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The effects of particle breakage and shape on the strength parameters of sandy soil

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The effects of particle breakage and shape on the strength parameters of sandy soil

D Youventharan[1], O Rokiah[2] and S Mohd Arif[2]

[1]Civil Engineering Department, College of Engineering, Universiti Malaysia Pahang, 26300 Gambang, Kuantan, Malaysia
[2]Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, 26300 Gambang, Kuantan, Malaysia

E-mail: youventharan@ump.edu.my

Abstract. Many laboratory and full-scale studies found that pile foundation is a reliable structure that has a long-term durability. This aspect makes it favourable when construction is in an area like the coastal where granular materials are normally in great scale. Generally, method used for the installation of pilling such as the drop hammer method will involve high energy to drive a single pile into the ground. Hence, the soil particles may undergo serious physical changes that will affect the engineering properties of soil used in the design work. The main aim of this research is to know the impact of pile installation work on sand particles. To understand the impact of sand particle breakage to the soil strength, an actual soil breaking mechanism simulated in the laboratory by using an automated soil compactor where the sand samples were crushed using 500 and 1000 times of blows respectively. The behaviour of sand were then analysed using a series of test which are; sieve analysis, specific gravity, relative density and the shear box test in order to measure the engineering properties of the sand. Mackintosh probe test was conducted in-situ to identify the undrained shear strength of sand and to correlate the cohesion of the sand with laboratory testing. This research confirmed that particle breakage has a significant influence with sand shape and therefore its strength changes with crushing impact.

1. Introduction

Soil particle breakage is one of the mechanisms that govern the behaviour of the granular soil by altering its grain size distribution. Granular soil associated with activities such as pile driving will experience loading which may cause particle breakage. The objective of this research is to study the impact of crushing of sand soils from different locations along the coastal area of East Coast of Peninsular Malaysia. Crushable sand which caused by high stress exert on the sand particles are considered brittle and are frequently encountered in areas prone to liquefaction like beaches due to strong tidal waves [1]. Apart from that, crushable sand soils too have its contribution from the human activities such as pile installation, construction of high earth or rock fill dams, impact of projectiles, laying foundations of the offshore gravity structures and so on [2-3]. The sand crushability characteristics will change from the original engineering properties, which a structure's initial design was based on. This brings the possibility of soil failure to occur due to significant change of the soil properties after crushing. Normally, pile foundations are used for large structures and in a situation

[1] To whom any correspondence should be addressed

where the shallow soil depth is insufficient to withstand excessive settlement, resist uplift, etc. Drop hammer method used for the installation of the piles will create vibration on the ground due to the high dynamic loading. As a results of this, particle breakage occurs when granular materials undergo excessive compression energy [4]. Some researchers claim that, piles that are being driven into sands and in debris flows will impose greater damage due to rather high energy level [5-7]. The breakage of particles will result in the increase of percentage of fine particles and also significantly change in the material grading [8][9]. Some studies also shows that aggregates with larger size appear to break more than the smaller-sized ones [10]. Therefore, the original engineering properties with which a structure was initially designed will change drastically during its engineering design lifespan [11]. In addition, a large number of experimental evidences suggested that particle breakage might significantly influence the soil behaviour [12]. Hence, to understand the soil behaviour and the changes that take place after crushing, indicators like the breakage factor and the breakage index are used in this research.

1.1. Breakage factor

The amounts of the particles breakage were evaluated from the grain size distribution curves using the method that was developed by empirical formula [13]. In this method, crushing impact was evaluated by using the particle breakage factor denoted as B_{10}. This parameter is based on the effective size, where B_{10} is the particle breakage factor, D_{10i} is the effective grain size of the initial gradation and D_{10f} is the effective grain size of the final gradation.

$$B_{10} = \frac{D_{10i} - D_{10f}}{D_{10i}} \qquad \text{(Eq 1)}$$

1.2. Breakage index

There are some empirical methods by which are used to quantify particle breakage considering the changes in specific particle size. For example relative breakage computed where the entire grain size distribution before and after loading is measured, in comparison to what recommended by other researchers. Relative breakage and surface area increments as shown in figure 1. Apart from that, one simple method known as the breakage index, is used in the study where D_{15i} is the effective grain size of initial gradation and D_{15f} is the effective grain size of final gradation [14].

