# An overview on the determination of the shear strength of coarse grain materials (rockfills) from small scale laboratory tests

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ABSTRACT
The shear strengths of rockfills are key parameters required in stability analysis of structures made of rockfills. Conducting laboratory tests using in situ materials and respecting the minimum ratio of specimen size to maximum particle size, $d_{max,}$ specified by the well-established standards are very difficult if not impossible. To overcome this difficulty, several scaling down techniques were proposed in the past on samples preparation. Among them, parallel method is largely used. The analyses show that the methodology used in the past to validate or invalidate a scaling down technique through direct comparison between the shear strengths of modeled and field samples is inappropriate. The reliability of the scaling down techniques (including parallel method) in determining shear strength of field rockfill has never been demonstrated. Further analysis shows that applying the minimum specimen size to $d_{max,}$ ratio required by the studied standards may result in unreliable results.

RÉSUMÉ
La résistance des remblais rocheux est importante dans la conception des structures en remblais rocheux. Faire des essais en laboratoire avec des matériaux du terrain en respectant le rapport minimum entre la taille d'une éprouvette et la taille maximale des grains, $d_{max}$, requis par les normes est très difficile si cela n'est pas impossible. Pour contourner cette difficulté, des techniques à l'échelle réduite ont été proposées. Parmi ces techniques, la méthode parallèle est largement utilisée. Les analyses montrent que la méthodologie utilisée dans le passé pour valider ou invalider une technique à l'échelle réduite en comparant directement la résistance d'un échantillon à l'échelle réduite avec celle d'un échantillon prototype est inappropriée. La fiabilité des techniques à l'échelle réduite n'a jamais été montrée. En plus, les analyses montrent que l'application du rapport minimum entre les tailles des éprouvettes et la $d_{max,}$ requis par les normes peut mener à des résultats non fiables.

## 1 INTRODUCTION

Mechanical behavior and shear strengths of rockfills have been studied by many researchers since rockfill is widely used in the construction of infrastructures like foundations, roads (Cambio and Ge 2007; Sevi 2008) and rockfill dams (Marachi et al. 1969; Leps 1970). However, conducting laboratory tests on coarse grain materials is difficult due to the large particle sizes of these materials while the dimensions of laboratory equipments are usually limited and the test specimen size must respect the minimum ratios required by different standards between the specimen size and the maximum particle size ($d_{max}$) of material. For direct shear tests, standard of ASTM D3080 (2011) requires a specimen width (*W*) and thickness (*T*) to be at least 10 and 6 times the $d_{max}$ value, respectively. Eurocode 7 (2007) standard suggests a minimum ratio of 10 between the specimen thickness and the $d_{max}$ value while AS 1289.6.2.2 (1998) requires a specimen thickness to be at least 6 times the $d_{max}$ value. Meanwhile, BS 1377-7 (1990) recommends the specified maximum particle sizes for given specimen widths and thicknesses. For fine particle materials like silt and fine sands with typical $d_{max}$ smaller than 2 mm, following the standards is not a problem. However, satisfying the requirements of the standards is a challenging task for coarse grain materials.

To overcome this difficulty, researchers usually conduct laboratory shear tests by excluding the over-size particles in sample preparation (Marachi et al. 1969, 1972; Hamidi et al. 2012; Chang and Phantachang 2016). This practice is known as scaling down technique. Several scaling down techniques have been proposed to reduce the maximum particle size of the prepared samples in order to respect the allowed $d_{max}$ defined by the ratio of specimen size to $d_{max}$ required by the standards. When the samples are prepared by simply exluding the over size particles, the technique is called scalping or truncated method (Zeller and Wulliman 1957). Another method is to modify the samples so that the particle size distribution curve of the new sample is parallel to that of the in situ material. This scaling technique is called parallel method (Lowe 1964). The third scaling down technique, called replacement method, consists to replace the oversize particles with particles retained on No. 4 sieve of the same weight (Frost 1973). Among these techniques, scalping and parallel are commonly used by engineers and researchers. Shear test results are used to establish a relationship between the shear strength and the maximum particle size. Then the shear strength of in situ material can be predicted by extrapolating the laboratory test results. It is, however, not yet clear which technique allows to reliably predict the shear strength of in situ materials by applying the extrapolation technique on the laboratory test results.

