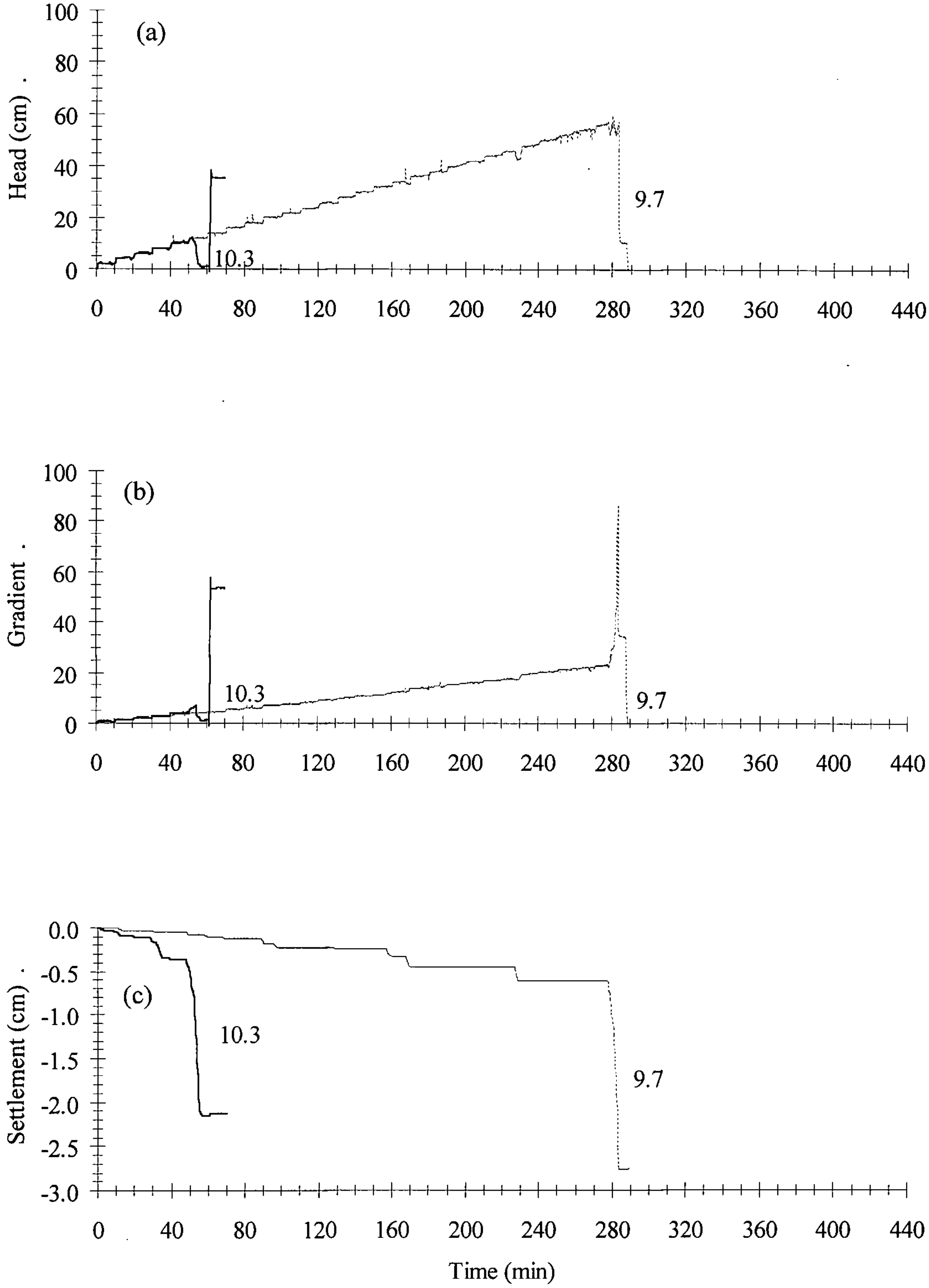

Figure 10 Soil/filter performance at σ' = 200 kPa.