$$B_{15} = \frac{D_{15i}}{D_{15f}} \qquad \text{(Eq 2)}$$

$$B_R = \frac{B_t}{B_p} \qquad \text{(Eq 3)}$$

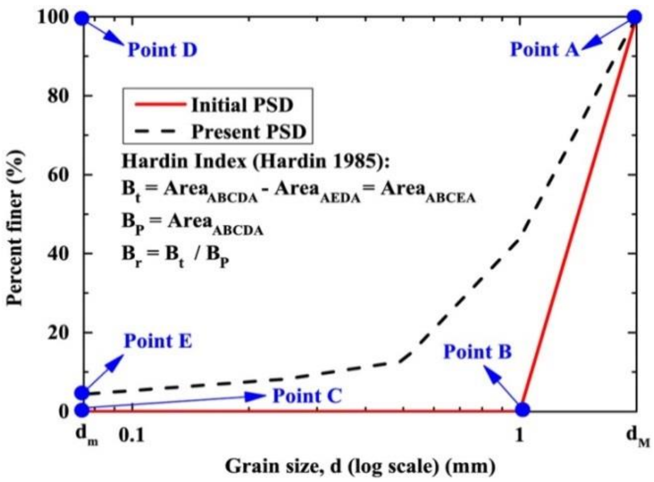


Figure 1. Definition of relative breakage, Br [15].

2. Materials and methodology

Sand deposits were obtained from three different locations in the East Coast of Peninsular Malaysia. The sand soil samples were collected from three different coastal areas at Kuantan district, which are Pantai Teluk Cempedak (PTC), Pantai Taman Gelora (PTG) and Pantai Batu Hitam (PBH). The soil samples were oven-dried at 110°C for 24 hours prior to conducting basic engineering properties tests. Approximately 1kg of soil samples from each location was isolated for sieve analysis test and the remaining soil was used for other relevant tests. The samples were then sieved by using ASTM standard for both the original soil and the crushed sand samples. Particle size distribution (PSD) curves were plotted and crushing indicators such as Breakage Factor (B_{10}) and Relative Breakage Index (B_r) were analysed.

In order to crush the sand, an automated soil compactor was used as shown in figure 2. Soil samples from each location were subjected to 500 and 1000 blows that are equivalent to 4 $x10^3$ kJ/m^3 and 8 $x10^3$ kJ/m^3 energy respectively. Thereafter, a series of test have been carried out with reference to standard manual to measure the basic engineering properties. Sieve analysis test (ASTM D422), specific gravity test using Pycnometer method (BS EN ISO 17892-3:2015) and relative density test (ASTM D4254, ASTM D4253) are some of the tests used in the analysis. The maximum and the minimum void ratio of each sample were used to determine relative density of sample. Engineering property tests were repeated twice for each of the original sample and repeated after crushing on the same sample again. The particle size distribution of coastal sand samples from three different locations used in the research is shown in Figure 3.To simulate the actual conditions of ground (that is when a structure transmits a load onto the sand) in the laboratory, an automatic mechanical compactor was used to crush the sand sample. The sand samples was crushed using different number of blows (500 blows and 1000 blows) for each sand sample, tests were performed in the same conditions to analyse the effect of particle breakage using the soil and geotechnical engineering testing facilities. For the field test, Mackintosh Probe Test was conducted at all the three locations with selected one point test only. The undrained shear strength was estimated based on Mackintosh blows using equation (4).

$$S_u = 18J^{0.3} \qquad \text{(Eq 4)}$$

Where, J is the number of blows.

