Scalp-and-replacement of oversize particles for internal erosion testing

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ABSTRACT
Internal erosion is one of the major risks managed by the owners of embankment dams. Zoned earthfill materials are widely graded, with a maximum particle in the coarse gravel to cobble size range. Thus, laboratory testing for internal erosion requires a relatively large specimen size. A brief review of the literature addresses specimen size for permeameter testing of soils with respect to the maximum particle size. The 'scalp-and-replace' method is then examined, whereby oversize particles are removed and replaced with smaller particles of equal mass, to yield a modified gradation. The results show that a widely graded mix of sand and gravel can be scalped-and-replaced up to 35% without significant change to its hydraulic response. Informed by the findings, a proposal is made for testing scalped-and-replaced gradations of embankment dam filters in a large flexible-wall permeameter (FXP) with a facility to monitor the rate of erosion and associated volume-change by means of double-walled triaxial cell.

RÉSUMÉ
L'érosion interne est l'un des risques majeurs gérés par les propriétaires de barrages en remblai. Les matériaux de remblai zonés sont largement calibrés, avec une particule maximale dans le gavier grossier à la taille de galets. Ainsi, les tests de laboratoire pour l'érosion interne nécessitent une taille d'échantillon relativement grande. La littérature aborde la taille des échantillons pour les tests de perméamètre des sols en ce qui concerne la taille maximale des particules est brève. La méthode « scalper et remplacer » est ensuite examinée, dans laquelle les particules surdimensionnées sont supprimées et remplacées par des particules plus petites de masse égale, pour donner une gradation modifiée. Les résultats montrent qu'un mélange largement calibré de sable et de gravier peut être scalpé et remplacé jusqu'à 35 % sans modification significative de sa réponse hydraulique. Informés par les résultats, une proposition est faite pour tester les gradations scalpées et remplacées des filtres de barrage en remblai dans un grand perméamètre à paroi flexible (FXP) avec une installation pour surveiller le taux d'érosion et le changement de volume associé au moyen de cellule triaxiale à double-paroi.

1 INTRODUCTION

Internal erosion of soil occurs through several mechanisms (FEMA 2015), one of which is internal instability of widely and gap-graded soils whereby the finer fraction erodes through its coarser fraction by a process of suffusion or suffosion (Fannin and Slangen 2014). Empirical methods are currently used to assess the potential for internal instability of a gradation (ICOLD 2017 and USBR-USACE 2019). Susceptible gradations may be evaluated in a program of laboratory permeameter testing, as described, for example, by Fannin, Li, and Anderlini (2017) for the construction records of a dam with a sinkhole incident.

1.1 Permeameter testing: minimum specimen size

Rigid-wall permeameter studies on the hydraulic conductivity of uniformly-graded spherical particles (see, for example, Carman 1937; Chu and Ng 1989; de Klerk 2003; Dixon 1988; Leva and Grummer 1947; McGeary 1961; and Zou and Yu 1995) show an increase of specimen porosity with diminishing permeameter-to-particle diameter ratio (D/d_{max}) less than approximately 10 (see Figure 1). The finding is attributed to the rigid wall of the permeameter imparting order to an otherwise random arrangement of particles.

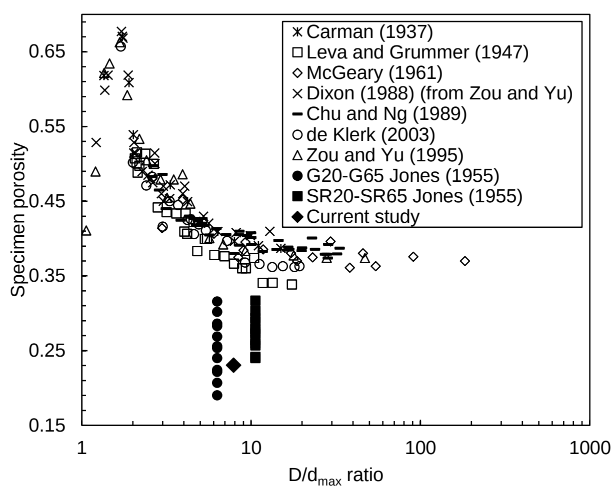

Figure 1. Porosity of monodisperse spherical particles in rigid-wall cylinders

Select studies reported in the literature on widely graded materials using a rigid wall permeameter (see Table 1) have involved a 3.4 ≤ D/d_{max} ≤ 14.6. Some of the studies were made to establish the hydraulic conductivity of a test gradation (see for example Jones 1955), and other studies were made to examine the potential for seepage-induced internal instability of a test gradation (see for example Kenney and Lau 1985).