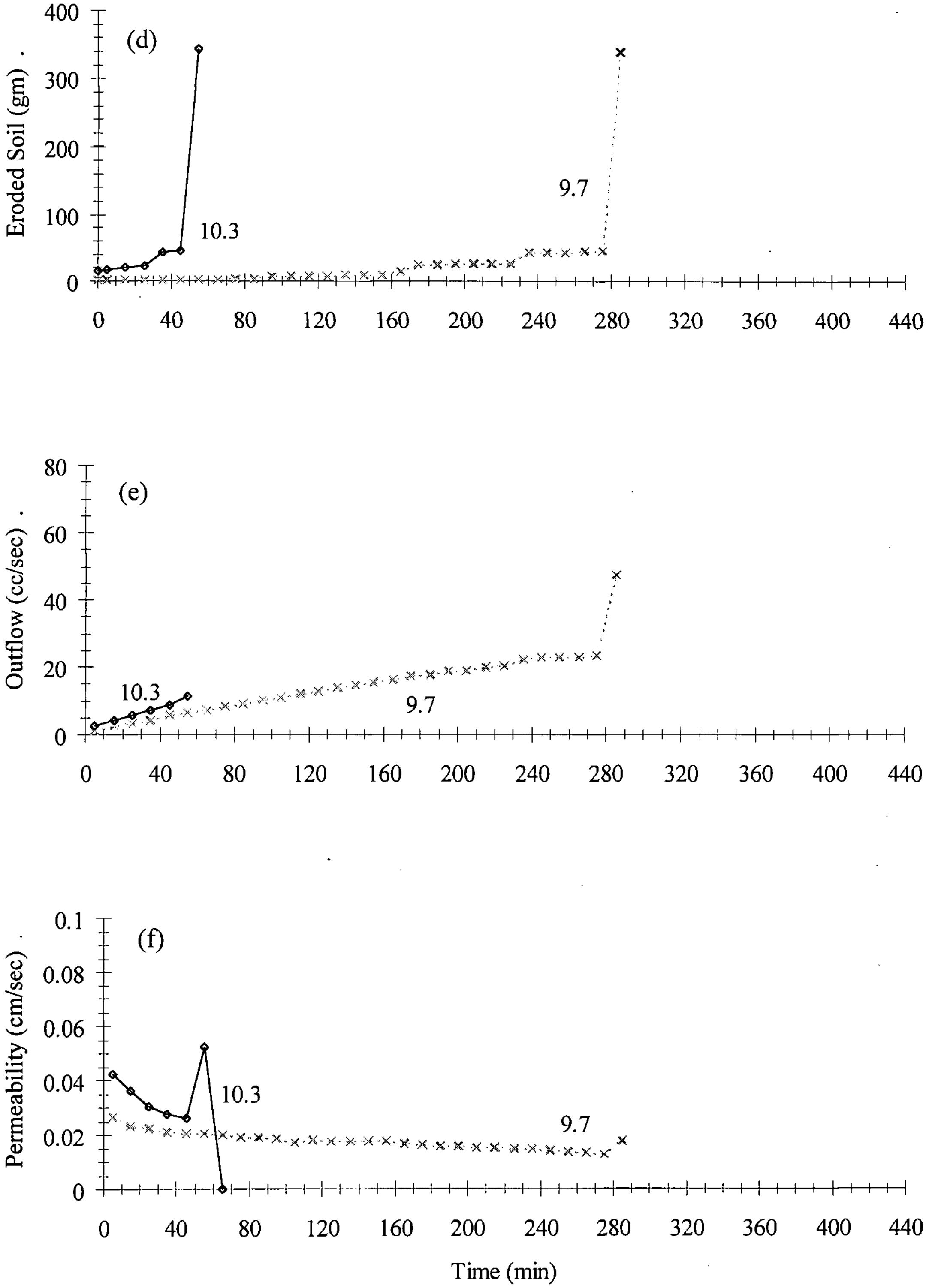

Figure 10 Soil/filter performance at σ' = 200 kPa (continued).

size ratio 9.7 test had several distinct steps in the settlement-time curve, shown in Figure 10c, indicating that bridges were collapsing and then rapidly forming as the gradient was increased. These steps are also reflected in the cummulative eroded soil plot, Figure 10d. It is interesting that the amount of eroded soil lost in each step increased, showing that the system is becoming less stable as the gradient is increased. The outflow rate for both systems, Figure 10e, increase with time steadily until piping occurred. The permeability, Figure 10f, for the size ratio 10.3 is greater but decreases sharply before piping and increases greatly after piping, similar to the results for the behaviour under $\sigma' = 100$ kPa (Sub-Section 4.4.2).

4.4.4 Behaviour at $\sigma' = 300$ kPa

The behaviour under a confining stress of 300 kPa with $D_{15f}/D_{85s} = 8.7$, 9.7 and 10.3 is illustrated in Figure 11. The head plots, Figure 11a, show that failure occurred at 211, 156, and 54 minutes, respectively, and the corresponding critical gradients, Figure 11b, are 37.2, 12.1, and 5.1, respectively. The settlement-time curves, Figure 11c, are consistent, but are steeper as the grain size ratio increases. The system with the grain size ratio of 10.3 had the largest initial amount of cummulative eroded soil, and further erosion occurs more rapidly, as shown in Figure 11d. This is clearly a result of the large difference in grain sizes between the soil and filter, so that significantly more soil can be washed through the larger filter openings. Outflow rates, Figure 11e, are similar for all tests. Permeabilities, Figure 11f, show trends similar to those previously described under lower confining stresses.

