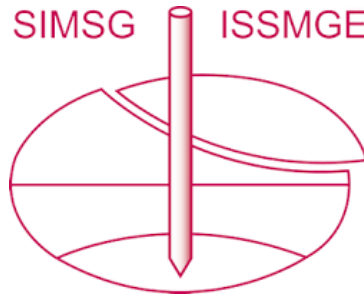


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Experiments on filter criteria under gentle hydraulic gradients

Expériences sur les critères de filtrage sous gradients hydrauliques doux

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ABSTRACT: Designing drainage structures for tailings facilities, requires considering filter ratios. The safety of existing criteria require consideration given that quality control can lapse over long construction periods. Tailings are often placed as slurries and it is questionable whether criteria developed under different conditions apply. Gold tailings at different water contents were placed above different filters and subjected to gentle seepage. Specimens were then frozen and later dissected to observe movement. Limited tests suggest movement starts to occur for $D_{15f}/D_{85b} > 9.2$ and that slurries do not flow into filters more readily than dry material.

RÉSUMÉ : La conception de structures de drainage pour les parcs à résidus miniers nécessite de prendre en compte les rapports de filtration. La sécurité des critères existants doit être prise en considération étant donné que le contrôle de la qualité peut s'éteindre sur de longues périodes de construction. Les résidus sont souvent placés sous forme de boues et on peut se demander si les critères élaborés dans des conditions différentes s'appliquent. Des résidus d'or à différentes teneurs en eau ont été placés au-dessus de différents filtres et soumis à une légère infiltration. Les spécimens ont ensuite été congelés et disséqués plus tard pour observer le mouvement. Des tests limités suggèrent que le mouvement commence à se produire pour $D_{15f}/D_{85b} > 9,2$ et que les boues ne s'écoulent pas plus facilement dans les filtres que le matériau sec.

KEYWORDS: filter criteria, gentle hydraulic conditions, embankment dams, tailings and mine waste

1 INTRODUCTION.

The stability of many geotechnical structures depends on safely draining seepage to prevent the buildup of pore pressures and ensuing reduction in effective stresses. However, drawing seepage to specific zones within a structure results in flow forces being applied to soil particles. It becomes important that considerations be made to ensuring these forces do not result in particle erosion. This is done by providing successive zones of geo-materials that meet filter design criteria. These criteria include: filter ability, propensity for internal stability, ability to self-heal, potential for material segregation during placement, drainage capacity and material durability (Messerklinger 2013).

This paper focuses on filter ability, or the particle size restrictions necessary between successive zones to prevent finer material from a base soil migrating into the subsequent filter material made up from coarser particles (Figure 1). These criteria are typically defined by ratios of grain size at particular percentage passing for the filter and base soil. For example, in 1926 Terzaghi proposed that D_{10f} (the particle size at 10%

passing on the filter particle size distribution) should not be larger than $10 \times D_{50b}$ (the particle size at 50% passing on the base soil particle size distribution) (Fannin 2008).

Subsequent work by Bertram, under the supervision of Terzaghi, refined this criterion first to $D_{15f}/D_{85b} \leq 6$ and later to $D_{15f}/D_{85b} \leq 4$. These criteria were largely developed for application as inverted filters for the control of seepage forces on the downstream toes of dams by the provision of a permeable surcharge heavy enough to balance seepage pressures (Fannin 2008). When applied to drainage zones in earth embankment dams, these were found inadequate as internal erosion was observed to take place in localized areas. These areas were formed as cracks, in impermeable cores, concentrated flow resulting in large hydraulic gradients (Messerklinger 2013).

Vaughan and Soares (1982) proposed the concept of a “perfect” filter based on observations following core cracking in the Balderhead Dam in the UK. This criterion was not based on a grading ratio but rather on the saturated permeability of the filter expressed as a function of the finest particles in the base soil. Filter ability is determined by its permeability and the criterion endeavors to ensure no particles are lost from the base soil (International Commission on Large Dams 2014). Vaughan and Soares (1982) defined their criteria as $k = 6.1 \times 10^{-6} \cdot \delta^{1.42}$, where k is the saturated permeability of the filter (m/s) and δ is the size of smallest particle retained (μm).