In this paper, an analysis is made on experimental results available in the literature in order to identify a reliable scaling down technique that can be used to predict the shear strength of in situ materials by using laboratory shear test results. The effect of specimen size on shear test results is also examined through the analysis of shear test results available in the literature. The analyses show that the minimum required ratios suggested by different standards between specimen size and the maximum particle size are not large enough. To verify this hypothesis, a series of direct shear tests have been done on a given material by using different size boxes. The preliminary results confirm again that the minimum ratio suggested by the different standards is not large enough to eliminate the

## 2 REVIEW ON THE RELIABILITY OF SCALING DOWN TECHNIQUES

### 2.1 Scalping, Replacement and Parallel Techniques

The scalping technique is the earliest scaling technique used for preparing samples to exclude oversize particles to conduct laboratory shear tests on coarse grain materials. In this technique, all particles larger than the allowed $d_{max}$ are removed. This technique was first introduced by Hennes (1953) and later used by Zeller and Wullimann (1957). This method is very simple and has been commonly used by many researchers (Holtz and Gibbs 1956; Leslie 1963; Morgan and Harris 1967; Hall and Smith 1971; Donaghe and Torrey 1985; Hamidi et al. 2012; Stober 2012). However, the application of this technique results in an increase of the percentages of fine particles smaller than the removed oversize particles compared to the gradation of in situ materials. To overcome this drawback and when the portion of the removed oversize particles represents more than 10%, USACE (1965) suggested another scaling down technique developed immediately after scalping technique, called “Replacement method”.

In the replacement technique, oversize particles are removed and replaced by the same weight of particles retained on No. 4 sieve (i.e. larger than 4.75 mm) and smaller than the allowed $d_{max}$. The percentages of particles finer than the No. 4 sieve thus remain unchanged (USACE 1965; Frost 1973; Donaghe and Torrey 1985). The replacement technique highly changes the percentage of gravel particles compared to that of in situ material. The mechanical properties are also changed compared to those of in situ material (Torrey and Donaghe 1991; Feng and Vitton 1997).

Another method, called parallel technique, was introduced by Lowe (1964). In this technique, the oversize particles (i.e. larger than the allowed $d_{max}$) are excluded. In the meantime, the sample is modified in a way that the new particle size distribution curve can be considered as a horizontal shift of that of the in situ material toward the fine particle side. This technique is commonly used by researchers (Marachi et al. 1969, 1972; Abbas et al. 2004; Gupta 2009; Vasistha et al. 2013; Honkanadavar et al. 2016).

### 2.2 Validation of Scaling Down Techniques

The parallel technique has been widely used by a number of researchers (Marachi et al. 1972; Varadarajan et al. 2006; Abbas 2011; Rao et al. 2011; Honkanadavar et al. 2016; Ovalle and Dano 2020). Marachi et al. (1972) studied the influence of maximum particle size on the friction angle of three samples. Two samples were made of well-graded very angular particles. The third one was made of a mixture of sub-angular and rounded particles. The portions of sub-angular and rounded particles were not specified. The degree of angularity or roundness of the particles was quantitatively unknown. Parallel technique was used to scale down the in situ material. The tested samples were prepared by using the minimum required specimen size ratio of ASTM D4767 (2011) for triaxial compression tests (i.e. a ratio of 6 between sample diameter and the maximum particle size). The results showed that the friction angles decreased as the $d_{max}$ increased.

Charles (1973) studied the variation of the friction angle of rounded rockfill as a function of the maximum particle size. The tested samples were prepared by applying parallel technique on the in situ material and using the minimum required specimen size ratio of ASTM D4767 (2011) for triaxial compression tests (i.e. a ratio of 6 between sample diameter and the maximum particle size). The results showed that the friction angle of rounded rockfill increased as the maximum particles size increased. This trend differs from that observed by Marachi et al. (1972) for angular particles.

Donaghe and Torrey (1985) studied the reliability of scalping and replacement techniques by performing a series of triaxial compression tests with confining pressure of 418 kPa on mixtures of sand and gravel particles. In situ material with $d_{max}$ of 76 mm was scaled down to samples with $d_{max}$ of 4.75 mm and 19 mm by applying the scalping and replacement techniques, respectively. The specimens were prepared by following the minimum required specimen size ratio of ASTM D4767 (2011). The friction angles of the scaled down samples were directly compared with that of the in situ material as presented in Figure 1. Without any surprise, the results of the scaled down samples are quite different to that of the in situ material. Donaghe and Torrey (1985) concluded that none of the scalping and replacement techniques are good to determine the friction angle of in situ material. Obviously, their methodology used to evaluate the reliability of the scaling down techniques is not correct and their conclusion is not reliable because the shear test result of the modeled samples should not be directly compared with that of the in situ material. Subsequently, the scalping and replacement techniques are not invalidated.