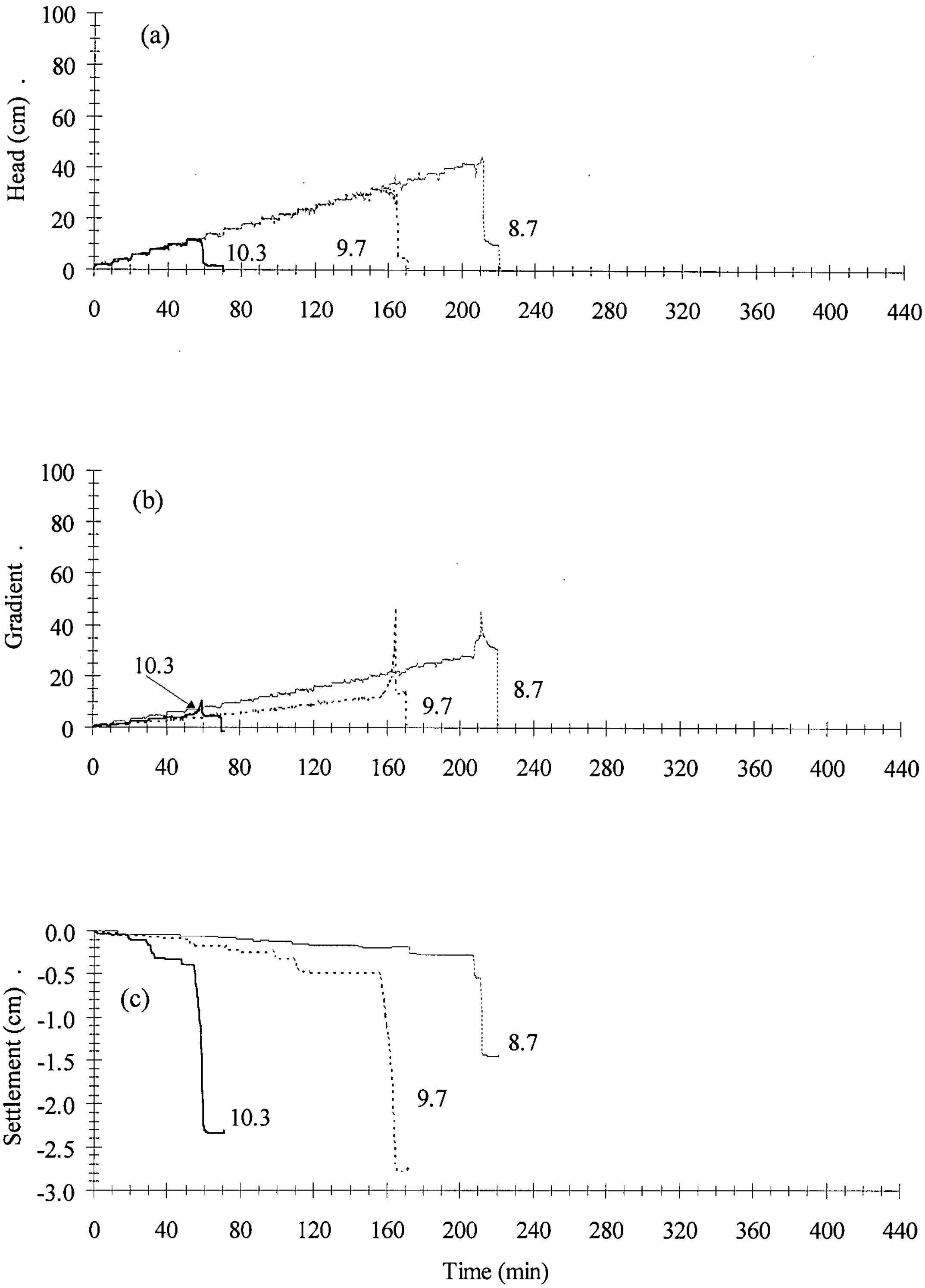

Figure 11 Soil/filter performance at σ' = 300 kPa.

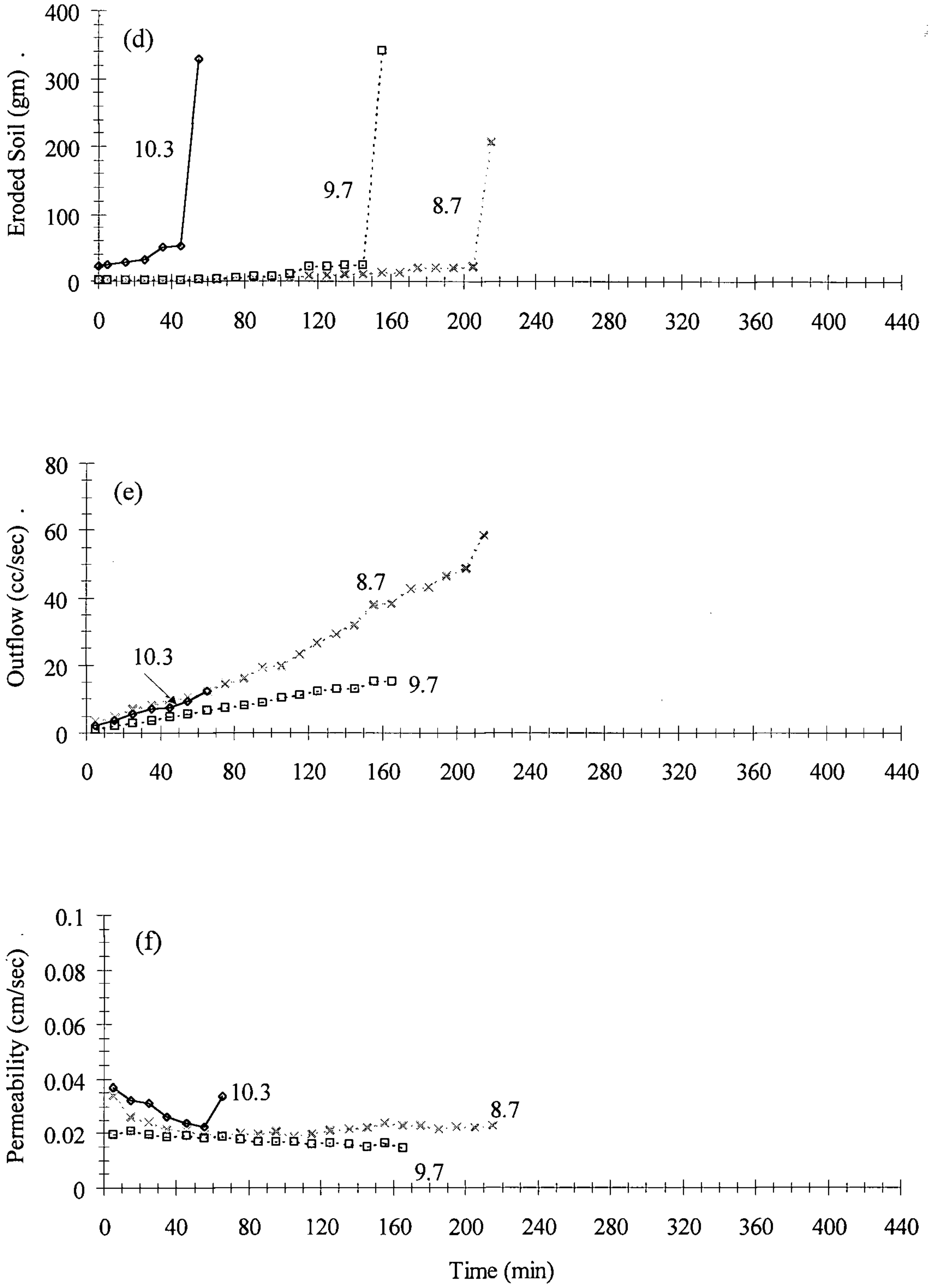

Figure 11 Soil/filter performance at σ' = 300 kPa (continued).

4.4.5 Behaviour at $\sigma' = 400$ kPa

Two different grain size ratio systems were tested at the maximum confining pressure of 400 kPa used in this study with size ratios 9.7 and 8.7. These tests failed relatively early at 100 and 169 minutes respectively, as can be noted from the head plots in Figure 12a. The critical gradients were also smaller, 9.4 and 31.7, Figure 12b. The settlement and cummulative eroded soil with time, Figures 12c and 12d respectively, show smaller rates for the size ratio 8.7 because there was less soil used (as explained previously). Outflow rates, Figure 12e, and permeabilities, Figure 12f, are similar for the two systems.