At roughly the same time James Sherard was investigating the performance of filters following core cracking, which he attributed to differential settlement or hydraulic fracturing during impounding (Messerklinger 2013). Laboratory work by Sherard and Dunnigan (1989) led to four criteria depending on the fines content (FC, % < 0.075mm) of base soils (see Table 1).

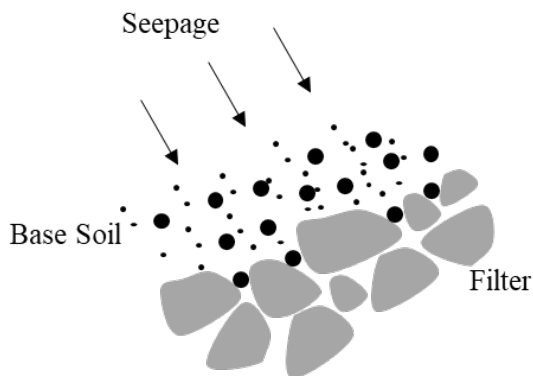


Figure 1. Illustration of a filter and base soil

Table 1. Critical filter criteria, after Sherard and Dunnigan (1989)

Soil type	Critical filter criteria
Group 1: FC = 85-100%	$D_{15f} \leq 9 \times D_{85b}$
Group 2: FC = 40-80%	$D_{15f} \leq 0.7 \text{ mm}$
Group 3: FC = 0-15%	$D_{15f} \leq 4 \times D_{85b}$
Group 4: FC = 15-40%	$D_{15f} \leq (40 - FC/40 - 15) \times (4 \times D_{85b} - 0.7 \text{ mm}) + 0.7 \text{ mm}$

The criteria cited above were determined by permeameter tests in which different base soils and filter material were placed and subjected to flow. These criteria can be considered conservative as they were developed using high seepage pressures and contain factors of safety. For instance, Bertram (1940) used hydraulic gradients between 6 and 20 and the filter ratio was reduced from 6 to 4. Vaughan and Soares (1982) judged a filter to have failed if 'dirty' seepage water was observed, although hydraulic gradients used are not stated Messerklinger (2013) states it as being determined for "high hydraulic gradients" and no consideration is made for base soil particles moving into the filter, choking pores and preventing further erosion. While Sherard and Dunnigan (1989) considered the ability of filters to become choked they pre-formed a 'crack' in the base soil, used water pressures of up to 412 kPa and applied a factor of safety in their final assessment.

Foster and Fell (2001) questioned the continued performance of existing dams that do not meet modern criteria. They reassessed the test work by Sherard and Dunnigan (1989) and carried out further testing in order to propose boundaries for the extent of erosion that could be expected. These were the no-erosion boundary, excessive erosion boundary and continuing erosion boundary (see Table 2).

Table 2. Criteria after Foster and Fell (2001)

Base soil	Excessive erosion boundary (flows 100 – 1000 l/s)	Continuing erosion boundary (flows > 1000 l/s)
$D_{95b} < 0.3 \text{ mm}$	$D_{15f} > 9 \times D_{95b}$	
$0.3 < D_{95b} < 2 \text{ mm}$	$D_{15f} > 9 \times D_{90b}$	
$D_{95b} > 2 \text{ mm}$, FC > 35%	$D_{15f} > \text{function of quantity of fine to medium sand in base}$	$D_{15f} > 9 \times D_{95b}$
$D_{95b} > 2 \text{ mm}$, FC < 15%	$D_{15f} > 9 \times D_{85b}$	
$D_{95b} > 2 \text{ mm}$, 15 < FC < 35%	$D_{15f} > 2.5 \times \{[(35 - FC) \times (4D_{85b} - 0.7 \text{ mm}) / 20] + 0.7 \text{ mm}\}$	

The design of filter zones in tailings dams to control phreatic regimes, typically uses the filter criteria cited above although questions remain such as:

- Are they overly conservative, considering tailings are often non-plastic and lie horizontal above filters making cracking less likely?
- How safe are criteria considering the limited availability of material and that site quality control often lapses over the long construction periods associated with tailings facilities?
- How should interface layers be designed when impounding mine tailings within waste rock embankments to prevent tailings run-out?
- What gradings are required so that tailings can be intermingled with waste rock?

