Impact of specimen preparation on erosion and post-erosion response of gap-graded soils

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ABSTRACT

Internal erosion is a major threat to the safety and operation of water management structures. Recent failures of embankment dams reported in Australia, Canada, and the US are fresh reminders of the importance of this ongoing issue. Suffusion, the focus of this paper, is one of the main modes of internal erosion occurring in internally unstable soils. It initiates internally, continues slowly with no visible signs, and leads to complete failure if not detected early.
Despite recent advances in understanding the influence of suffusion on the mechanical behaviour of internally unstable soils through laboratory investigations, the impact of sample preparation techniques on the soil response during erosion and afterwards is yet to be fully undrstood. When it comes to laboratory investigation of remoulded soils, it has been understood that soil specimens prepared by different techniques show different characteristics and soil fabrics. This research studied the influence of sample preparation methods on the erosion of non-plastic fine particles in internally unstable soils and their mechanical consequences. Soil samples with two gradations, on the borderline of stable and unstable and one fully unstable, were prepared using moist-tamping and wet pluviation techniques and were subjected to a two-hour downward seepage. The erosion progress and pre- and post-erosion drained mechanical behaviour of samples were investigated. Tests result showed a difference in the erodibility of fine particles for the sample on the borderline of internal stability prepared by different techniques, but similar mechanical behaviours for both gradations.

Keywords: Internal erosion; Specimen preparation; Mechanical behaviour; Erodibility.

1. Introduction

Internal erosion is a leading cause of failure in earthen structures (ICOLD 2017) which can happen under four mechanisms: concentrated leaks, backward erosion, contact erosion, and suffusion. Suffusion, the focus of this study, starts with the detachment of selective loose fine particles and continues with their transport under seepage flow (ICOLD 2017). These fine particles are washed through the voids of the soil structure, mainly made by coarse particles. This mode of internal erosion occurs typically in the gap or broadly graded internally unstable soils where fine particles are not fully involved in the stress fabric. Suffusion modifies the soil microstructure, which could later lead to deformations at the macroscopic scale and accordingly impacts the mechanical behaviour of the soil (Hosn et al. 2018).

Several studies have been performed to examine the effective factors controlling suffusion. (Kézdi 1979) implemented laboratory tests on gap-graded materials and postulated that suffusion occurs when the coarse particles are not able to act as a filter to retain the fine particles. Later, (Kenney et al. 1985) proposed that suffusion can only occur when three distinct criteria are met: (*i*) fine particles must not be held in place by other particles or be under low effective stress (mechanical criterion); (*ii*) fine particles must fit and move freely through constrictions of the void spaces between coarse particles (geometric criterion); and (*iii*) there must be sufficient seepage forces to carry the fine particles through the void spaces (hydraulic criterion).

Among the various experimental stages designed to determine the soil's mechanical behaviour, the sample preparation technique has been proven to influence the soil's geometric properties. It can change the soil's fabric and pore and contact networks. Such changes can impact the hydraulic and mechanical behaviour of soil samples making the result misleading if the constructed soil fabric is different from the real conditions (Cai et al. 2018; Sze and Yang 2014; Yang, Li, and Yang 2008).

The main aim of sample preparation for laboratory testing is to produce a reconstituted specimen that reflects the in situ properties of the material, as it is difficult to obtain the real undisturbed sample (Rad and Tumay 1987). More importantly, the preparation technique must be capable of repeatability (Kuerbis and Vaid 1988; Vaid and Negussey 1988).

Although several widely applied sample preparation methods exist, no standard approach has been established to date. This has led to the development of distinct methods based on the factors imitating the in situ conditions, such as the soil's moisture content, soil's placement method and the medium through which the soil is placed (Cai et al. 2018). Depending on how the samples are prepared, the soil specimen could exhibit a different mechanical response under loading, which may be related to the particular fabrics formed by different preparation methods. (Been, Jefferies, and Hachey 1991; White 2020).

Several studies have been carried out to explore the relations between the soil response and the fabric anisotropy caused by different specimen preparations. These experiments demonstrated that soil behaviour is fabric-dependent, and anisotropy has a considerable influence (Yang 2005). Despite the efforts conducted to explore the impact of sample preparation on the mechanical behaviour of the soil, this problem has not been addressed yet for the soil subjected to internal erosion.