4.4.6 Summary of Grain Size Ratio Effects

The results for the previous series of tests are summarized in Figure 13, showing the critical gradient to cause piping versus the grain size ratio. For $D_{15f}/D_{85s} < 8$ no piping could be induced up to the maximum gradient applied regardless of confining stress level. This agrees with Fischer and Hotz's (1996) review of 9 works comprising 158 experiments in which any dependence on confining stresses was not explained. For $D_{15f}/D_{85s} > 12$ piping occurred spontaneously under no gradient. The soil merely passes through the filter opening during placement. This is the same conclusion reached by Sherard et al (1984). For $8 < D_{15f}/D_{85s} < 12$ the occurrence of piping depends on the critical gradient being reached (Myogahara et al, 1993). The critical gradient decreases dramatically with the size ratio, and for a given size ratio has some dependence on the confining stress level for smaller grain size ratios.

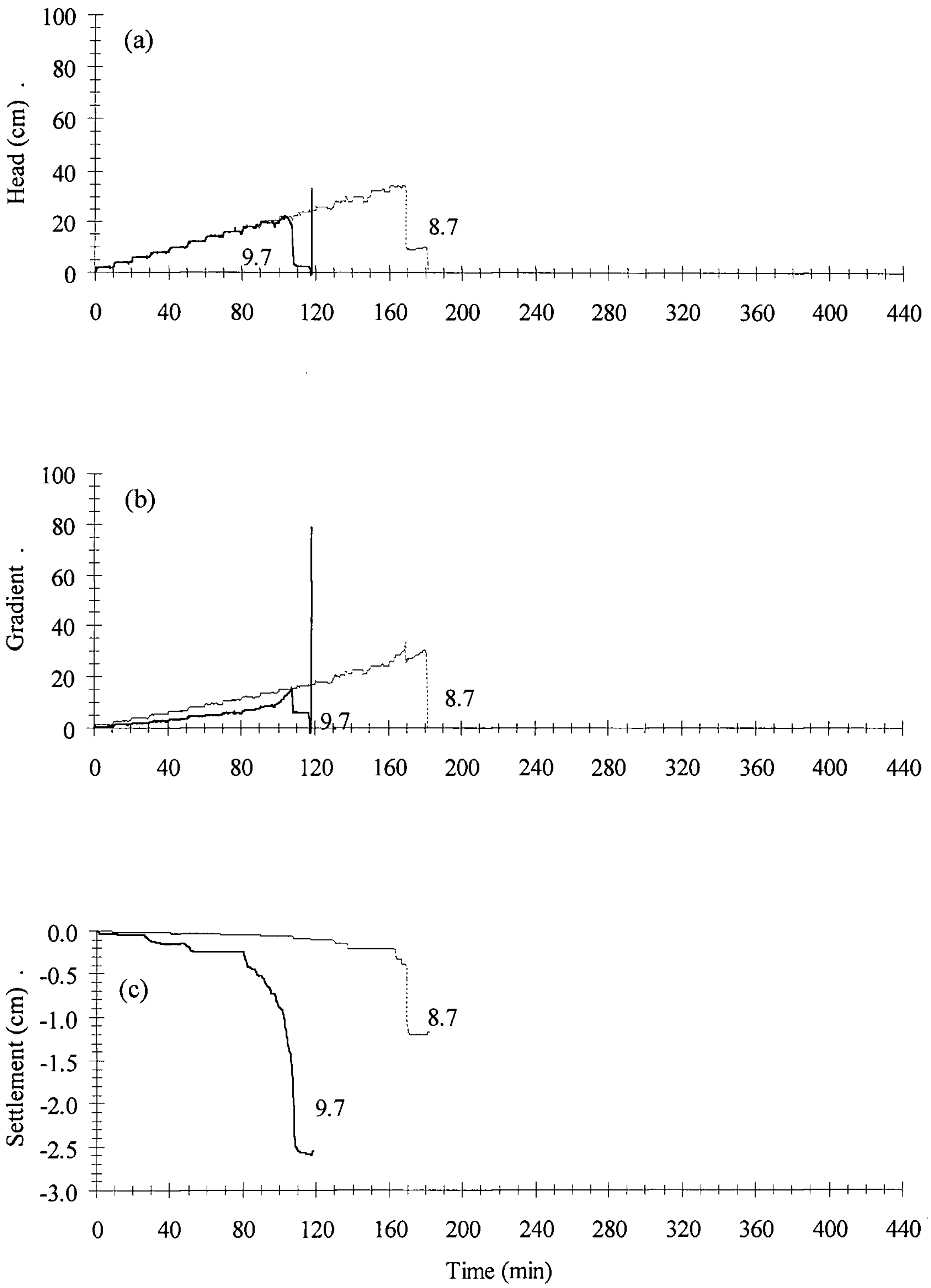

Figure 12 Soil/filter performance at σ' = 400 kPa.