Table 1. Summary of specimen size ratios from previous studies on widely graded materials

Study	C_u range	d_{max} (mm)	D (mm)	D/d_{max}
Jones (1955)	5.4-10.5	19.1	203.2	10.6
	5.9-21.1	76.2	482.6	6.3
Moffat (2005)	79	76.2	279	3.7
	24-36	19.1	279	14.6
Kenney and Lau (1985)	3-28	40	240	6.0
	18-79	100	550	5.5
Garner and Sobokowicz (2002)	79	50	304.8	6.1
Lafleur (1984)	-	38	150	3.9
Sherard et al. (1984)	1.4 - 37	25.4	85.7	3.4
Crawford-Flett (2014)	173-5384	38	279	7.3
Wan (2006)	21-5709	76	300	3.9

In permeameter testing of widely graded embankment dam materials, consideration may be given to limit the maximum particle size of the test gradation (d_{max}) in order to limit the diameter (D) of the specimen in a permeameter test device. Complete removal, or scalping, of the oversize particles is believed acceptable when the microstructure of the grain assemblage renders them 'floating' in a matrix of finer particles. Otherwise, the option of scalp-and-replacement must be considered, in which the coarsest grains are removed and replaced up to a relatively smaller maximum particle size. A necessary requirement is that the porosity, hydraulic conductivity, and susceptibility of the test gradation to internal instability be largely unchanged by the action of scalping-and-replacement.

In the current study, material from the South Moraine borrow source for the WAC Bennett Dam (see Figure 2) has been sampled for testing in a Flexible-wall Permeameter (FXP) device (see Figure 3). The objective of the current study is to examine the onset and continuation of any seepage-induced internal instability in gradations believed representative of the zoned Transition material of the Bennett dam. The Transition zone serves as the first of a two-zoned filter to the till Core material of the embankment dam. Soil from the South Moraine borrow source was processed to meet a specification for the zoned Transition material: the 80% limits of the as-placed sand and gravel material (see Figure 4) are reproduced from records of the construction period.

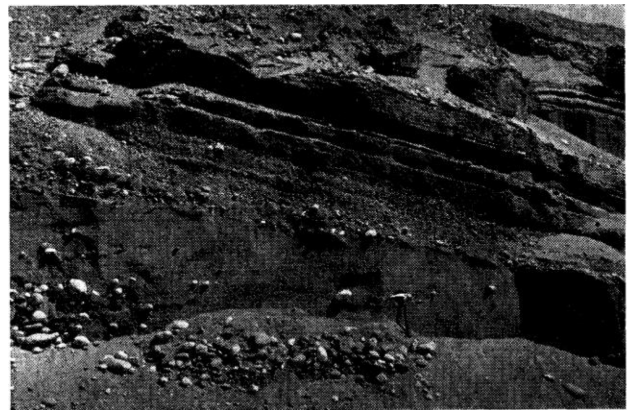

Figure 2. Well-bedded sands and gravels in the South Moraine borrow source of the WAC Bennett Dam (from Morgan and Harris 1967 © Canadian Science Publishing or its licensors)