The main objective of this study is to investigate the impact of sample preparation techniques on the erodibility of fine particles and the post-erosion mechanical behaviour in internally unstable soils. To this end, the under-compaction moist-tamping technique, presented by (Ladd 1978) with modification employed by (Jiang, Konrad, and Leroueil 2003), and wet pluviation implemented in previous studies (Andersen 2015; Ghionna and Porcino 2006; Oda, Koishikawa, and Higuchi 1978; Vaid and Sivathayalan 2000; White 2020) were chosen for this experiment. The moist-tamping method is known for its repeatability and is well-analogous with the embankment dam structures (Chang and Zhang 2011; Ke and Takahashi 2014; Mehdizadeh et al. 2017; Mehdizadeh et al. 2018). Wet pluviation, on the other hand, was introduced to make uniform samples with a structure and fabric similar to the ones in nature by mimicking the natural soil deposition (Castro 1969; Castro et al. 1982; Kuerbis and Vaid 1988; Miura, Toki, and Tanizawa 1984; White 2020).

This paper discusses the erosion and post-erosion behaviour of the soil specimens with two gradations, one on the borderline of stable and unstable and the other fully unstable. The samples were prepared using two aforementioned techniques at a relative density of about 70 percent and under confining pressure of 100 kPa, followed by a two-hour downward seepage and a drained shearing.

2. Experimental Program and Procedure

2.1. Testing Apparatus

The combined erosion-triaxial machine, developed by (Mehdizadeh, Disfani et al. 2017), was used to perform saturation, consolidation, erosion, and shearing successively without disturbing the samples and losing the saturation. During the erosion phase, a downward flow was applied to the top of the sample. The eroded particles were collected using a water collection tank.

2.2. Testing Material

Two gap-graded soil samples with 25 percent initial non-plastic fine content were used for this analysis, one as a representative of the samples on the borderline of stable and unstable and the other as fully unstable. The particle-size distribution and geometric properties of the soil samples are presented in Figure 1 and Table 1, respectively.

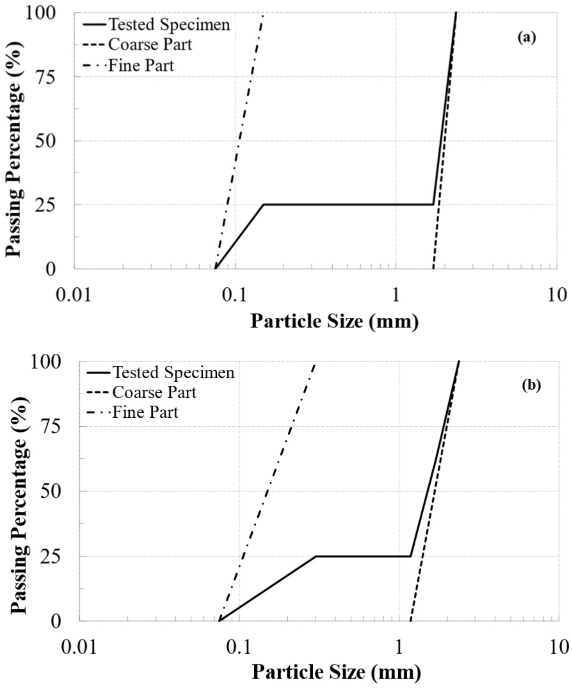

Figure 1. Particle-size distribution of the tested soils: (a) fully unstable, (b) on the borderline of stability.

According to available methods such as (Chang and Zhang 2013b; Dallo, Wang, and Ahmed 2013; Kenney and Lau 1986; Kezdi 1969; Moraci, Mandaglio, and Ielo 2014; Sherard 1992), both gradations were internally unstable, indicating that the fine particles are erodible if the hydraulic gradient is high enough (Mehdizadeh et al. 2018).

Table 1. Physical properties of tested soil samples.

