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Technical Note

Particle breakage of granular materials during sample preparation

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ABSTRACT

Particle breakage is commonly observed in granular materials when subjected to external loads. It was found that particle breakage would occur during both sample preparation and loading stages. However, main attention was usually paid to the particle breakage behaviour of samples during loading stage. This study attempts to explore the breakage behaviour of granular materials during sample preparation. Triaxial samples of rockfill aggregates are prepared by layered compaction method to achieve different relative densities. Extents of particle breakage based on the gradings before and after test are presented and analysed. It is found that particle breakage during sample preparation cannot be ignored. Gradings after test are observed to shift away from the initial grading. Aggregates with larger size that appear to break are more than the smaller-sized ones. Irrespective of the initial gradings, an increase in the extent of particle breakage with the increasing relative density is observed during sample preparation.

1. Introduction

Particle breakage, a critical issue for granular aggregates subjected to static and dynamic loads, has drawn increasing attention of researchers (Einav, 2007; de Bono and McDowell, 2016; Xiao et al., 2017a, b; Yu, 2017a, b) recently. To understand the effect of particle breakage on the strength and deformation behaviours of granular aggregates, different laboratory and numerical tests, including the triaxial test, hollow cylinder test, and simple shear test, have been carried out on samples with different initial void ratios (Coop et al., 2004; McDowell and Li, 2016; Zhang et al., 2016; Sun and Zheng, 2017). It was found that particle breakage would reduce the strength of granular aggregates and induce more irrecoverable deformation (Yu, 2017a). A hyperbolic relationship was often suggested to correlate the extent of particle breakage with the axial/shear strain or the applied plastic work (Lade et al., 1996; Einav, 2007; Yu, 2017a). Apart from the mechanical factors causing particle breakage, several physical properties were also reported to significantly influence the final breakage extent of granular aggregates. For example, the extent of particle breakage was found to decrease with the increasing coefficient of uniformity (Sun and Zheng, 2017) when the relative densities were similar. However, the effect of initial density or void ratio on the breakage behaviour of granular aggregates was not conclusive. For example, an increasing extent of particle breakage with the decreasing initial void ratio was found in Xiao et al. (2016) while an opposite evolution trend was reported (Lackenby et al., 2007; Sun and Zheng, 2017; Xiao et al., 2017b) due to high stress concentration between internal angular aggregates. Nevertheless, all the above analyses focused on the particle breakage phenomenon occurring during loading stage. The effect of particle breakage of granular aggregates during sample preparation process was not considered properly, which may exert an influence on the subsequent analysis results. For example, it was reported that the intercept of the critical state line (CSL) with the ordinate of very dense gravelly soils decreased with the decreasing initial void ratio or increasing compaction level (Winter et al., 2017), which might be attributed to the considerable particle breakage occurring during sample preparation and consolidation, as explained by Xiao et al. (2014). To avoid the influence of particle breakage during sample preparation on the mechanical behaviour of rockfill, Gao et al. (2009) suggested manual shift of the initial grading away from the target grading, so as to allow the evolution of the initial grading towards the target grading during sample preparation.

Therefore, it is of critical importance to study the particle breakage behaviour of granular aggregates during sample preparation. To start with, Section 2 describes the test materials and relevant procedures for preparing triaxial samples. Section 3 presents the gradings of samples before and after test where the extent

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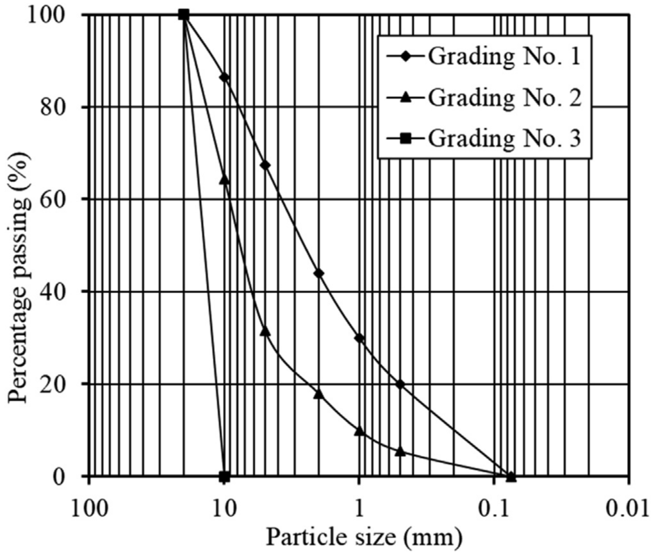

Fig. 1. Grading of the materials used in this study.