In order to answer some of these questions, this paper proposes an experimental procedure and provides some initial findings to guide further research.

2 METHOD

A 110 mm diameter PVC pipe was used to construct a permeameter to investigate filter criteria under low hydraulic gradients (Figure 2). A bottom cap with three 4 mm holes sealed the base above which a non-woven geosynthetic was placed. Prior to placing any material, the PVC pipe was lined with releasing agent (grease). 170 mm of filter material was then placed above the non-woven geosynthetic followed by 170 mm of base soil. 160 mm of water was then placed above the base soil and allowed to drain (akin to the falling head permeability test). The rate at which the head of water fell was recorded.

Five different filter materials and a single base soil were used resulting in five filter ratios (D_{85b}/D_{15f}). The particle size distributions for the six materials are shown in Figure 3.

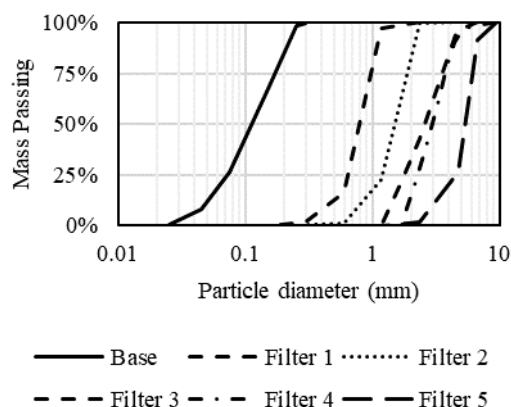


Figure 2. Particle size distributions tested

The base soil is a gold tailings from the Witwatersrand goldfields in South Africa. The three coarser filter materials were crushed andesite and the two finer filter materials were crushed silica. In addition to different filter ratios, the water content ($w = \text{mass of water, } m_w / \text{mass of solids, } m_s$) of the base soil was varied to model dry and slurry placement. Table 3 details the combinations tested.

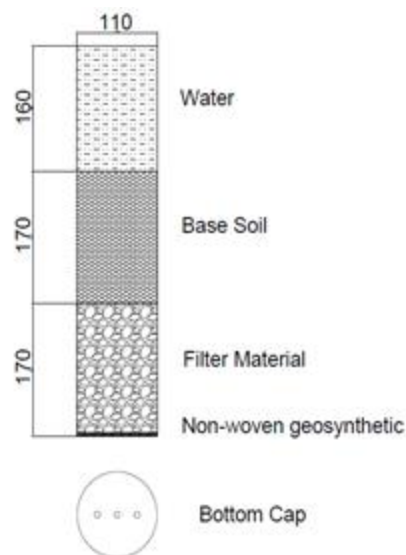


Figure 3. Experimental setup

Table 3. Experimental combinations

Test Number	Filter ratio (D_{15f}/D_{85b})	Water content of base soil (w)
1	2.8	0%
2	2.8	50%
3	2.8	100%
4	4.7	0%
5	4.7	50%
6	4.7	100%
7	7.5	0%
8	7.5	50%
9	7.5	100%
10	9.2	0%
11	9.2	50%
12	9.2	100%
13	17	0%
14	17	50%
15	17	100%

Once all the water had seeped through the sample, the sample was placed in a deep freezer ($-15 \pm 5^\circ\text{C}$) for 24 hours, in order to freeze the entire column. After freezing, the end cap was removed and hot water ($\pm 60^\circ\text{C}$) run over the outside of the PVC pipe and the sample gently pushed out. The column was then dissected and a photographic record kept to determine whether base soil had migrated into the filter.

3 RESULTS

Figures 4 show the first series of tests on materials with a filter ratio of 2.8. Some smearing of filter material onto the base soil took place during dismantling, however, no base soil migrated into the filter. Figure 5 shows similar observations for tests on materials with a filter ratio of 4.7. In both cases, the filter soil did not saturate significantly, suggesting that a constant head would be required to facilitate a longer seepage period.