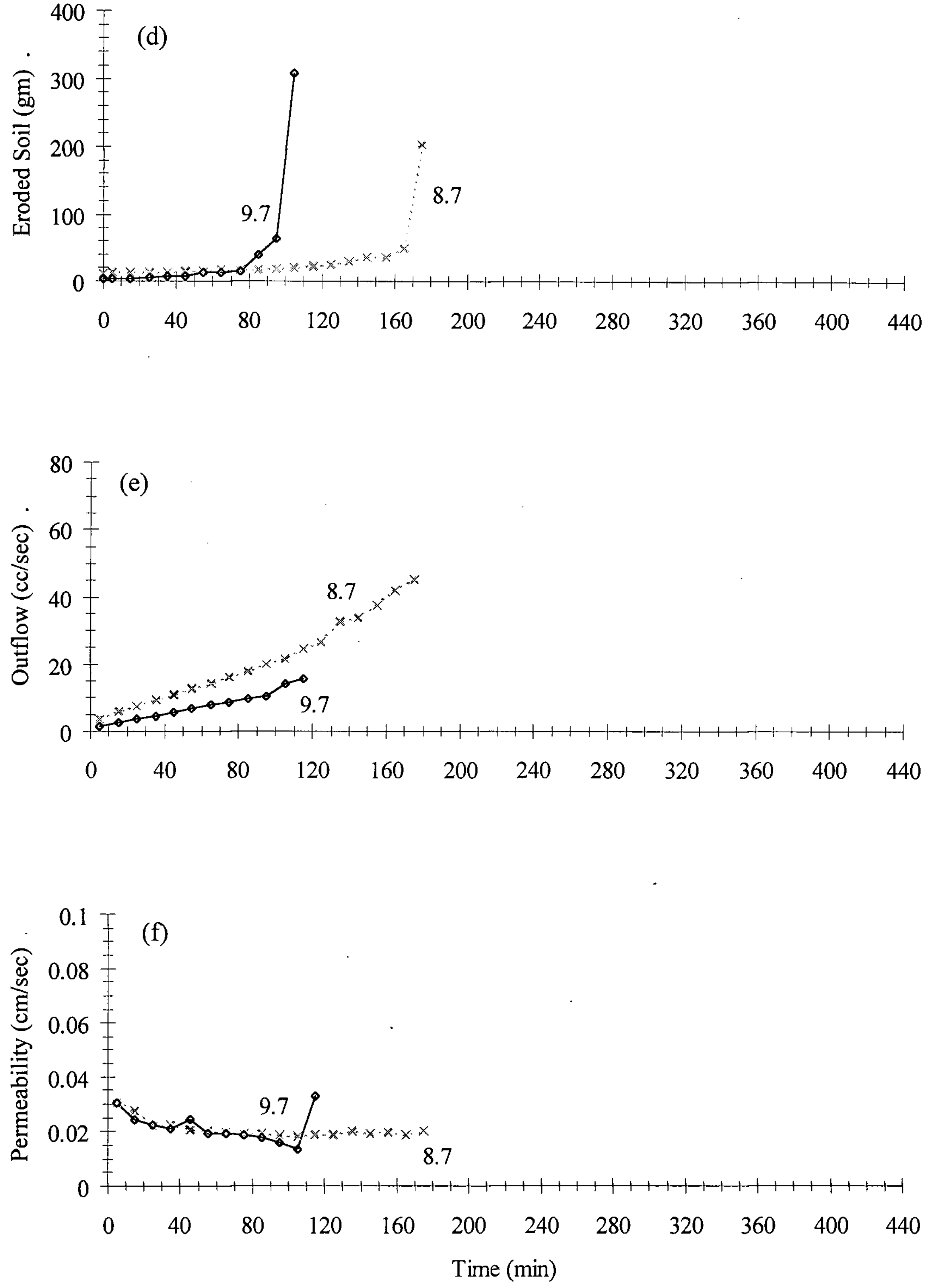

Figure 12 Soil/filter performance at σ’ = 400 kPa (continued).

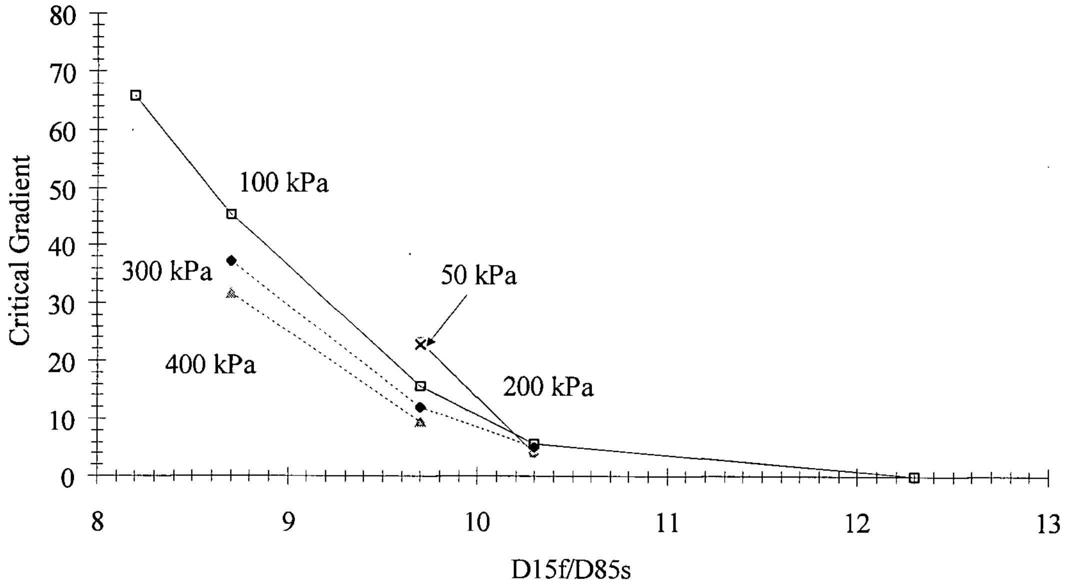

Figure 13 Grain size ratio effects on piping erosion.

4.5 EFFECT OF CONFINING PRESSURE

That confining pressure has a minor influence on stability is evident from the results, where the critical gradient that triggers piping varies depending on the confining pressure applied. The results of the tests summarized in Figure 13 are replotted in Figure 14 to yield the effect of confining pressure at a given size ratio. Little effect may be noted for the largest size ratio used, but manifests itself in a mild way as the size ratio decreases. This minor trend tends to imply that larger confining pressures may act as a destabilizing force, and thus a lower gradient will trigger erosion. The larger interparticle stresses caused by the increased confining pressure may force key blocks to be pushed out from the arch, analogously to what occurs when the system is disturbed by vibrations