Gradations	Physical Property	Value
$\left(\frac{D'_{15}}{d'_{85}}\right)^{a}_{max} = 5.2$	Specific Gravity, $\boldsymbol{G_s}$	2.64
	Fine Content[b], $\boldsymbol{FC}$ (%)	25
	Maximum Void Ratio, $\boldsymbol{e_{max}}$	0.67
	Minimum Void Ratio, $\boldsymbol{e_{min}}$	0.36
	Uniformity Coefficient, $\boldsymbol{C_u}$	12.14
	Curvature Coefficient, $\boldsymbol{C_c}$	7.1
	Relative Density, $\boldsymbol{D_r}$ (%)	70
$\left(\frac{D'_{15}}{d'_{85}}\right)_{max} = 13.85$	Specific Gravity, $\boldsymbol{G_s}$	2.64
	Fine Content[b], $\boldsymbol{FC}$ (%)	25
	Maximum Void Ratio, $\boldsymbol{e_{max}}$	0.49
	Minimum Void Ratio, $\boldsymbol{e_{min}}$	0.34
	Uniformity Coefficient, $\boldsymbol{C_u}$	20
	Curvature Coefficient, $\boldsymbol{C_c}$	16.2
	Relative Density, $\boldsymbol{D_r}$ (%)	73

[a]: $\chi = (\frac{D'_{15}}{d'_{85}})_{max}$ is the ratio of the particle diameter in which 15% by weight of coarse particles passed (D'_{15}) to the particle diameter in which 85% by weight of fine particles passed (d'_{85}).

[b]: Fine content is a percentage of the soil mass that is finer than the smallest coarse particle diameter.

2.3. Sample Preparation

Under-compaction moist-tamping and wet pluviation techniques were employed to prepare samples of 75 mm diameter and 150 mm height. The sample prepared by the moist-tamping method had an initial water content of 6%, and the test specimen was constructed and compacted in 10 layers according to the method proposed by (Jiang, Konrad, and Leroueil 2003; Ladd 1978). Further details are reported by (Mehdizadeh, Disfani et al. 2017).

The wet pluviation technique introduced by (Ishihara 1993; Jefferies and Been 2015) with some modifications were followed in this study. First, the total dry weight of the sample was calculated, mixed with the de-aired water uniformly and left for several hours to get moisture-estabilized. Afterwards, the mould was filled up to a certain level with the de-aired water close to the brim. Using a funnel and a plastic tube, the saturated material was added gradually to the mould at a constant rate. During this process, the distance between the nozzle and the top of the forming sample was kept at almost zero. The added amount of soil specimen would change the water level inside of the mould, so a slight amount of vacuum pressure was applied to the sample to drain the extra water from the bottom and keep the water level constant. This process continued until the specimen's desired height (i.e., required relative density) was achieved. The schematic illustration of the procedure is indicated in Figure 2. To erode the samples under a downward seepage, the samples were required to be placed on a meshed plate. This mesh was a barrier for the wet pluviation method as the fine particles got washed through the process. Hence, it was impossible to construct the sample on the erosion-triaxial base as was normally done when moist-tamping technique was used. Therefore, it was decided to make the samples on a solid plate followed by a freezing technique to make the non-cohesive samples temporary stable for transferring during the test set-up.

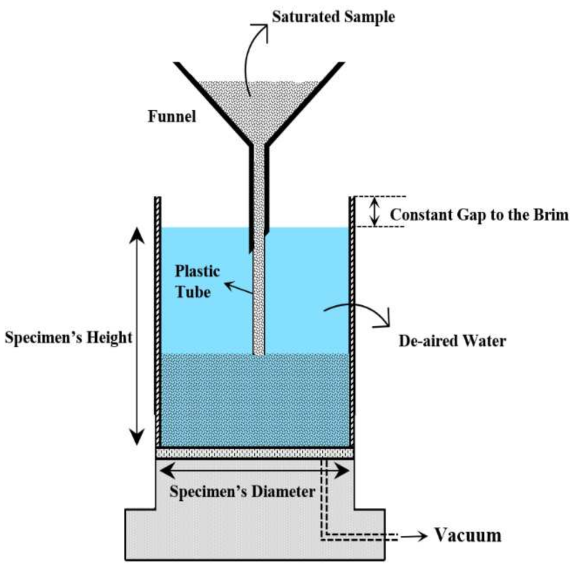

Figure 2. The schematic illustration of the wet pluviation technique.