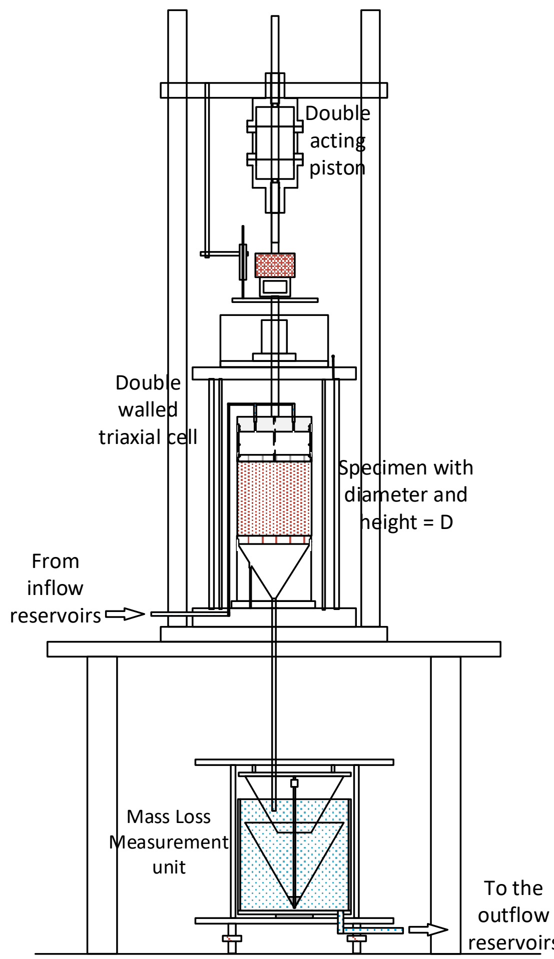

Figure 3. Schematic drawing of the Flexible-wall Permeameter (FXP) for the current study.

Herein, we reanalyze the rigid-wall permeameter test data of Jones (1955) for specimens of widely-graded sand and gravel, with the objective of determining an acceptable percentage limit for removal of oversize particles. Informed by that finding, we then propose a limit for scalp-and replacement of Transition material that yields a maximum particle size (d_{max}) for the test gradations. The diameter (D) of the flexible-wall permeameter test specimen is governed by a recommended ratio (D/d_{max}).

2 REANALYSIS OF JONES (1955)

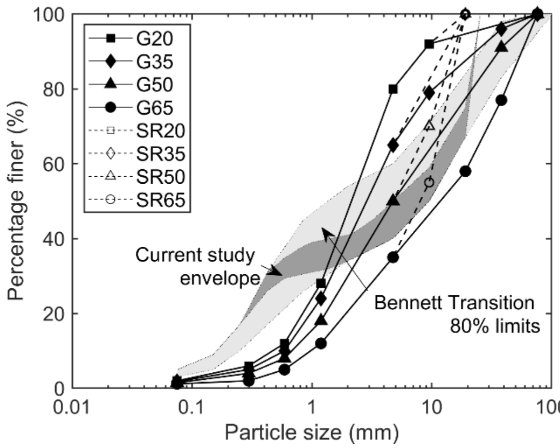

Figure 4. Particle size distribution curves (from Jones 1955): Gxx-SRxx refers to the original and scalped-and-replaced gradation pair, with 'xx' being % gravel content

Jones (1955) examined the influence of relative density and gravel content on the hydraulic conductivity of sand-gravel mixes (see Figure 4). Two rigid-wall permeameters of diameter 203 mm and 483 mm were used in testing, yielding two different values of D/d_{max} (see Table 1). In reanalyzing the Jones (1955) data, we identify and relabel four gradation-pairs, SR20-G20, SR35-G35, SR50-G50, and SR65-G65 with d_{max} = 19 mm (Figure 4 open-symbol), and d_{max} = 76 mm (Figure 4 closed-symbol). As a consequence of their respective shapes, these four gradation-pairs offer opportunity to address the influence of scalp-and-replacement by means of a reanalysis that is beyond the scope of the original study in 1955.

For example, the SR35 gradation represents a scalp-and-replace to 19 mm minus of the G35 gradation that has 35% gravel content to 76 mm. In all four pairings, the SRxx-Gxx combinations may be used to study the impact of removing all of the coarse (19 to 76 mm) gravel content and replacing it with a greater content of fine (4.75 to 19 mm) gravel. Accordingly, each SRxx-Gxx gradation-pair has the same percentage gravel content and the same size-distribution curve in the sand (4.75 mm minus) range.

Jones (1955) reported the porosity and hydraulic conductivity obtained for the eight gradations at three relative densities of 50%, 60%, and 70% in a total of 24 rigid-wall permeameter tests (see Figure 5). A common trend is that of increasing conductivity with greater porosity. The relatively low values of specimen porosity $0.15 < n < 0.35$ are attributed to the wide range of particle sizes in the Jones (1955) test gradations.