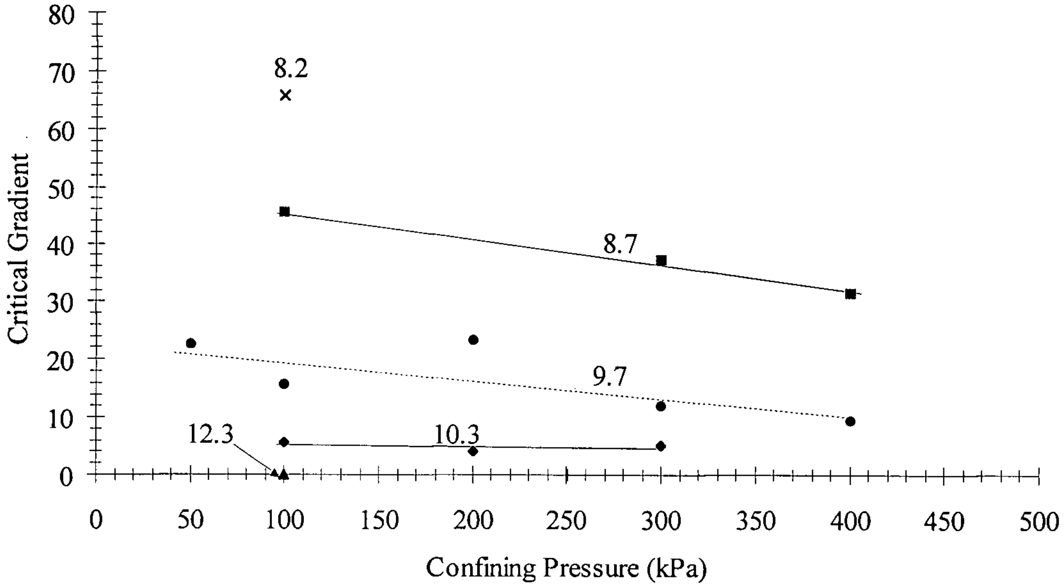

Figure 14 Effect of confining pressure on piping erosion.

(Kenney et al, 1985). This collapsing of arches will possibly occur during the application of the confining stress, and not during flow. This is because if the seepage forces are instrumental in collpasing some arches they would not be smaller in magnitude at higher confining stresses. As the grain size ratio increases, the confining pressure has less influence on the critical gradient. This may be because the soil/filter systems with larger grain size ratio are already metastable due to the large number of monosized soil particles that can potentially be mobilized, and so confining pressure does not have as large a relative influence. As previously stated, confining pressure probably has the greatest effect on particle stability during consolidation, when high stresses may cause the collapse of bridges formed at the soil/filter interface during pluviation (Section 4.2).

While the series of consistent results described previously demonstrate the influence of grain size ratios and confining pressure on seepage erosion, there are factors other than these that may influence stability. Filter thickness should have a similar effect as does grain size ratio since there are less traps through a thin filter, allowing more mobile grains in the soil to erode before the development of a sufficient filtration zone. Also, rapid gradient increases may not allow sufficient time to allow for bridge formation under the ambient gradient much in the same way as large confining pressures. The effects of filter thickness and rate of gradient increase are described in the subsequent sections.

4.6 EFFECT OF FILTER THICKNESS

While there has been much investigation into the behaviour of the filter, there has been little research into the form of the filter. Section 4.2 discussed some aspects of the filter construction, but one of the most basic attributes is the filter thickness. It is essential that a filtration zone is formed within the filter to effectively retain the soil particles from eroding away (Okita and Nishiaki, 1993). The filter thickness requirements sufficient to allow a filtration zone to develop were investigated in a series of experiments. Two soil/filter systems were evaluated under identical conditions of $D_{15f}/D_{85s} = 9.7$, confining pressure of 100 kPa, and using standard test procedures. One system had a standard filter thickness of 3.7 cm while the other had only 2.5 cm (both systems had identical soil thicknesses of 3.1 cm). The results of these tests are shown in Figure 15.

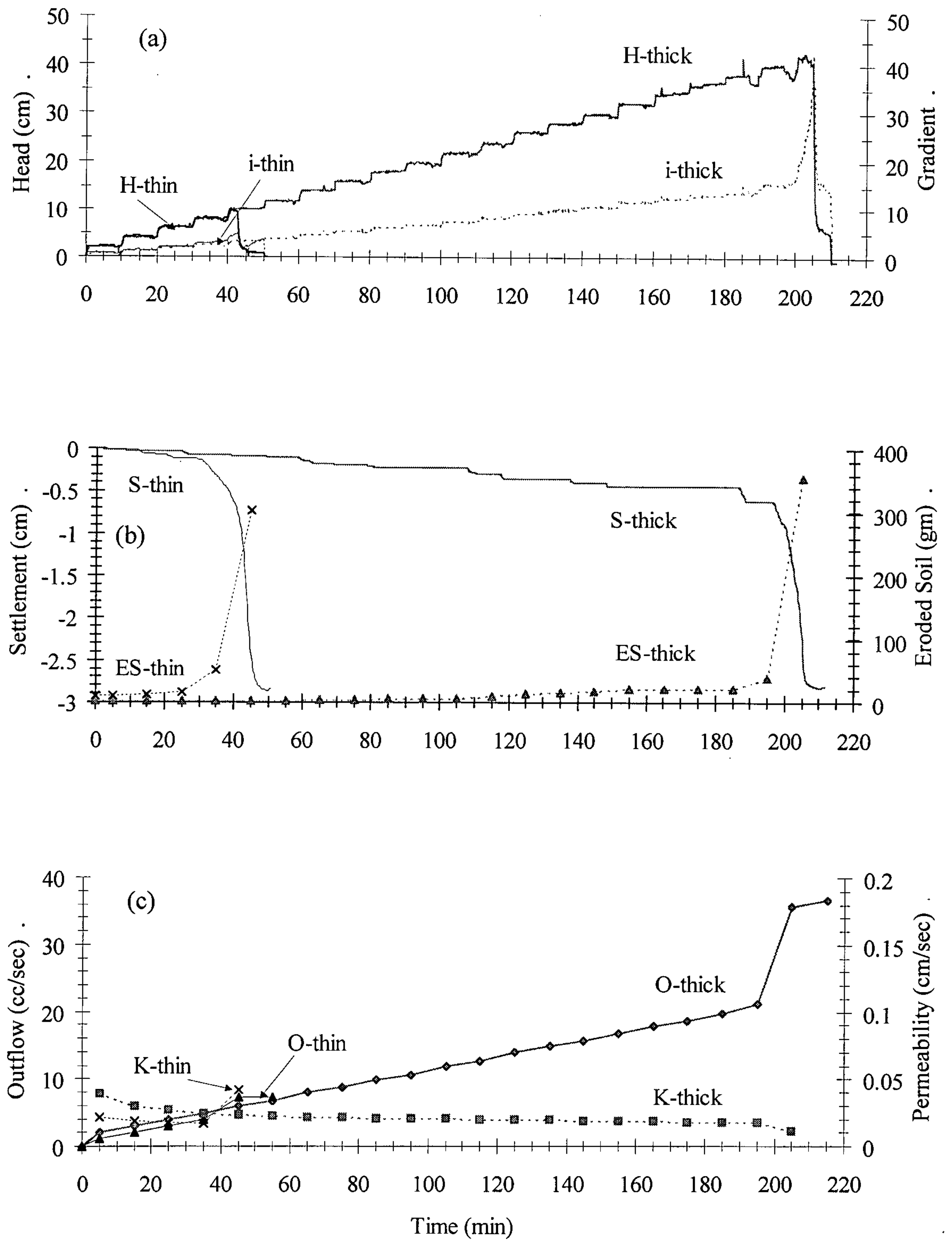

Figure 15 Effect of filter thickness on seepage erosion.