Contrary to the moist-tamping technique, some precautions must be taken into consideration to ensure that results are not affected by sample preparations. While the reliability of the moist-tamping approach has been proven by several researchers (Chang & Zhang, 2011; Ke & Takahashi, 2014; Mehdizadeh et al., 2018; Mehdizadeh et al., 2017), the reliability of the wet pluviation technique, employed here, required to be examined first considering the implemented freezing stage. To this end, two samples of 63.5 mm in diameter and 126 mm in height were reconstituted according to the wet pluviation procedure explained here. One more sample was also constructed under the same procedure but also was subjected to the freeze-thaw process to investigate the possible impacts of freeze-thaw stage on the mechanical behaviour of the prepared samples. All three samples were then subjected to the same saturation, consolidation, and shearing phases.

The test results showed similar volumetric strain and stress-strain behaviors, validating the new specimen reconstitution method and its repeatability (Figure 3).

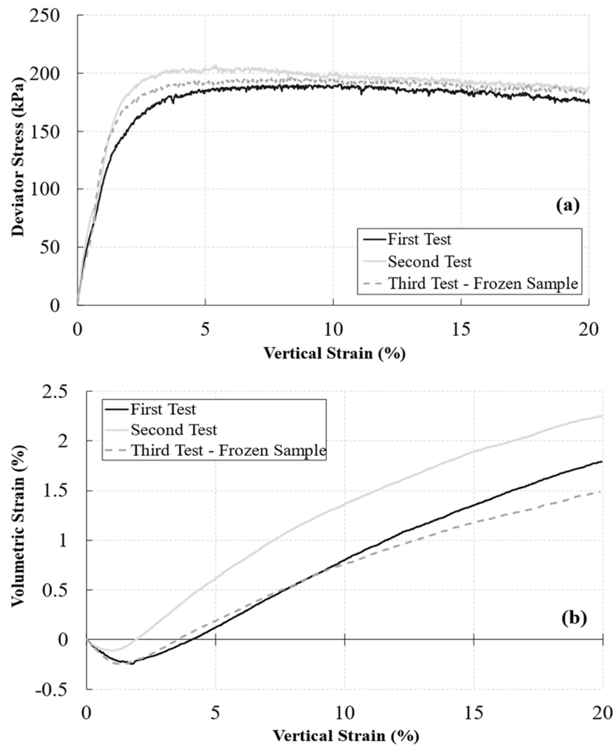

Figure 3. Repeatability and freezing impact of the sample with a diameter of 63.5mm: (a) the drained stress-strain and (b) the volumetric and vertical strain relationships.

2.4. Testing Procedure

The specimens were constructed in dimensions of 75*150 mm for the main experiments. A negative pressure of 10 kPa was applied to the specimen to avoid any disturbance during the test set-up. This negative pressure was replaced by a 20kPa cell pressure afterwards. In the next stage, carbon dioxide was injected into the bottom of the specimen for 2 hours at a low rate of 1 kPa/min to accelerate the removal of the trapped air. To saturate the samples, the cell and back pressure were gradually increased at a low rate of 1 kPa/min to reach 400 and 380 kPa, respectively and was kept steady for another 100 minutes. At the end of the saturation stage, Skempton's B-value was measured. If this value was over

0.93, the samples were then consolidated to 100 kPa isotropic pressure for 2 hours. The erosion phase started after the consolidation by applying a downward flow to the top of the specimen. The flow was gradually increased to 52 mm/min (270 mL/min) and was kept for 120 minutes. The eroded particles were then collected and weighed during the erosion phase. Finally, the sample were sent to a drained shearing stage.

3. Test Results

Figure 4 shows the erosion progress in terms of normalized residual fine contents for two soil gradations using two preparation techniques, moist-tamping and wet pluviation. Where normalized residual fine content is defined as the fraction of fines remaining in the soil structure relative to the amount of fines at the beginning of the experiment.