Table 1
Physical properties of the granular materials.

Material No.	ρ_m (g/cm^3)	ρ_M (g/cm^3)	d_m (mm)	d_{50} (mm)	d_M (mm)	C_u
1	1.69	2.2	0.075	2.6	20	20
2	1.6	2.12	0.075	7.65	20	9.1
3	1.26	1.56	10	15	20	1.45

Note: d_m and d_M are the minimum and maximum particle sizes, respectively.

of particle breakage is analysed and discussed. Main findings are summarised in Section 4.

2. Test materials and setup

The granular material used in this study consisted of angular granites that were usually used for constructing the infrastructures, such as rockfill dam and concrete-pile. The specific gravity of the granite aggregate was 2.56. Two different initial gradings of the material shown in Fig. 1 were used for the tests. Following the standards ASTM D4253-14 (2014) and ASTM D4254-14 (2014), the minimum (ρ_m) and maximum (ρ_M) densities of the material No. 1 were determined to be 1.69 g/cm^3 and 2.2 g/cm^3, respectively; while the ones of the material No. 2 were 1.6 g/cm^3 and 2.12 g/cm^3, respectively. Table 1 lists the values of the coefficient of uniformity (C_u) and medium particle size (d_{50}) among others for each grading.

Aggregates selected from six size ranges were carefully washed, air-dried, and then weighed separately and mixed before being divided into five equal parts (ASTM D4253-14, 2014). Each part was then placed inside a lubricated rubber membrane in five separate layers by compaction to achieve initial density and relative density (R_d), as prescribed in Tables 2 and 3. The compaction was carried out by dropping a hammer of 1.25 kg from a constant height of 150 mm into a typical split cylindrical mould (diameter × height = 100 mm × 250 mm) used for preparing triaxial samples (Fig. 2). Details of each sample with different relative densities before test can be found in Tables 2 and 3. After each test, samples were sieved and weighed separately following the standard ASTM D4253-14 (2014).

Figs. 3–5 present the sieve analysis results of each sample after test. As can be observed, all the sample gradings after test are shifted right where smaller aggregates were generated, when compared with the initial grading. With the increase in relative density, the sample grading shifts more towards left, irrespective of the initial grading. This indicates an increasing extent of particle breakage when preparing denser samples.

3. Results and discussion

Table 3 shows the percentage retaining of the granular aggregates at each sieve size. It can be found that a considerable reduction in aggregates mass occurred in larger-sized aggregates (10–20 mm), indicating the generation of a substantial amount of particle breakage. However, for materials with gradings Nos. 1 and 2, only a small amount of mass decrease is observed in the size ranges of 5–10 mm and 1–2 mm. This can be attributed to the supplement of aggregates induced by particle breakage from the upper size ranges. In addition, an apparent increase in aggregates

Table 2
Sample preparation of different granular materials.

Material No.	Relative density	Density (g/cm^3)	Total mass (g)	Mass of each size range (g)					
				10–20 mm	5–10 mm	2–5 mm	1–2 mm	0.5–1 mm	0.075–0.5 mm
1	0.7	2.017	3167.26	427.58	601.779	744.306	443.416	316.726	633.452
	0.75	2.046	3211.697	433.579	610.222	754.749	449.638	321.17	642.339
	0.8	2.075	3257.4	439.749	618.906	765.489	456.036	325.74	651.48
	0.85	2.105	3304.421	446.097	627.84	776.539	462.619	330.442	660.884
	0.9	2.136	3352.82	452.631	637.036	787.913	469.395	335.282	670.564
	0.95	2.167	3402.658	459.359	646.505	799.625	476.372	340.266	680.532
	1	2.2	3454	466.29	656.26	811.69	483.56	345.4	690.8
2	0.7	1.932	3032.711	1079.039	998.368	409.416	242.617	136.472	166.799
	0.75	1.961	3078.289	1095.255	1013.373	415.569	246.263	138.523	169.306
	0.8	1.991	3125.258	1111.967	1028.835	421.91	250.021	140.637	171.889
	0.85	2.021	3173.683	1129.196	1044.776	428.447	253.895	142.816	174.553
	0.9	2.053	3223.632	1146.968	1061.22	435.19	257.891	145.063	177.3
	0.95	2.086	3275.178	1165.308	1078.189	442.149	262.014	147.383	180.135
	1	2.12	3328.4	1184.245	1095.709	449.334	266.272	149.778	183.062
3	0.7	1.456	2285.92	2285.92	–	–	–	–	–
	0.75	1.472	2311.604	2311.604					
	0.8	1.489	2337.873	2337.873					
	0.85	1.506	2364.745	2364.745					
	0.9	1.534	2392.242	2392.242					
	0.95	1.542	2420.386	2420.386					
	1	1.56	2449.2	2449.2					

Table 3
Particle breakage ratio of different granular materials.