Figure 2. Automatic soil compactor used to crush soil samples

Mackintosh Probe Test was performed to acquire the undrained shear strength (directly through correlations) and consistency of the subsoil layering for coastal sandy soils was determined. Meanwhile the sandy soil samples were tested for shear strength parameters (cohesion and angle of friction) using Direct Shear Box test in the laboratory. Moisture content test is performed to determine the water content of the sand soil sample by using simple oven drying method. Specific gravity test is performed to confirm the type of soil minerals using a density bottle method. Specific gravity was calculated by the ratio of the mass of unit volume of soil at a specific temperature to the mass of the same volume of gas free distilled water at same specific temperature. In granular soils, the relative density of the soil in the field can be measured according to the formula given in equation 5:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100 \qquad \text{(Eq 5)}$$

Where e_{max} = void ratio in soil in loosest state, e_{min} = void ratio in soil in densest state, and e= natural void ratio of in-situ soil.

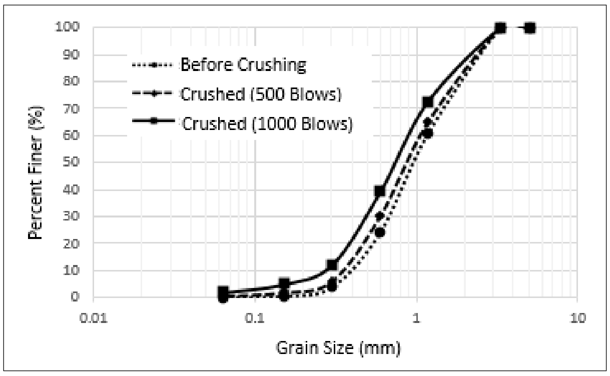
3. Results and discussions

The results and the discussions included in this section only cover a small aspect from the bulk of data obtained during the process of completing this research. This is because some of the data is deemed irrelevant with the scope and the objective of this paper outlined in the introduction part.

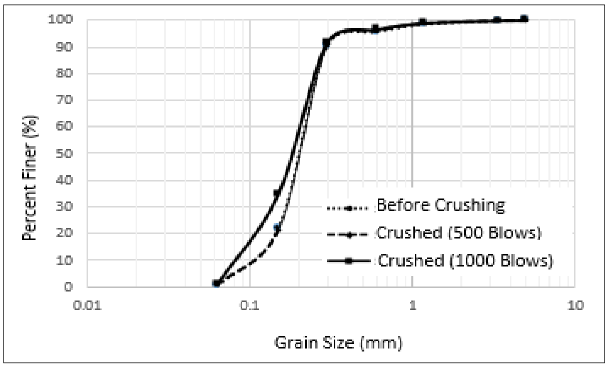
3.1. Particle size distribution (PSD)

Figure 3 shows the effect on the PSD curve due to crushing of sand. The PSD of sand crushed after 500 blows and 1000 blow was calculated separately. The PSD shows that the percentage of finer sand for all three samples for different location has increased as the number of blow increases. The particle size distribution curve of soil samples from all three locations PTC, PTG, and PBH before and after crushing has been plotted from the result of Sieve Analysis Test which is shown in figure 3 (a), (b) and (c).

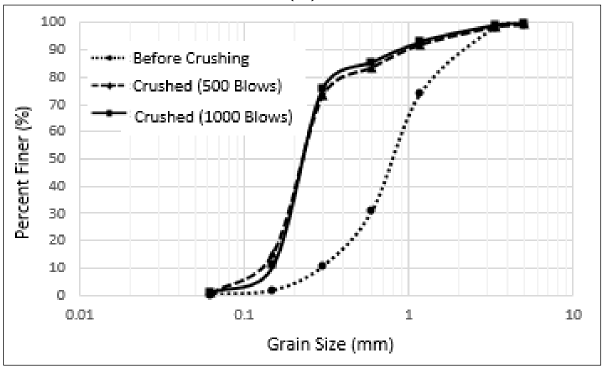
After the different force or energy level applied on each sand samples, the sand particles tend to break. The breakage of sand particles were evaluated and calculated using Breakage Factor and Breakage Index equations. The pattern of soil breakage can be easily observed in samples after being crushed when plotted in graphs like in figure 3. Based on this study, the particle breakage pattern of soil samples is well reflected as the horizontal distance between the curves of before and after crushing process is not similar. The ratio of D_{15} of the soil particles before crushing to the D_{15} of the soil particles after crushing is analyzed for each soil samples. Breakage index of 1.0 is seen as the breakage does not occur with the soil particles. On the other hand, if the particles undergo signifiant amount of crushing, the anticipated breakage index should be more than 1.0.