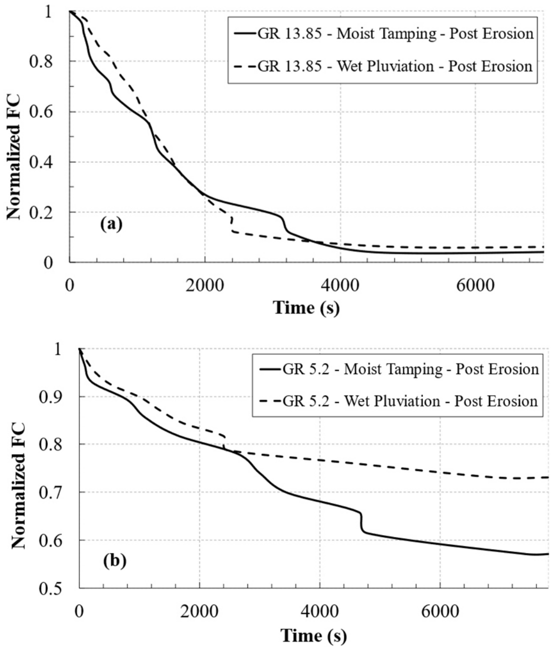

Figure 4. Real-time normalized residual fine content variation: (a) $\chi = 13.85$, (b) $\chi = 5.2$.

A very similar trend was observed for the samples prepared with $\chi = 13.85$, regardless of the preparation technique. The erosion initiated with a sharp decrease in the fine contents for the first 30 mins and then continued at an almost identical rate for both samples for another 30 minutes and finally left unchanged for the rest of the erosion phase (Figure 4(a)). For the $\chi = 5.2$, the erosion rate was almost the same for the first 30 minutes, but a noticeable variation was observed for the rest of the test. The sample prepared using the moist-tamping approach showed much intensive erosion in contrast to the sample prepared using the wet pluviation. (Figure 4(b)). The result clearly shows that the sample preparation technique impacted the erodibility of the fine particles for the gradation on the borderline of stable and unstable, and it was negligible for the samples with $\chi = 13.85$. The fine particles were noticeably smaller compared to the pore sizes in the soil samples with $\chi = 13.85$. Therefore, the sample preparation technique did not change their stability in the soil structure, while this was not the case for the samples with a much smaller gap ratio.

The drained stress-strain relationship of the samples with $\chi = 13.85$, the initial relative density of 73 percent and initial fine content of 25 percent is shown in Figure 5.

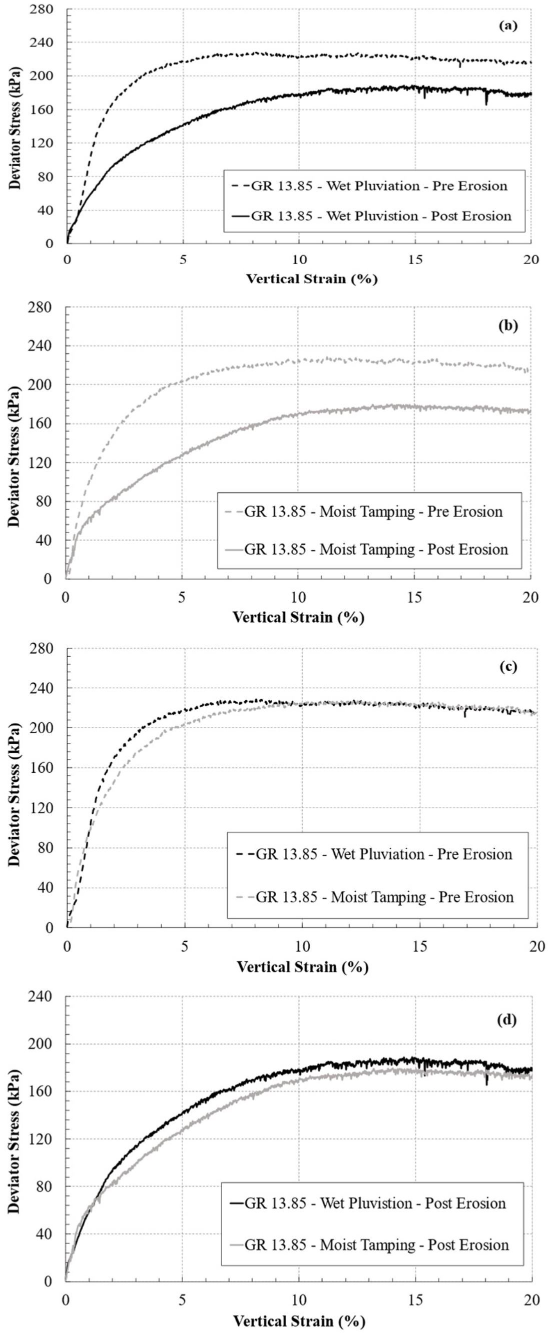

Figure 5. Impact of different sample preparation on the drained stress-strain relationship before and after erosion ($\chi = 13.85$): (a) wet pluviation, pre- vs post-erosion; (b) moist-tamping, pre- vs post-erosion; (c) pre-erosion, wet pluviation vs moist-tamping; (d) post-erosion, wet pluviation vs moist-tamping.