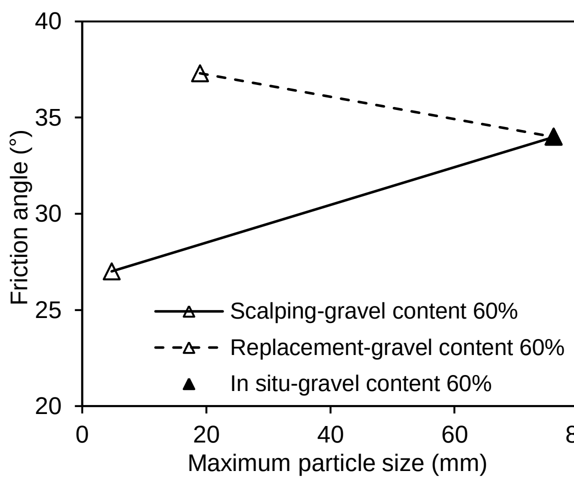



Figure 1. Comparison of friction angles of the scalping and replacement samples with that of the in situ material (data taken from Donaghe and Torrey, 1985)

The same methodology was followed by Hamidi et al. (2012), who studied the reliability of scalping and parallel techniques by performing direct shear tests. The in situ material was a sand and gravel mixture with $d_{max}$ of 25.4 mm. The modeled samples with $d_{max}$ of 12.5 mm were prepared by following scalping and parallel techniques with loose (relative density $D_r$ = 35%), medium ($D_r$ = 60%) and dense ($D_r$ = 85%) states, respecting the requirement of specimen size to $d_{max}$ ratio of ASTM D3080 (2011). Figure 2 shows the test results. If the reliability of a scalping technique is based on the direct comparison between the shear strengths of the modeled and prototype samples, one tends to conclude that the parallel technique is not reliable while the scalping technique is not good neither except for scalped loose sample. Once again, this methodology is not reliable in evaluating the reliability of the scaling down techniques. The scalping and parallel techniques are thus neither validated, nor invalidated.

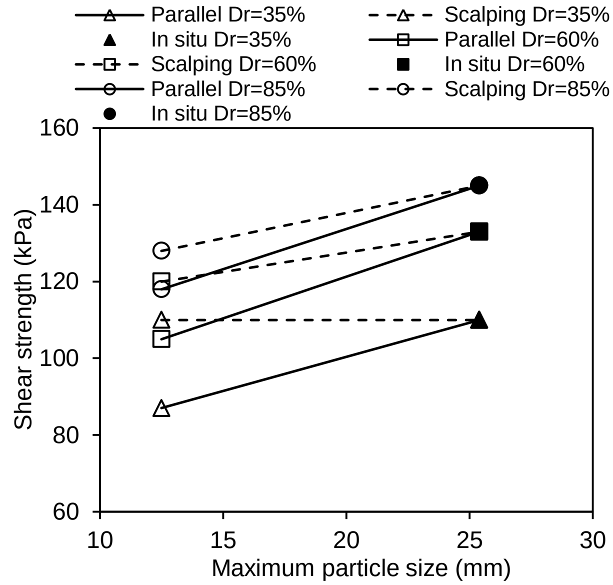



Figure 2. Variations of shear strengths (normal stress = 100 kPa in direct shear test) of the in situ, parallel and scalping samples with maximum particle size (data taken from Hamidi et al. 2012).