(a)



(b)



(c)

Figure 3. Particle size distribution curve of (a) PTC (b) PTG and (c) PBH.

The results of the Breakage Index indicates that soil sample PBH has the highest crushability compared to PTC and PTG. Moreover PBH soil particle breaks until a certain limit where there is no changes in breakage index was seen when the number of blows were increased to 1000. The breakage index of soil sample PTC at different level of energy shows that particles crushed gradually as the number of blows increased. Meanwhile, soil sample PTG has the lowest crushability since there is no breakage occurred when the 500 blows was applied and the particles only started to crush after the blows were increased to 1000. A slight increase was seen in the breakage index of PTG after 1000 blows. All the soil samples are classified as Poorly Graded Sand (SP) according to Unified Soil Classification System (USCS). The summary of classification index from sieve analysis test is recorded in Table 1.

Table 1. Summary of classification index for soil sample tested using sieve analysis.

Location	Type	D_{10}	D_{30}	D_{60}	D_{25}	D_{75}	C_u	C_c
PTC	Original	0.395	0.800	1.500	0.715	2.000	3.797	1.080
	500 blows	0.390	0.800	1.500	0.715	2.000	3.846	1.094
	1000 blows	0.310	0.640	1.200	0.570	1.700	3.871	1.101
PBH	Original	0.145	0.210	0.325	0.195	0.460	2.241	0.936
	500 blows	0.140	0.210	0.330	0.195	0.460	2.357	0.955
	1000 blows	0.130	0.190	0.380	0.180	0.390	2.923	0.731
PTG	Original	0.135	0.450	0.420	0.220	0.530	3.111	3.571
	500 blows	0.100	0.220	0.390	0.195	0.510	3.900	1.241
	1000 blows	0.095	0.215	0.390	0.190	0.510	4.105	1.248

3.2. Engineering properties

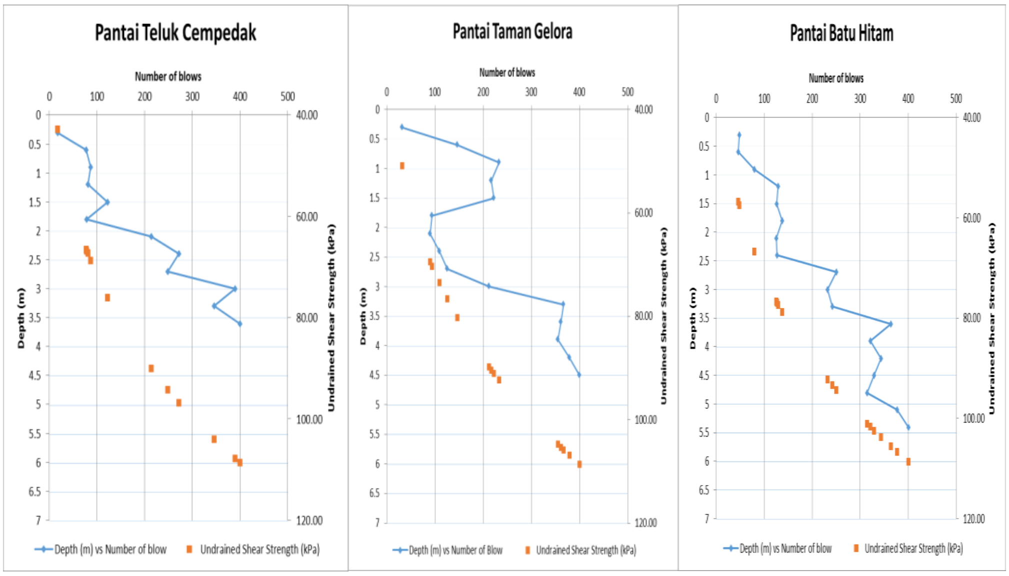
Table 2 shows the engineering properties of the sample before and after crushing. After the maximum crushing impact, the value of specific gravity for both PBH and PTG decreased while PTC increased. Similarly, the value of relative density for PTC, PBH and PTG too changes after crushing. Similar to any other standard tests, three repetitions of soil testing for each location were used and the average result of these three sets were used as the value of specific gravity of the soil. Before the soil samples were crushed, the specific gravity value attained was 2.81, 2.7, and 2.83 for Pantai Teluk Cempedak, Pantai Batu Hitam, and Pantai Taman Gelora was respectively. However, after soil samples were crushed and tested for its specific gravity, the values changed significantly. The value of specific gravity for both Pantai Batu Hitam and Pantai Taman Gelora decreases after the crushing, which are 2.64 and 2.55 respectively. For Pantai Teluk Cempedak the value of specific gravity decreases after the samples crush with 500 blows (2.72) but increases after 1000 blows (2.78). The results shown in Table 2 on relative density was calculated using equation (5). The value obtained for the sandy soil samples from Pantai Teluk Cempedak, Pantai Batu Hitam and Pantai Taman Gelora is 54.57%, 54.02% and 56.69% respectively. However, after the samples were crushed using an automatic mechanical compactor with 500 blows and 1000 blows, the values of the relative density increases. The value obtained after the maximum crushing for the sandy soil samples from Pantai Teluk Cempedak, Pantai Batu Hitam and Pantai Taman Gelora is 57.64%, 56.99% and 66.9% respectively.