It is evident that by erosion of the fine particles from the soil structure, the drained shear strength of the soil decreased. This confirmed previous findings by (Chang and Zhang 2013a; Chen, Zhang, and Chang 2016; Ke and Takahashi 2015) that a decline in the drained shear strength happens following erosion of the fine particles. Moreover, post-erosion contractive behavior was also reported, which is consistent with the findings of this study (Figure 6). In addition, it was found that the behaviour of the samples prepared by wet pluviation, before and after erosion, is more dilative than the samples constructed by moist-tamping. The similar behaviour was reported by several researchers for the sample prepared by pluviation techniques (Abdelkader et al. 2016; Della and Arab 2010; Mahmoudi et al. 2019).

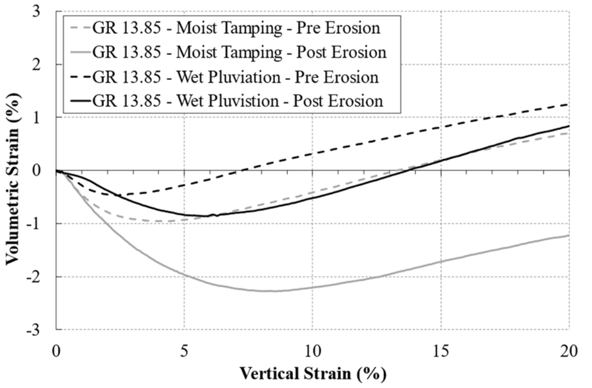

Figure 6. The volumetric and vertical strain relationship of the sample with χ = 13.85 subjected to the drained shearing.

The drained response of samples prepared by different techniques showed identical behaviours when they were subjected to similar conditions (Figure 5(c), 5(d)). Samples showed almost the same peak shear strength and the initial stiffness. The same trend was also observed after erosion. In this gradation, almost all the fine particles were eroded (1 % and 1.5 % residual fine contents for the moist tamping and wet pluviation samples respectively), leaving behind the coarse particles mainly, building the stress matrix; hence, even with different specimen reconstitution, the soil skeleton was not impacted much.

In this experiment, the moist-tamping and wet pluviation approach showed the same behaviour at critical state for both pre and post-erosion experiments, assuming the critical state was reached at 20% vertical strain. This was in agreement with previous finding that the critical state behaviour is independent from initial soil fabric (Raghunandan, Juneja, and Hsiung 2012).

The drained stress-strain relationship and the volumetric strain chnages of the sample with χ = 5.2, the relative density of 70 percent and the fine content of 25 percent are shown in Figures 7 and 8.

For the soil in borderline of stable and unstable; it can be seen that the wet pluviation samples have a higher shear strength at small strains and a different initial stiffness. However, the same mechanical behaviours were observed at large strains. (Figure 7(c and d)). Furthermore, the results showed that despite the different residual fine contents, both samples showed almost the same post-erosion drained behaviour (Figure 7(d)). Similar to previous results, samples prepared by wet pluviation showed a more dilatant behaviour (Figure 8).

Interestingly, similar pre- and post-erosion mechanical behaviours and very different erosion patterns (14 % and 18 % residual fine content for the moist tamping and wet pluviation respectively) were observed for the samples with χ = 5.2.