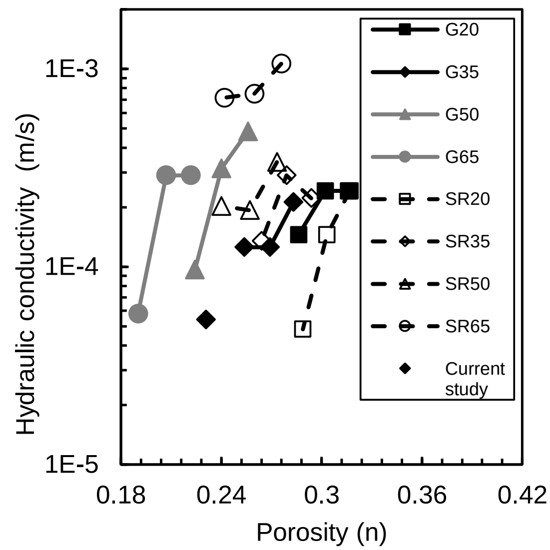

Figure 5. Measured hydraulic conductivities from Jones (1955)

2.1 D/d_{max} ratios of Jones (1955)

The combination of eight widely-graded soils and two permeameters in the Jones (1955) study yield a $6.3 \leq D/d_{max} \leq 10.7$ (see Table 1). On the matter of the SRxx gradations, the SR20, SR35, and SR50 comply with the ASTM D2434-19 Standard Test Method for Permeability of Granular Soils (Constant Head) recommended minimum D/d_{max} ratio of 8 (see Table 2). The SR65 is non-compliant but is deemed acceptable for reanalysis because of its well-graded size range in combination with a D/d_{max} ratio close to the ASTM D2434-19 requirement of 12 (see Table 2).

Table 2. Specimen size compliance of Jones (1955) with ASTM D2434-19

Particle size distribution	D/d_{max}		Mass fraction smaller than 19mm (%)	ASTM compli-ance
	Jones (1955)	ASTM D2434-19		
G20	6.3	8	95	No[1]
G35	6.3	8	88	
G50	6.3	12	77	No[2]
G65	6.3	12	58	
SR20	10.7	8	100	Yes
SR35	10.7	8		
SR50	10.7	8		
SR65	10.7	12		No[1]

[1]ASTM non-compliant, but deemed acceptable; [2]ASTM non-compliant

Although the four Gxx gradations are ASTM D2434-19 non-compliant (see Table 2), the G20 and G35 gradations are deemed acceptable for reanalysis because of the significant percentage of particles smaller than 19 mm in combination with a D/d_{max} ratio close to the ASTM D2434-19 requirement of 8. In contrast, the non-compliance of G50 and G65 is expected to yield an overestimate of hydraulic conductivity (Chapuis, Gatien, and Marron 2020), which introduces a limitation that is explicitly addressed in the reanalysis.

2.2 Non-dimensional porosity-conductivity relation

The porosity-conductivity relation of the four gradation-pairs at each of the three relative densities is presented in non-dimensional form (see Table 3). Scalp-and-replacement to 35% gravel content, with its commensurate removal of up to nearly 12% coarse gravel content (see Figure 4), is found to impart a negligible change to specimen porosity and a relatively small change in conductivity of less than about two ($0.3 \le k_{SR}/k_G \le 2.3$). Scalp-and-replacement to 50% gravel content, which involves removal of about 25% coarse gravel content (see Table 3), yields a small change in porosity of less than 10% ($1.0 \le n_{SR}/n_G \le 1.07$) and a change in conductivity that is again less than about two ($0.6 \le k_{SR}/k_G \le 2.1$). In contrast, the scalp-and-replacement to approximately 65% gravel content is associated with removing close to 40% of the coarse gravel content and yields a relatively large change of nearly 25% in the porosity ($1.24 \le n_{SR}/n_G \le 1.27$) and a change of up to an order of magnitude in hydraulic conductivity ($2.6 \le k_{SR}/k_G \le 12$). As noted previously, the limitation of the Jones (1955) permeameter tests means the hydraulic conductivity from the six permeameter tests on the G50 and G65 gradations is believed too large and the corresponding k_{SR}/k_G ratios are thus believed too small (see the gray data points in Fig. 5).