Table 2. Engineering properties of soil and the crushing effects.

Properties	Before Crushing			After Crushing					
				500 blows			1000 blows		
	PTC	PBH	PTG	PTC	PBH	PTG	PTC	PBH	PTG
Specific Gravity	2.81	2.70	2.83	2.72	2.67	2.69	2.78	2.64	2.55
Relative Density (%)	54.57	54.02	56.69	49.72	47.06	58.11	57.64	56.99	66.9

3.3. Relationship between type of sand and material properties

The result of the mackintosh probe test is shown in figure 4 (a), (b) and (c) for all the three locations, PTC, PTG and PBH respectively. The results show a good pattern of number of blows when plotted with depth for all three locations. The increases in undrained shear strength with increasing soil depth are well portrait using equation (4). The maximum depth obtained with 400 blows is at 3.6 m, 4.5 m and 5.4 m for PTC, PTG and PBH respectively. The graph of undrained shear strength, S_u versus the number of blows (J-Value) was constructed not only to develop the correlation but also to identify the cohesion of soil at the surface where sampling was carried out. The average undrained shear strength predicted from the Mackintosh probe test is 40 kPa. This value is reasonably close to cohesion value obtained from Direct Shear Box test conducted on samples before crushing. A graph of cohesion versus the number of blows in samples is shown as in figure 5. The data clearly show that as the sand samples are crushed there is a significant change in shear parameters. The impact is more when the cohesion value drops drastically like in PTC sample. Figure 6 and 7 both shows the impact of crushing to sandy soil in coastal area. The indicators such as the Breakage Index and the Breakage Factors show that the variances in impacts are dependent on the type of granular soil and its characteristics. The mineral properties and the shape factors certainly play a vital role in samples collected from different locations for this study. Figure 6 and 7 both show that sample from PTG is more vulnerable in terms of potential to crushing.



(a) **(b)** **(c)**

Figure 4. Mackintosh probe test versus undrained shear strength in (a) PTC (b) PTG and (c) PBH