Material No.	Relative density	Test state	Percentage retaining on each size range (%)						B_g
			10–20 mm	5–10 mm	2–5 mm	1–2 mm	0.5–1 mm	0.075–0.5 mm	
1	0.7	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.065
		After	0.12859	0.17416	0.24104	0.12976	0.11580	0.21066	
	0.75	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.066
		After	0.12845	0.17399	0.24049	0.12957	0.11646	0.21104	
	0.8	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.104
		After	0.12371	0.17276	0.2382	0.11658	0.11864	0.23011	
	0.85	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.121
		After	0.11949	0.17135	0.23928	0.11377	0.11701	0.23909	
	0.9	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.122
		After	0.12029	0.16681	0.25078	0.11707	0.12277	0.22228	
	0.95	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.147
		After	0.11619	0.1651	0.24396	0.11008	0.12427	0.24040	
	1	Before	0.135	0.19	0.235	0.14	0.1	0.2	0.147
		After	0.11456	0.16506	0.25119	0.11193	0.12617	0.23109	
2	0.7	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.095
		After	0.31986	0.31788	0.16514	0.08077	0.05034	0.06602	
	0.75	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.114
		After	0.31538	0.31438	0.16981	0.07815	0.05726	0.06502	
	0.8	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.133
		After	0.32973	0.29861	0.17339	0.07016	0.05579	0.07232	
	0.85	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.129
		After	0.33318	0.29862	0.17441	0.0688	0.05692	0.06807	
	0.9	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.194
		After	0.28037	0.32095	0.17768	0.06664	0.05656	0.09779	
	0.95	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.186
		After	0.30788	0.29459	0.18898	0.06971	0.06311	0.07573	
	1	Before	0.3558	0.3292	0.135	0.08	0.045	0.055	0.206
		After	0.29978	0.29492	0.19511	0.06709	0.06574	0.07736	
3	0.7	Before	1	0	0	0	0	0	0.146
		After	0.69575	0.2155	0.06412	0.00946	0.00404	0.01113	
	0.75	Before	1	0	0	0	0	0	0.158
		After	0.72811	0.18877	0.05948	0.01138	0.00243	0.00983	
	0.8	Before	1	0	0	0	0	0	0.183
		After	0.73313	0.19112	0.05413	0.01026	0.00182	0.00954	
	0.85	Before	1	0	0	0	0	0	0.239
		After	0.76087	0.1675	0.05307	0.00824	0.00115	0.00917	
	0.9	Before	1	0	0	0	0	0	0.267
		After	0.81679	0.11825	0.04885	0.00626	0.00161	0.00824	
	0.95	Before	1	0	0	0	0	0	0.272
		After	0.84153	0.10075	0.04399	0.00526	0.00179	0.00668	
	1	Before	1	0	0	0	0	0	0.304
		After	0.85397	0.10771	0.02743	0.00332	0.00362	0.00395	

Fig. 2. Apparatus used for sample preparation.

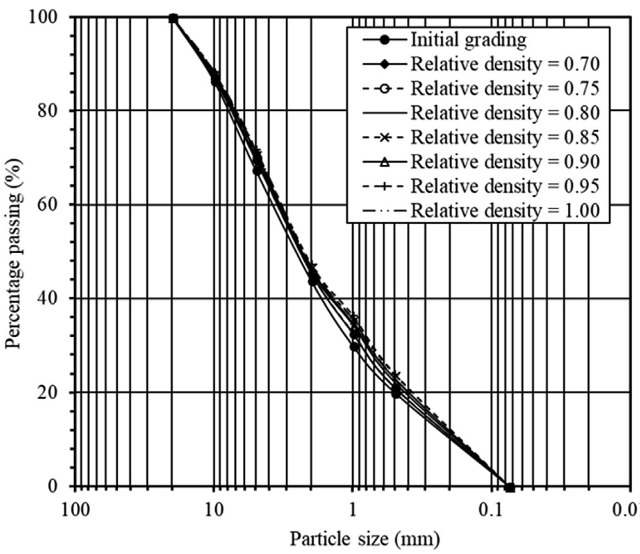

Fig. 3. Gradings of the material No. 1 before and after test.

mass is found in the size range of 2–5 mm whereas only a small amount of mass increase is found in the size ranges of 0.5–1 mm and 0.075–0.5 mm, indicating that most larger aggregates were broken into smaller aggregates with sizes between 2 mm and 5 mm.