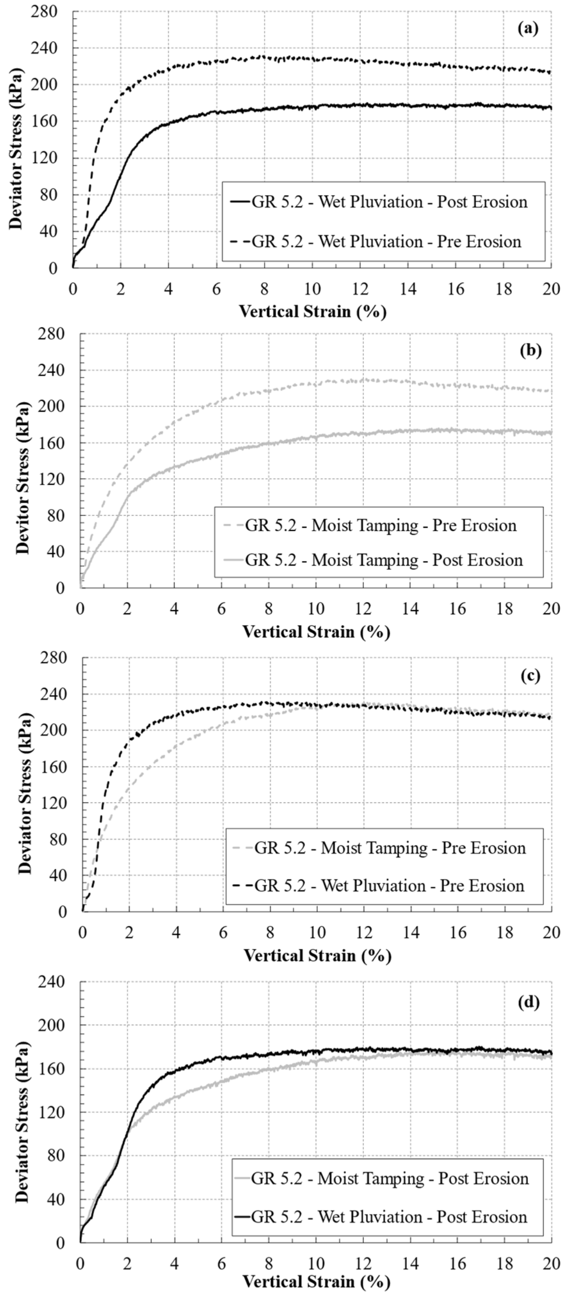

Figure 7. Impact of different sample preparation on the drained stress-strain relationship before and after erosion (χ = 5.2): (a) wet pluviation, pre- vs post-erosion; (b) moist-tamping, pre- vs post-erosion; (c) pre-erosion, wet pluviation vs moist-tamping; (d) post-erosion, wet pluviation vs moist-tamping.

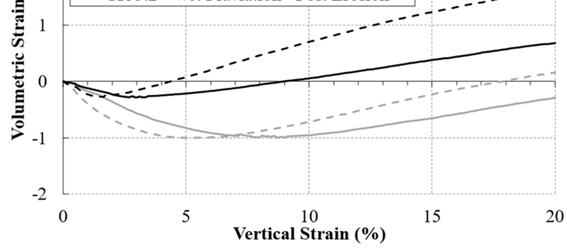

Figure 8. The volumetric and vertical strain relationship of the sample with χ = 5.2 subjected to the drained shearing.

It seems that the sample preparation technique had no impact on the contribution of the fine particles to the soil structure for the soil samples with χ = 5.2 and a fine content of 25 percent. However, the sample preparation technique influenced the pore network which controlled the erodibility of the fine particles. In other words, a fraction of fine content did not contribute to the soil stress matrix (free to move) but were unable to pass through the voids either due to a higher level of clogging or a weaker pore connectivities in the sample made using the wet pluviation. Gap-graded soils are vulnerable to the segregation of fine particles, which is also a drawback of the wet pluviation technique (White 2020). (Yu, Peng, and Su 2021) examined the influence of grain segregation on the drained stress-strain relationship of silica sand. They found that the grain segregation enhanced the dilatancy of the sample prepared by the air pluviation technique. Previously it was indicated in Figure 8 that wet pluviation samples tend to show more dilatancy which may be an indicator for the fine particles' segregation. Therefore, different erodibility behaviour in this study, could possibly be due to the fine particles' segregation during sample preparation, which might have formed smaller local constriction sizes and narrower pore throats while did not impact the global mechanical behaviour. This hypothesis can be validated through 3D x-ray imaging.