Table 3. Non-dimensional porosities and hydraulic conductivities of the paired gradations.

Gradation pair	n_{SR} / n_G range	k_{SR} / k_G range	Acceptable
SR20/G20	1.00-1.01	0.33-1.00	Yes
SR35/G35	1.04-1.04	1.05-2.31	Yes
SR50/G50[1]	1.07-1.07	0.62-2.10	No
SR65/G65[1]	1.24-1.27	2.58-12.33	No

[1]D/d_{max} ratios ASTM non-compliant

2.3 Gradation shape analysis for internal instability

The susceptibility of a gradation to internal instability is assessed using empirical criteria (see, for example ICOLD 2017 and USBR-USACE 2019). The Kenney and Lau (1985) gradation shape analysis and limiting $(H/F)_{min} = 1$ criterion (Kenney and Lau 1986) is commonly advocated for widely-graded coarse-grained soils (see, for example, Fannin, Li, and Anderlini 2017 and Molina-Gomez and Chapuis 2021). The empirical method yields a shape curve of the mass fraction (H) between 'd' and '4d' versus the percentage finer (F) than 'd'. The boundary between internally stable and potentially unstable soils is characterized by the H/F ratio to F = 30 % for soils with a narrowly graded ($C_u < 3$) coarse fraction, which is the case for the SR20, SR65 and G20 gradations and to F = 20 % if the coarse fraction is well-graded like that of SR35, SR50, G35, G50, and G65. None of the Jones (1955) gradations is assessed as potentially internally unstable and, with the exception of the SR65-G65 gradation pair, the remaining Sxx-Gxx pairs yield identical H-F shape curves (see Figure 6). The change of the H-F shape curve from G65 to SR65 indicates the latter gradation is relatively less susceptible to internal instability. All gradations were also found internally stable according to the commonly used Wan and Fell (2008) method, and the Li and Fannin (2008) adaptation of Kenney and Lau (1986) and Kezdi (1979). Given the findings are solely from analysis of internally stable gradations, further tests and analysis need to be conducted on internally unstable gradations in order to assess their general applicability.

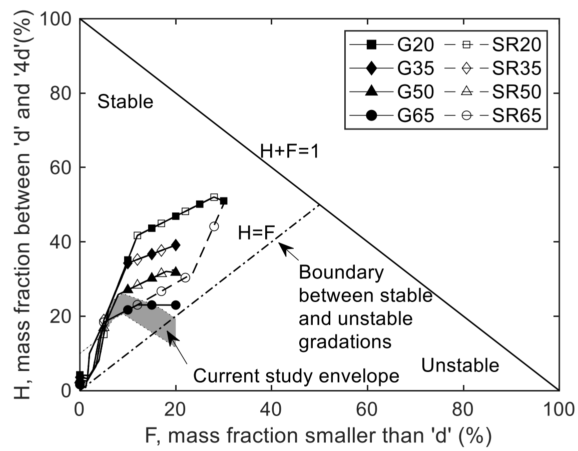

Figure 6. Kenney-Lau shape analysis of the Jones (1955) test gradations

3 CURRENT UBC-BCH-NSERC STUDY

In the current study, material from the South Moraine borrow source for the WAC Bennett Dam has been sampled for testing in a Flexible-wall Permeameter (FXP) device. The primary objective is to examine factors governing the rate of any mass loss arising from internal erosion that might occur in the test specimen.

The gradations of greatest interest plot within the dark grey 'current study envelope' shown in Figure 7. This envelope is an internally unstable subset of the 'as placed' gradations of the Bennett Transition (see Figure 6). The gradations are being tested in a Flexible-wall Permeameter (FXP) designed and built at UBC (see Figure 8). The permeameter has a capacity to monitor the mass loss due to internal instability in real-time using a mass loss measurement unit placed below the specimen. Any associated volume change is measured by the double-wall cell arrangement that monitors the volume of the cell fluid.

The diameter of the FXP test specimen is selected based on the rationale described below.