Figure 15a shows plots of head and gradient with time for the thin and standard filter thicknesses. The two tests performed identically until about 30 minutes, when the thin filter started to pipe at a gradient of 1.9. The system with the thicker filter, however, did not pipe until a critical gradient of 15.7.

The settlement and cummulative eroded soil-time plots for the two tests are shown in Figure 15b. The settlement curves are similar, until the thin filter system fails, and in both tests only a small amount of soil is being transported. Nevertheless, the thin filter sample consistently shows more soil eroding through than the thick filter sample. This indicates that, while the soil with the thick filter is being trapped within the filter, the soil with the thin filter is passing through. The thin filter apparently is not thick enough to form a full filtration zone for this soil/filter system.

At identical gradients the thin filter test showed similar but slightly lower outflow rates than the thicker filter, Figure 15c. This confirms the earlier assumption that the head loss is essentially over the soil length, as the filter length does not influence the outflow rate. If the head was being dissipated over the soil and filter lengths combined, then from Darcy's law a decrease in the total length (i.e. from a thinner filter) would result in an increase in the flow rate. The lower flow rate is clearly due to the thin filter sample having a slightly lower permeability, also plotted on Figure 4.8c. The system permeability is controlled by that of the soil, and not the filter, and should not be different in these two tests. The slight variation observed may be due to the thin filter sample experiencing more soil loss during consolidation. The thin filter allows the soil to move freely through (as the full filtration zone is unable to form which would retard the movement of soil particles). As the soil layer above the thin filter is experiencing significant restructuring as the soil particles move, there is an opportunity for the soil grains to rearrange in a denser state, decreasing permeability.

The lower critical gradient that triggers piping erosion indicates that the thin filter sample is less stable than the thick. From the settlement and cummulative eroded soil-time relationship (Figure 15c) it is evident that this instability is due to a lack of filtration zone formation. In a thicker filter, there is sufficient length available that it is probable the coarser fraction of the soil is more likely to intersect a constriction to retain it. This allows the smaller fraction to become entrapped behind this coarser fraction, forming a filtration zone (Okita and Nishiaki, 1993). A very thin filter presents fewer opportunities for a coarse soil particle to become trapped, allowing the coarser soil (and subsequently the fine soil particles) to escape. This was evident from examination by diagonally splitting the specimen after the test. In thicker filters, the soil only penetrated partially into the filter, showing a completely developed filtration zone. In the thin filter test, the soil had penetrated completely through the entire filter thickness, indicating an incomplete filter zone.

Clearly, filter thickness is of concern only in soil/filter systems where the development of a filtration zone is necessary to prevent piping erosion. For the system with D_{15f}/D_{85s} 7.3, no piping occurred despite a thin (2.1 cm) filter (up to the maximum achievable gradient). This is because at this low grain size ratio, which approaches the theoretical limit of 6.5 (below which the soil can no longer pass through the filter openings, as described in Chapter 1), the soil gets geometrically blocked essentially at the filter interface (Koenders, 1996).

4.7 EFFECT OF RATE OF GRADIENT INCREASE

As described in Sections 4.4 and 4.5, the absolute value of the gradient influences initiation of piping, whereas the duration over which it acts is not very critical. What has not been demonstrated by these experiments or the previous work is the influence of the rate at which the gradient is applied. Two tests were carried out at identical grain size ratio (D_{15f}/D_{85s} = 8.7) and confining pressure (100 kPa). In, one test the head was increased at the normal rate of 2 cm increments every 10 minutes, while in the other a very rapid rate of increase of 23 cm in 1 minute was imposed. This second test simulated the conventional practice used by previous researchers (Sherard et al, 1984) of applying the maximum head a municipal water supply system would allow right at the onset of the experiment. The results are shown in Figure 16. For the test which had the head incremented at the normal rate, the results are similar to those presented earlier, with the head reaching a maximum of 48 cm when the system failed with a corresponding critical gradient of 45.5, 235 minutes into the test, Figure 16a. Settlement and cummulative eroded soil-time curves in Figure 16b and outflow rate and permeability-time curves in Figure 16c are also typical and confirm the time of failure. The test which had a fast rate of gradient increase failed much sooner at approximately 0.75 minutes into the test. A head of only 23 cm was reached and a critical gradient of only 14.7 triggered failure. This gradient is only 32 % of the critical gradient necessary when the head was applied gradually. Thus systems that would normally be stable at a given gradient may become