To get a better understanding of this observation, post-erosion particle size distribution (PPSD) was performed along the height of the samples at different levels (Figure 9). ´

It can be seen that the specimen prepared by the moist-tamping approach was eroded more uniformly than the sample prepared by wet pluviation. While for the sample prepared using moist-tamping method the top layer experienced a higher erosion rate compared to the middle and the bottom sections, the post-erosion fine content was almost the same along the sample's height, made by the wet pluviation technique. The PSD of the sample constructed using the wet pluviation pre-erosion (Figure 9 (c)) showed that the fine content was not the same along the sample height. This clearly shows that for such a gradation, the wet pluviation procedure, explained here, was unable to make uniform specimens. However, the imposed variation was not high enough to impact the mechanical behaviour.

4. Conclusion

The impact of sample preparation on the erodibility and mechanical behaviour of the two gap-graded soils, one on the borderline of internal stability and the one falling into the category of fully unstable, was investigated using moist-tamping and wet pluviation techniques. Results indicated that for the soil in a fully unstable condition, regardless of the method of sample preparations, the mechanical behaviours of the soil and the erodibilities of fine particles were similar. However, for the sample on the border line of internal stability, the mechanical behaviours were similar but the erosion of fine particles was different. It was understood that fine particle segregation occurred when the samples was prepared by wet pluviation, which led to different erosion behaviours. The observed behaviour was believed to be due to different pore network and not different levels of fine particle contribution to the soil structure as the samples showed similar pre- and post-erosion mechanical behaviours. The sample preparation technique was found to play a noticeable role when the aim is the investigation of internal erosion.

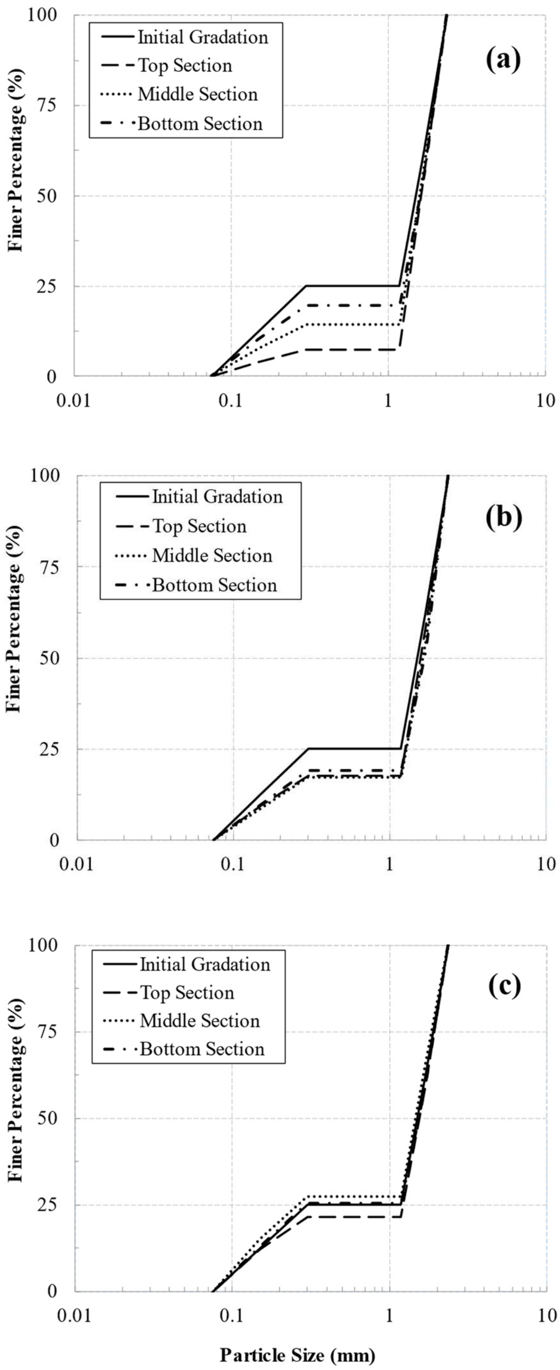

Figure 9. Particle size distribution (PSD) plots for the different sections of the samples prepared by separate techniques (χ =5.2): (a) post-erosion, moist-tamping; (b) post-erosion, wet pluviation; (c) pre-erosion, wet pluviation.

Acknowledgements

The first author is grateful for the financial support provided through the research scholarship funded by the University of Melbourne.

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