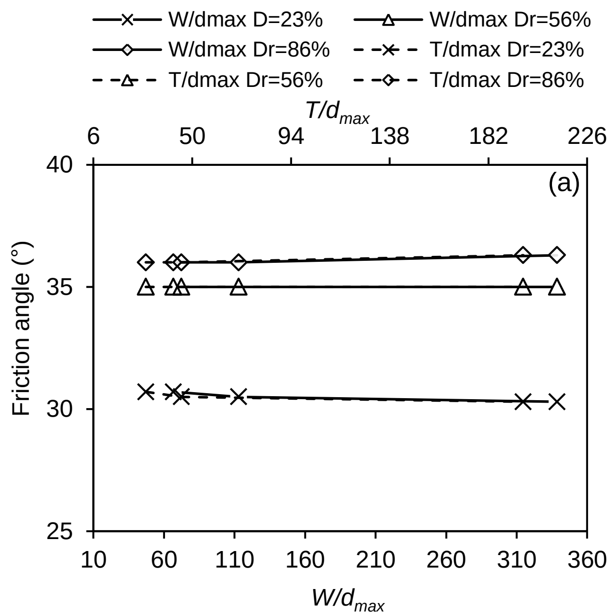
## 3 SPECIMEN SIZE EFFECT

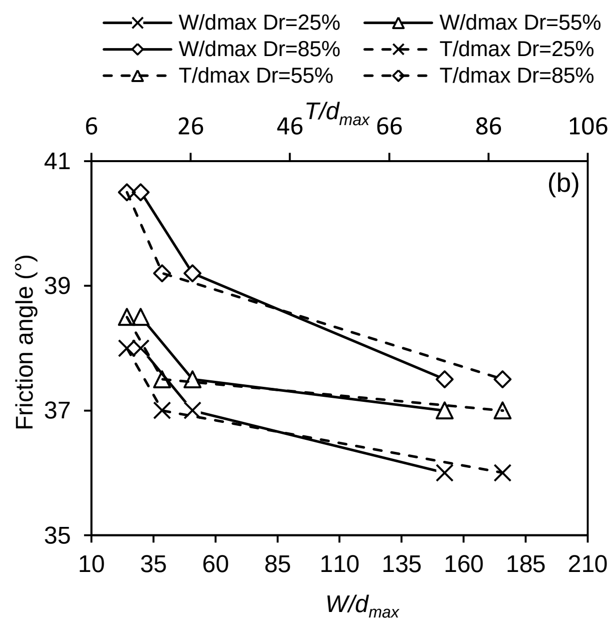
In ASTM D3080 (2011), a specimen of direct shear test is required to be at least 50 mm wide and 13 mm thick. In addition, the specimen width and thickness should be at least 10 and 6 times the maximum particle size, respectively to eliminate the specimen size effect. Similar requirements are given in other standards (e.g. AS 1289.6.2.2 and Eurocode 7). Based on these requirements, one can prepare specimens having a ratio between the specimen sizes and the maximum particle size ranging from the minimum required value to any higher value. It will be seen that the ratio is usually automatically much higher than the minimum required value for fine particle materials tested with standard shear test equipment while the minimum required ratio values were commonly used for coarse grain materials such as gravel and rockfill. In some cases, the specimens were prepared by using a ratio even slightly smaller than the minimum required values suggested by the diverse standards. Can the specimen size effect be eliminated by using specimens having the minimum required ratio between the specimen size and the maximum particle size? To answer this question, analyses will be made on experimental results available in the literature.

Palmeira and Milligan (1989) conducted direct shear tests on a sand with $d_{max}$ of 1.2 mm by using small (60 mm × 60 mm × 32 mm), medium (252 mm × 152 mm × 152 mm) and large (1000 mm × 1000 mm × 1000 mm) shear boxes. The ratios of specimen width over $d_{max}$ with the three boxes were 50, 126.7 and 833, respectively, while the ratios of specimen thickness over $d_{max}$ were 26.7, 126.7 and 833, respectively. The results showed that the friction angles of the tested specimens remained almost constant when the ratio of specimen width to $d_{max}$ increases significantly from 50 to 833. As the specimen size ratios are much larger than the minimum required specimen size ratio of ASTM D3080 (2011) and there were no experimental results with specimens having $W/d_{max}$ ratios from 10 to 50, the minimum required ratio between specimen size and the maximum particle size of ASTM D3080 (2011) is not validated by these test results.

Ziaie Moayed et al. (2017) studied the specimen size effect on the friction angle of dense sand with $d_{max}$ of 0.8 mm mixed with different silt contents (0, 10%, 20% and 30%). Three shear boxes having dimensions of 60 mm × 60 mm × 24.5 mm, 100 mm × 100 mm × 35 mm and 300 mm × 300 mm × 154 mm were used. The ratios of specimen width to $d_{max}$ were 75, 125 and 375 respectively. For sand mixed with 30% silt, the friction angle decreased by 1.3 degrees when the $W/d_{max}$ ratio increased from 75 to 125 and remained almost constant when the $W/d_{max}$ ratio further increased from 125 to 375. There is no any experimental data for the specimen with $W/d_{max}$ ratio between 10 and 75. The minimum requirement of ASTM D3080 (2011) is not validated. For pure sand, the friction angle decreased by more than 3 degrees when the $W/d_{max}$ ratio increased from 75 to 125 and then by 2 degrees when the $W/d_{max}$ ratio further increased from 125 to 375. These results tend to indicate that the $W/d_{max}$ ratio of 75 is not large enough to eliminate the specimen size effect. The minimum required ratio of the ASTM between the specimen size and the maximum particle size is invalidated.