To quantify the extent of particle breakage, the Marsal's breakage ratio (B_g) (Marsal, 1967), which measures the percentage increase in mass of particles that pass through each sieve size, is used in this study:

$$B_g = \sum_i \Delta_i^c \tag{1}$$

where Δ_i^c is the positive value of the percentage difference of each aggregate size fraction before and after each test. Fig. 6 represents the variation of the particle breakage ratio with the relative density. It is observed that the particle breakage ratio increases with the increasing relative density, irrespective of the material grading. An

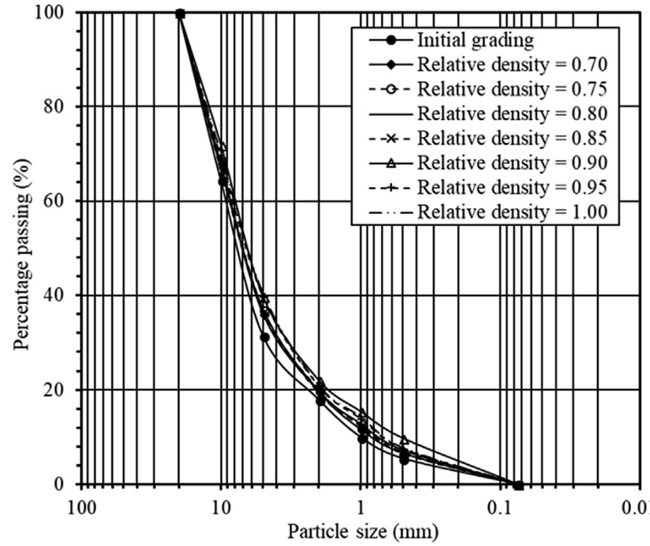

Fig. 4. Gradings of the material No. 2 before and after test.

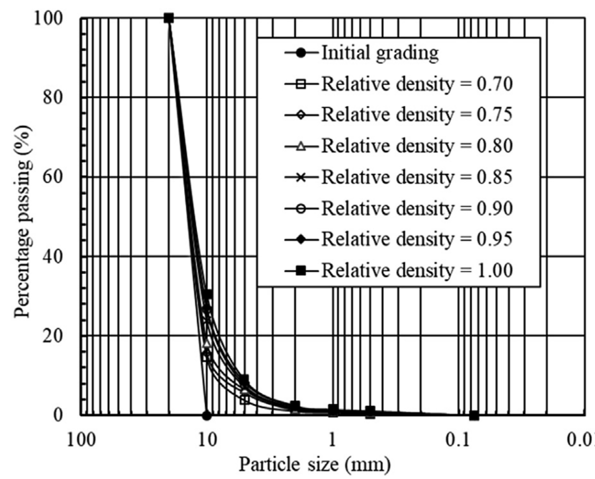

Fig. 5. Gradings of the material No. 3 before and after test.

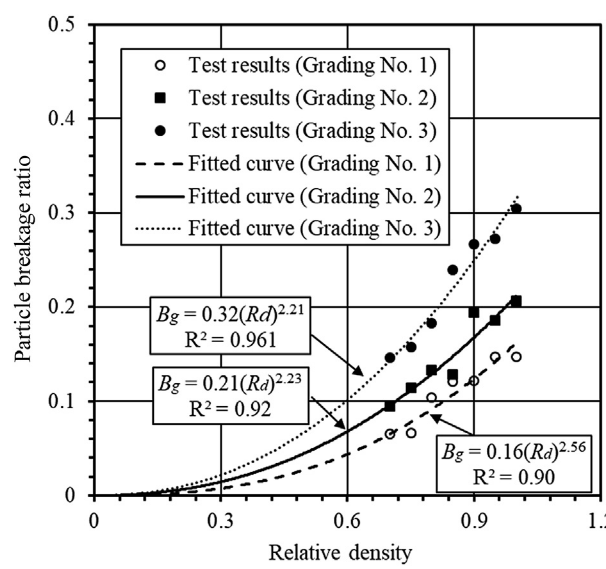

Fig. 6. Particle breakage ratio vs. relative density.

empirical relationship between the particle breakage ratio and relative density during sample preparation is suggested:

$$B_g = mR_d^n \quad (2)$$

where m and n are the material constants influenced by the grading parameters, such as C_u and d_{50}. In addition, a generally lower particle breakage ratio can be also found in material No. 1 which has a relatively higher coefficient of uniformity as well as lower median particle size, indicating that well-graded aggregates break less. This is in accordance with the study performed on ballast aggregates (Sun and Zheng, 2017) and sand aggregates (Xiao et al., 2018). Therefore, special care should be taken to avoid significant particle breakage when preparing granular materials with uniform grading. Particle breakage during sample preparation may not be ignored, especially when performing test on denser samples.