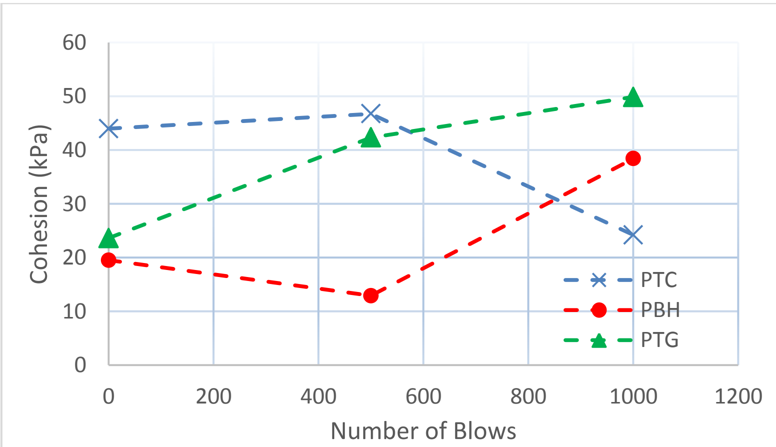


Figure 5. The effect of crushing impact to cohesion value in sandy soil

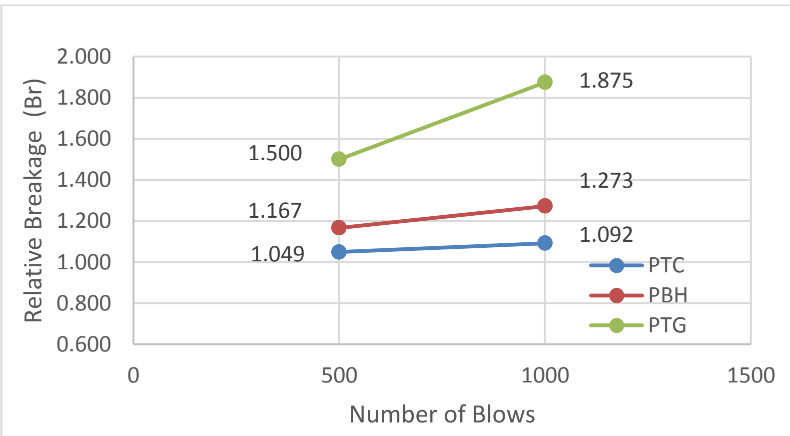


Figure 6. Relative breakage versus number of blows in sandy soil

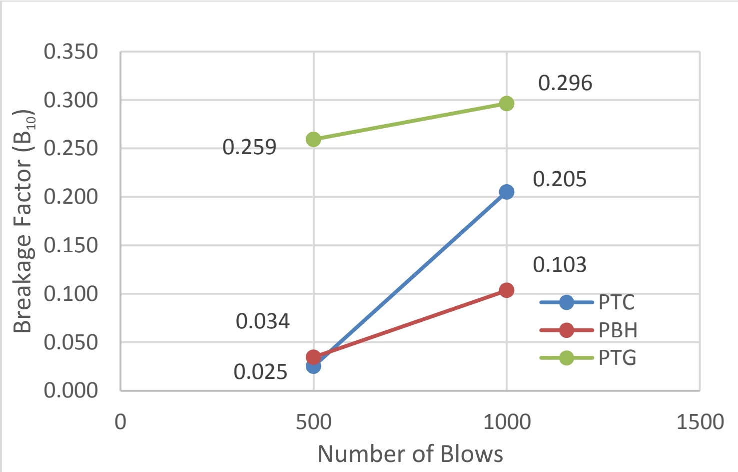


Figure 7. Breakage factor versus number of blows in sandy soil.

4. Conclusion

Crushing of particles did bring significant changes in the geotechnical properties of soil. The following conclusions can be made from this research work.

The type of mineral, relative density and shape (angularity) of soil samples from Pantai Teluk Cempedak, Pantai Taman Gelora and Pantai Batu Hitam influence the breakage potential of these soils. The Breakage Index and Breakage Factor is used to gauge the crushability potential of the soil samples and also to determine the relationship between the particle breakage and the influencing factors such as the relative density and angularity of soil samples.

1) The gradation (PSD) curve of crushed soil changed significantly. Increase in the number of blows crushing on soil particles will increases the percentage of finer particles from various sieve, especially the ones with larger aperture size.
2) The specific gravity for PBH and PTG decrease while PTC increase as the number of blow crushing the sample increase. In addition, the relative density increases as the number of blow increase.
3) Breakage Factor and Breakage Index increase with an increase in number of blows reflecting the changes in PSD curve. Hence, Breakage factor and Breakage Index can be used as an indicator to predict changes in shear strength parameters.

The change of cohesion will affect the shear strength of the samples. The shear strength for PBH and PTG increase as the cohesion increase while for PTC the shear strength decrease as the cohesion decrease.

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