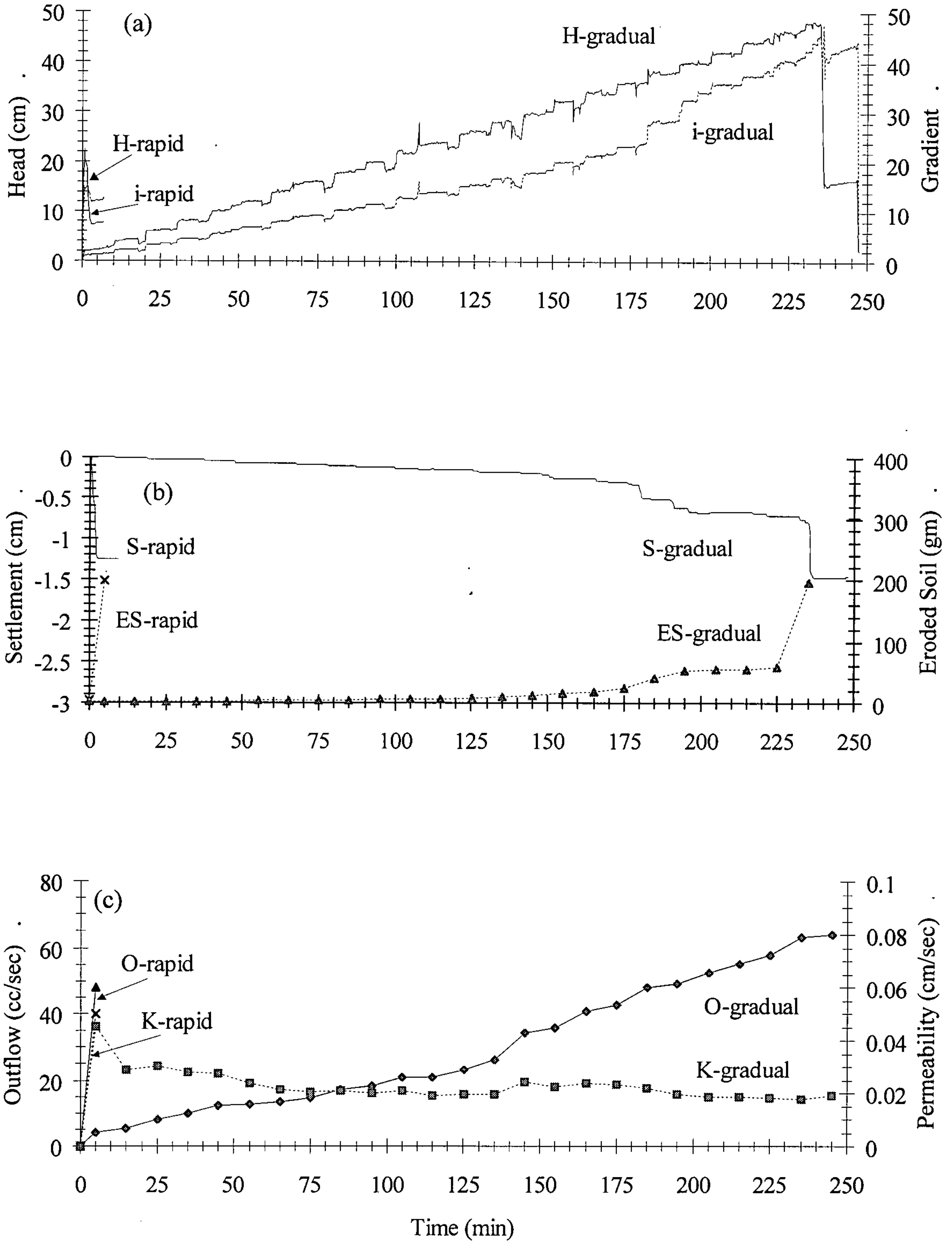

Figure 16 Effect of rate of gradient increase on seepage erosion.

unstable if the same gradient was imposed rapidly. A sudden large gradient may cause many particles that are metastable to become mobile at once. This may not allow enough time for a filtration zone to develop in addition to eroding out additional finer fraction of the soil. As noted by Kohler (1993), the temporary clogging of the filter by a sudden in-rush of fine particles would result in an increase of pore pressures, destabilizing the arch formation process. Under most pratical conditions (e.g. the filling of an earth dam resevoir), the head will be applied gradually, and experiments should use a procedure which more realistically reflects real conditions.

CHAPTER 5 CONCLUSIONS

The susceptability of cohesionless soils to piping through granular filters was studied using artificial glass beads in a newly designed permeameter. Different sizes of soils and filters were matched to produce soil/filter systems of several grain size ratios and their performance evaluated under several confining pressure levels. The purpose of the study was to investigate the effects of grain size ratio, confining pressure, filter thickness, and gradient flux and rate of gradient increase on the triggering of piping. The following conclusions are drawn from the test results presented in this thesis.

I. Literature Review

    A. Previous experimental studies have concentrated on establishing filter criteria based only on grain size ratio, that establishes whether a particular soil/filter system will experience piping. Terzaghi's criteria of $D_{15f}/D_{85s} \leq 4$ is generally considered conservative.

    B. Establishing criteria for the commencement of piping is often based on visual observation of soil movement. This movement may be due to the formation of a filtration zone rather than piping erosion.

    C. Apparatus design, soil/filter materials used, and testing procedure varied widely among different experimenters, making comparison of results difficult.

II. Experimental Aspects

A. To understand piping phenomena in a fundamental manner it is necessary to control more than just the grain size ratio. Confining pressure, filter thickness, and both the magnitude and the rate of gradient increase may all influence initiation of piping.

B. Establishing the commencement of the piping necessitates the monitoring of gradient and settlement continuously during the flow. Sampling the rate of eroded soil and outflow with time provided confirmation that piping had occurred.

C. Using artificial glass beads and forming saturated soil/filter systems by pluviation allowed for consistent sample preparation.

III. Test Results

A. The reliability of the experiments was demonstrated by excellent repeatability.

B. The grain size ratio D_{15f}/D_{85s} is the most important parameter in determining if a soil/filter system is susceptable to piping erosion. However additional criteria was found necessary to ensure the grain size ratio is compatible with the gradients imposed. It was found that:

   1. $D_{15f}/D_{85s} < 8$ was immune to piping. It is possible that this criteria may be lowered under more severe conditions than those investigated.

2. $D_{15f}/D_{85s} > 12$ spontaneously piped.
3. $8 < D_{15f}/D_{85s} < 12$ piping could occur only if a critical gradient was reached. As implied by (i) and (ii), this critical gradient decreases as the grain size ratio increases.

C. Confining pressure had a minor negative impact on stability. This is apparently due to the collapse of arches in the filtration zone from the increased stress, primarily during the application of this stress. Confining pressure level did not influence stability of soil/filter systems with a larger grain size ratio.

D. A minimal filter thickness is necessary to establish a filtration zone. A filter thinner than this minimum will allow piping to occur more readily (i.e. at a lower the critical gradient).

E. Imposing the gradient rapidly prevented a filtration zone from properly forming, thus triggering piping at a smaller critical gradient. Under almost all geotechnical applications a filter would not be subject to such rapid gradient changes and a gradual rate of change is more realistic.

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