Figs. 7 and 8 show the variations of the material constants, m and n, with the grading parameters, d_{50} and C_u. It can be observed that m increases with the median particle size, d_{50}, while n decreases with d_{50}. In contrast, m decreases with the coefficient of uniformity, C_u, while n increases with C_u, indicating that less particle breakage would occur in granular materials with a better grading. However, it should be noted that a generally well-defined quantitative relationship between m, n, d_{50} and C_u cannot be given, as different soils would have different extents of breakage performance during compaction (Xiao et al., 2018).

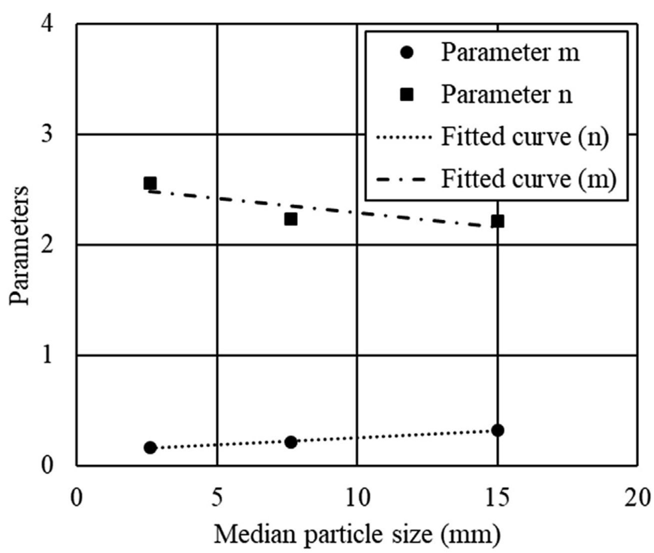

Fig. 7. Variations of m and n with d_{50}.

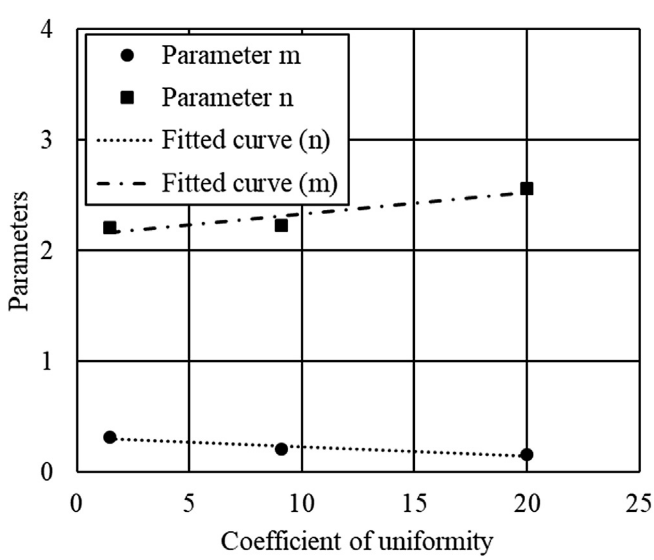

Fig. 8. Variations of m and n with C_u.

4. Conclusions

Most studies on the particle breakage behaviour of granular materials were focused on loading stage where samples were sheared or compressed by external loads. The mechanism for particle breakage during initial sample preparation was often ignored where the extent of particle breakage was often added to the one induced by subsequent loading. To investigate the particle breakage behaviour of granular materials during sample preparation, a series of laboratory tests was conducted by using layered compaction to prepare triaxial samples. Three different gradings and seven different relative densities were used. The main findings are summarised as follows:

(1) It was observed that all the gradings after test were observed to shift away from the initial grading, where smaller-sized aggregates were generated.
(2) Aggregates with larger size that appeared to break were more than the smaller-sized particles. Regardless of the initial grading, an increase in the extent of particle breakage with the increasing relative density was observed, which can be described by a power-law function.
(3) Less extent of particle breakage was found in well-graded granular material. It should be careful to avoid significant particle breakage when preparing granular materials with uniform grading.

However, it should be noted that this study was based on samples prepared by layered compaction. For those prepared by vibration, further studies are needed before a more general conclusion can be made.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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