Cerato and Lutenegger (2006) studied the effect of specimen size on the friction angle of five materials with different maximum particle sizes. Three shear boxes of small (60 mm × 60 mm × 26.4 mm), medium (101.6 mm × 101.6 mm × 40.64 mm) and large (304.8 mm × 304.8 mm × 177.8 mm) were used. Figure 3 shows the variation of the friction angle as functions of $W/d_{max}$ and $T/d_{max}$ for fine (Figure 3a), intermediate (Figure 3b) and coarse grain (Figure 3c) materials. For the fine particle materials with $d_{max}$ of 0.9 mm, the $W/d_{max}$ ratios corresponding to the small, medium and large shear boxes were 67, 113 and 339, respectively while the $T/d_{max}$ ratios were 29, 45 and 198, respectively. The friction angle remains almost constant as ratio $W/d_{max}$ increases from 67 to 339 while ratio $T/d_{max}$ increases from 29 to 198. The effect of specimen size was indeed eliminated for the tested specimens. However, there were no experimental results on specimens having ratio $W/d_{max}$ from 10 (the minimum required ratio value) to 67. It is unclear if the effect of specimen size is eliminated for the specimen size in this range. The minimum required ratio of specimen size to $d_{max}$ of ASTM D3080 (2011) is not validated. For the intermediate materials with $d_{max}$ of 2 mm, the $W/d_{max}$ ratios were 30, 51 and 152, respectively while the $T/d_{max}$ ratios were 13, 20 and 89, respectively. The friction angle decreases more than 2 degrees as ratio $W/d_{max}$ increases from 30 to 152 and $T/d_{max}$ increases from 13 to 89. The specimen size affects the friction angle of the intermediate materials for $W/d_{max}$ between 30 and 152. The minimum required ratio of ASTM D3080 (2011) between the specimen size and the maximum particle size is invalidated. For coarse grain materials with $d_{max}$ equaling to 5 mm, the $W/d_{max}$ ratios were 12, 20 and 61, respectively while the $T/d_{max}$ ratios were 5, 8 and 36, respectively. The friction angle decreased more than 5 degrees as ratio $W/d_{max}$ increased from 12 to 20 and ratio $T/d_{max}$ increased from 5 to 8, and further decreased by 2 degrees when the $W/d_{max}$ ratio further increased from 20 to 61 and the $T/d_{max}$ ratio increased from 8 to 36. The specimen size effect on the friction angle of coarse grain materials is not eliminated for the $W/d_{max}$ ratio between 12 and 61. Thus, the minimum required specimen size ratio of ASTM D3080 (2011) is invalidated.



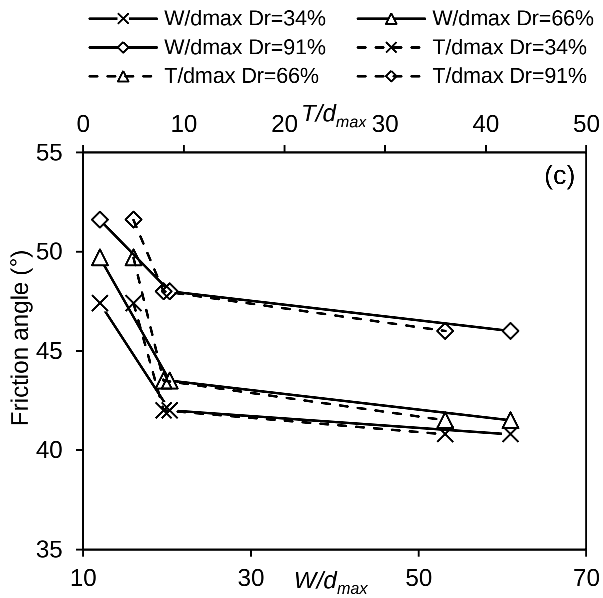



Figure 3. Variations of friction angle in terms of specimen width and thickness to $d_{max}$ ratios for fine (a), intermediate (b) and coarse (c) materials (data taken from Cerato and Lutenegger, 2006)

## 4 CONCLUSIONS AND RECOMMENDATIONS

The analyses of the experimental results of shear tests on fine and coarse grain materials available in the literature lead to the following conclusions:

- The methodology used to validate or invalidate the scaling down techniques by directly comparing the shear strengths of modeled and prototype samples is incorrect.
- Parallel technique is widely used while scalping technique is occasionally used and replacement technique is seldom used. However, the reliability of these techniques in predicting shear strength of in situ coarse grain material is not yet demonstrated.
- The minimum required ratio of specimen size over $d_{max}$ of ASTM D3080 (2011) is not validated or invalidated by results for fine particle materials like sand, but is invalidated by results for coarse grain materials like gravel and rockfill. This ratio needs to be revised to eliminate specimen size effect and obtain reliable experimental results of shear strength.

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