For materials with a filter ratio of 7.5 (see Figure 6) a ± 10 mm layer of clogged filter material developed, however no migration of base soil was observed further than this. Movement of base soils started to occur for materials with a filter ratio of 9.2 (see Figure 7). However, perhaps counterintuitively, the most movement occurred with the dry base soil and the least with the base soil prepared at $w = 100\%$. For the dry base soil fines migrated ± 100 mm into the filter, for the base soil at $w = 50\%$ fines migrated ± 10 mm and practically no migration took place for the base soil at $w = 100\%$. A possible reason for this was that the dry tailings tended to flow under gravity more than wet tailings. Wet tailings tended to adhere together which could have been sufficient to prevent initial movement prior to seepage taking place.

Once the filter ratio reached 17 (see Figure 6) failure of the filter to retain base soil was patently obvious with fines having clogged up the entire length of filter present.

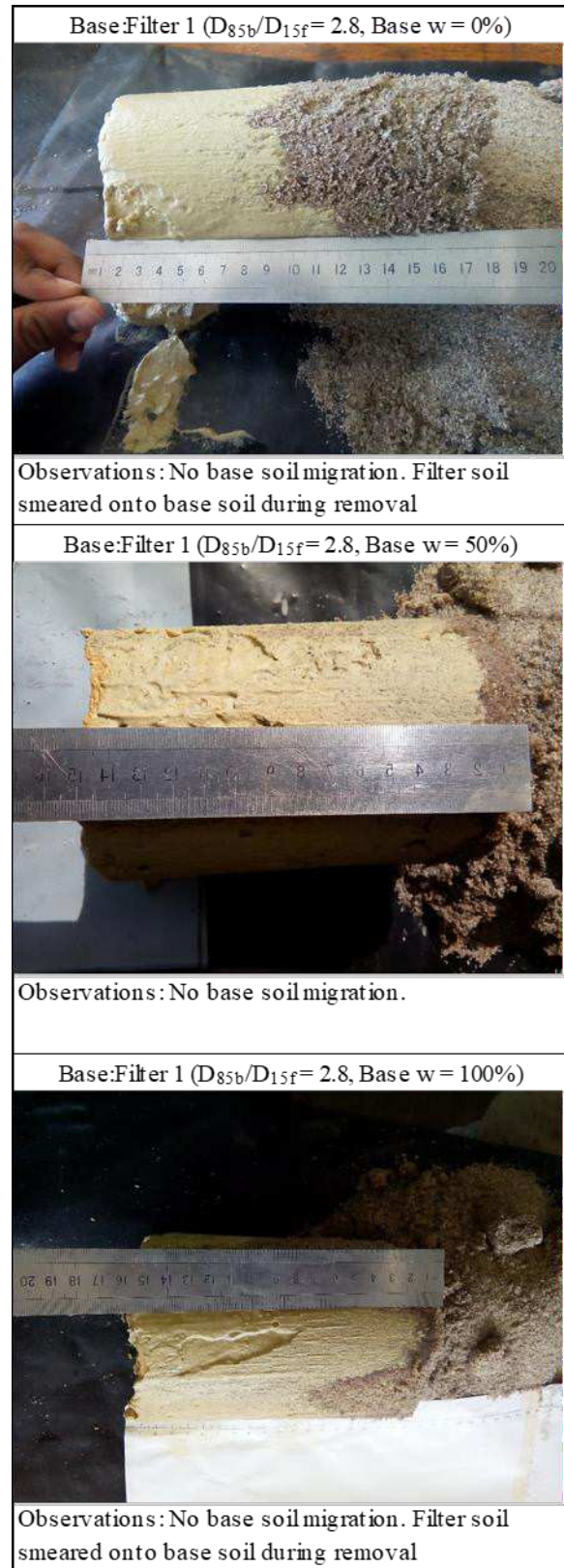


Figure 4. Results from Tests No. 1 to 3

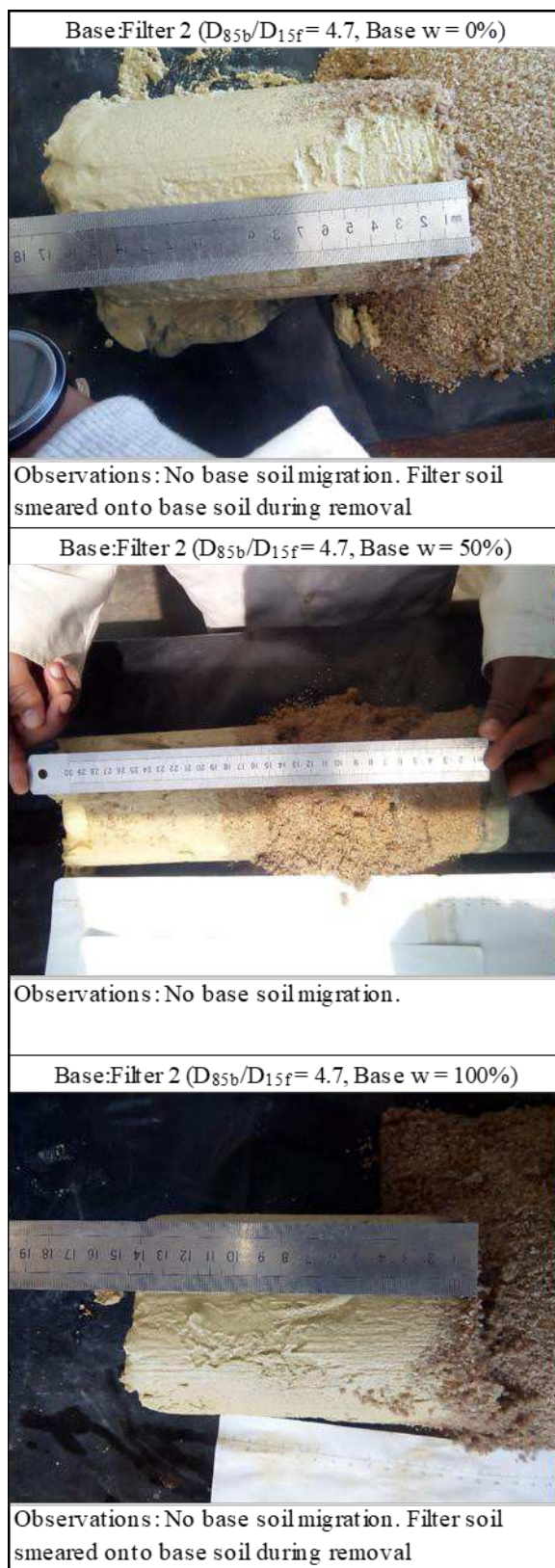


Figure 6. Results from Tests No. 4 to 6

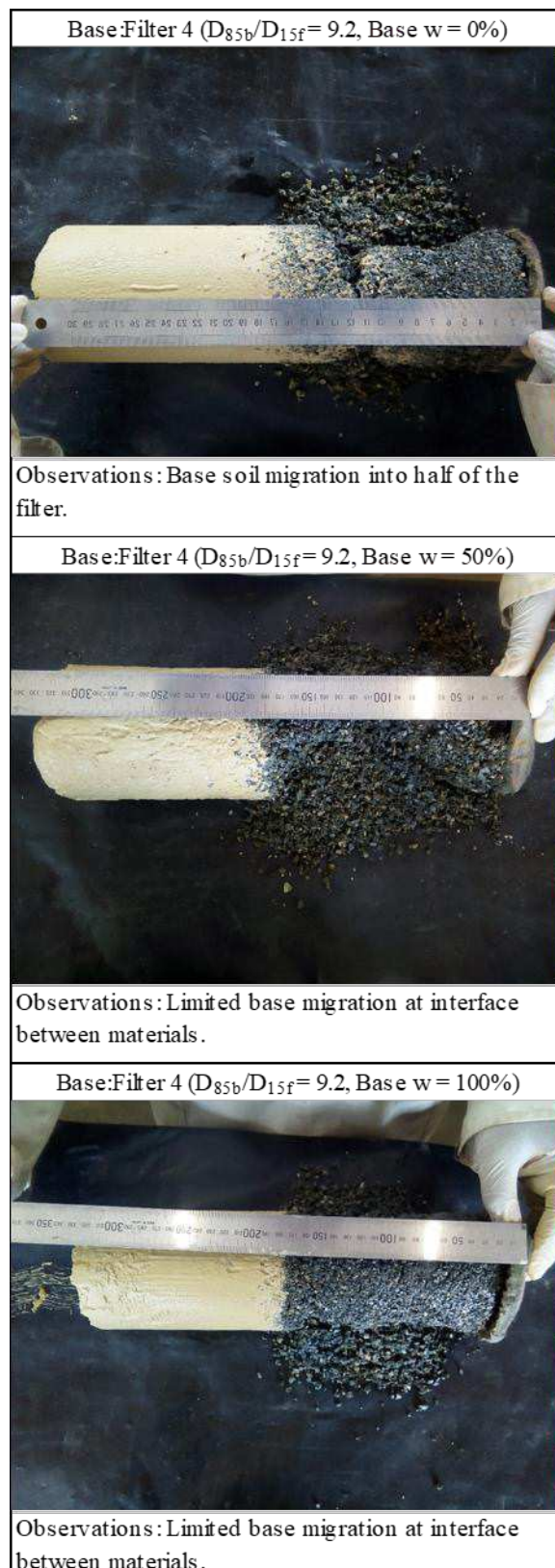


Figure 5. Results from Tests No. 7 to 9

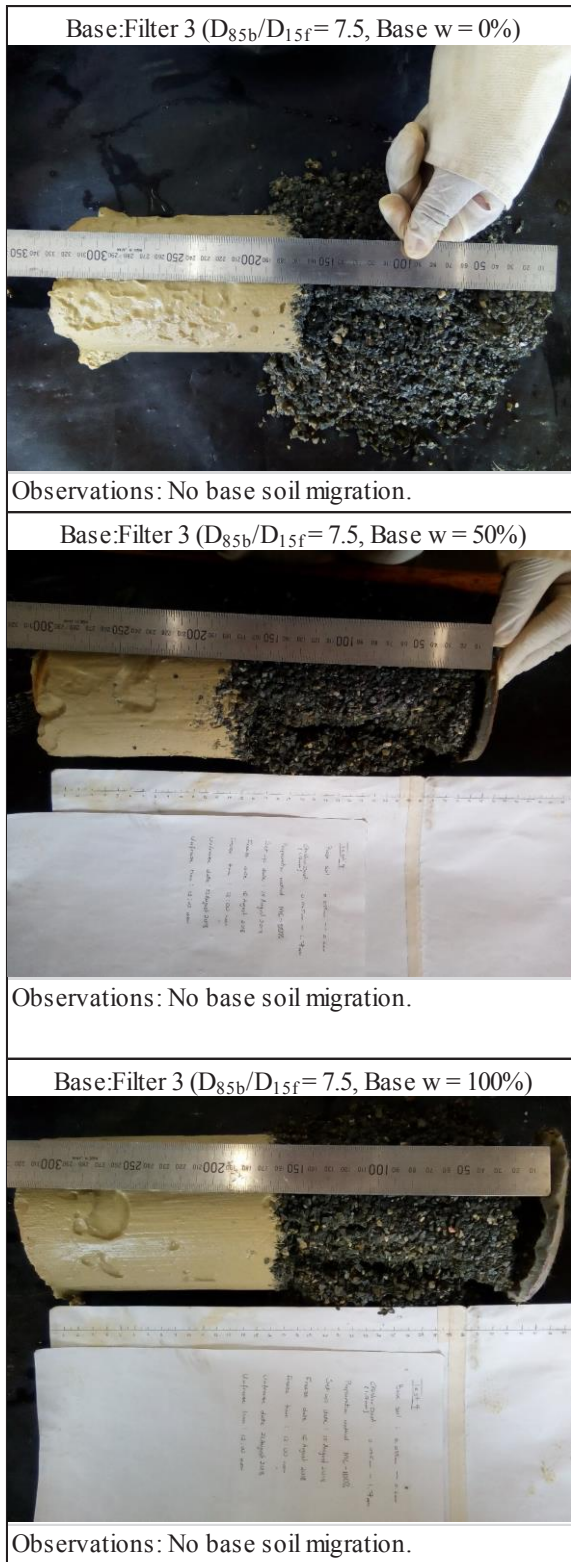


Figure 7. Results from Tests No. 10 to 12

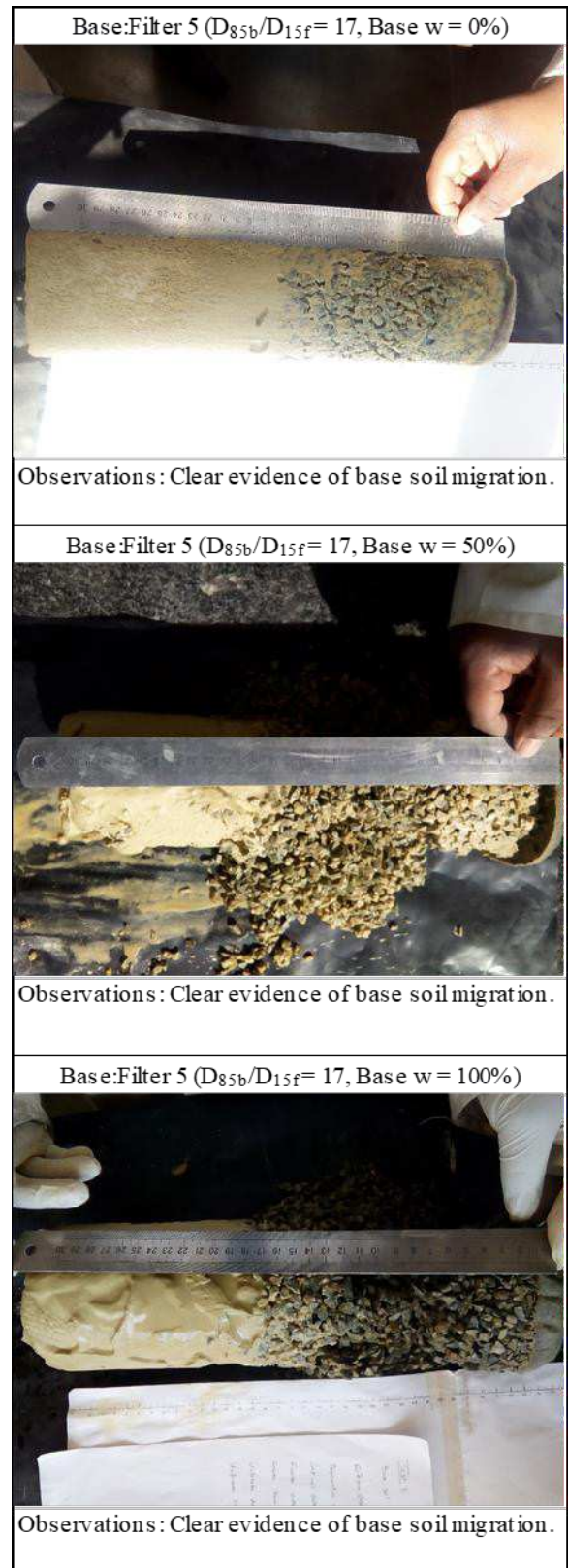


Figure 8. Results from Tests No. 13 to 14

4 SUMMARY

Modern filter ability criteria have been widely adopted in practice; however, questions remain about how conservative they are and what level of safety they provide. Within the domain of tailings disposal, questions remain about how slurries interact with filters.

An experimental approach is proposed in this paper in which, following permeameter testing, the permeameter is frozen and dissected to observe particle movement. In this case, gentle hydraulic gradients were used and base soils prepared at different water contents to model slurries.

Gentle hydraulic gradients were used to give an idea of the safety inherent to existing criteria. Findings suggested that particle movement only occurred for filter ratios (D_{15f}/D_{85b}) of 9.2 and above. However, the flow regime may be too gentle to be representative and further work is required on this aspect.

The slurry tests can be used to give insight into the design of interface layers for waste rock impoundments for tailings. Tests at $D_{15f}/D_{85b} = 9.2$, suggested that slurries are less likely to move into filters compared to dry soils. However, this requires further investigation. This should include thinking about how to better align the experimental method to field conditions. Further, the tailings were observed to develop some adhesion when saturated and this requires further investigation, particularly with other tailings. Tests at $D_{15f}/D_{85b} = 17$ showed no dependence on tailings water content (i.e. slurried versus dry).

Results from only five filter ratios are reported in this paper and additional work is required to extent these findings to more general conditions.

4 ACKNOWLEDGEMENTS

Test work was done at the University of the Witwatersrand.

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