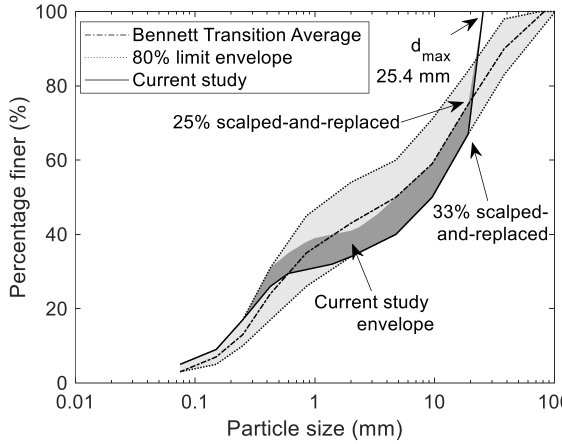

Figure 7. A comparison of gradations examined in the current study with W.A.C. Bennett dam Transition gradations as reported by Morgan and Harris (1967)

Based on the data for the porosities of uniform spheres contained in a rigid wall cylinder (see Figure 1), a D/d_{max} ratio of 8 is deemed sufficient for the current study because of following reasons: (i) at a ratio of 8, the overall porosity is similar to the porosity of a very large specimen in a rigid cell, (ii) the rigid wall effects are mitigated by the flexible wall of the FXP, and (iii) with a widely graded material, the relatively smaller particles are to fill the voids formed between the wall and the larger particles, which further reduces the wall effects. A diameter of 200 mm is chosen for the FXP test specimen with a view to limit the d_{max} to 25.4 mm.

A maximum particle size of 25.4 mm equates to a scalp-and-replacement of 25% to 33% of the Bennett Transition gradations as shown in Figure 7. This is considered acceptable as the reanalysis of Jones (1955) data showed that a scalp-and-replacement of up to 35% causes only negligible changes in the material's porosity and hydraulic conductivity and its susceptibility to internal instability.

Figure 8. The 200 mm Flexible-wall Permeameter (FXP) of the current study in the UBC graduate soils laboratory

4 SUMMARY AND CONCLUSIONS

In permeameter testing of widely graded embankment dam materials, consideration may be given to limit the maximum particle size of the test gradation (d_{max}) in order to limit the diameter (D) of the specimen in a permeameter test device. A requirement of any scalp-and-replacement, in which the coarsest grains are removed and replaced up to a relatively smaller maximum particle size, is that the porosity, hydraulic conductivity, and susceptibility of the test gradation to internal instability be largely unchanged.

An examination of past rigid-wall permeameter studies on the hydraulic conductivity of uniformly-graded spherical particles shows an increase of specimen porosity with diminishing permeameter-to-particle diameter ratio (D/d_{max}) less than approximately 10. A smaller limiting ratio of D/d_{max} = 8 is assumed acceptable for flexible-wall permeameter studies of widely graded soil.

Reanalysis of the Jones (1955) test data identifies four gradation-pairs that provide insight on the effect of scalp-and-replacement of oversize particles. The data take the form of specimen porosity and hydraulic conductivity, obtained at three values of relative density, for eight widely-graded sand-gravel mixes with the gravel content in the range of 20% to 65%. The SR20-G20 and SR35-G35 gradation pairs indicate that the scalp-and-replacement to 35% of the gradation curve results in no significant change to porosity and little change to the hydraulic conductivity. In contrast, the SR65-G65 pair confirms that any attempt to scalp-and-replace to 65% of the curve yields a significant increase in porosity, and conductivity and change in H-F shape curve, which collectively render the SR65 gradation materially different to the G65 gradation.

Informed by these findings, the following conclusions are drawn:

- Scalp-and-replacement to 35% of widely graded gravel-sand mixtures is believed acceptable for permeameter testing, because it imparts no significant change to the porosity and hydraulic conductivity of the specimen.
- Bennett Transition gradations may be scalped-and-replaced in accordance with this provision to yield a d_{max} = 25.4 mm
- Assuming a D/d_{max} = 8 is acceptable for testing of widely graded soil in a flexible-wall permeameter establishes a minimum specimen diameter D = 200 mm for testing of the scalped-and-replaced Bennett Transition soil.

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