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Effect of arbitrarily manipulated gap-graded granular particles on reinforcing foundation soil

Zhen H. Xin[1a], Jun H. Moon[1b], Li S. Kim[1c], Kab B. Kim[2d] and Young U. Kim[*1]

[1]*Department of Civil and Environmental Engineering, Myongji University, Youngin 17058, South Korea*
[2]*Bosiddol Inc., Nonhyeon-ro 63, Gangnam-gu, Seoul, 06256, South Korea*

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Abstract. It is generally known that high strength soil is indicative of well-graded particle size distribution. However, there are some special cases of firm ground despite poor grade distribution, especially a specific gap-graded soil. Based on these discoveries, this study investigated the development of an additive of gap-graded soils designed to increase soil strength. This theoretical concept was used to calculate the mixed ratio required for optimal soil strength of the ground sample. The gap-graded aggregate was added according to Plato's polyhedral theory and subsequently calculated ratio and soil strength characteristics were then compared to characteristics of the original soil sample through various test results. In addition, the underground stress transfer rate was measured according to the test conditions. The test results showed that the ground settlement and stress limit thickness were reduced with the incorporation of gap-graded soil. Further field tests would confirm the reproducibility and reliability of the technology by using gap-graded soil to reinforce soft ground of a new construction site. Gap-graded soil has the potential to reduce the construction cost and time of construction compared to other reinforcing methods.

Keywords: gap-graded soil; plate load test; bearing capacity; jamming; aggregate

1. Introduction

Ground strength is the most basic yet vital factor in the design of civil engineering structures. The stronger the ground, the more economical the design and construction can be. Therefore, various studies have been carried out to improve ground strength in a variety of ways. Attempts have also been made to apply newly developed methods in the field. Cherif *et al.* (2014) conducted a shear test by adjusting the particle size distribution of silt sand and found that the porosity of the soil affected the soil strength. The porosity ratio and internal friction angle are also related to particle size. According to studies by Hyodo *et al.* (2017) and Alias *et al.* (2014), the greater the particle size of soil, the greater the effect of internal friction angle and compressibility. On the other hand, Hsiao *et al.* (2014) found that the ratio of small silt particles to larger particles in the binary granular mixture of silty soil significantly affects the shear strength. Kim *et al.* (2016), Yilmaz *et al.* (2009) and Monkul (2013) constructed samples composed of two different particle diameters and investigated the effects of volume ratio on shear strength. These are indicative of a well-established assumption, that ground strength is affected by many factors, in particular particle size distribution.

Usually, good particle size distribution is indicative of a stronger soil while the inverse is usually weaker, though this is not all ways the case. One such instance is the Sagot beach located in South Korea, which is designated a natural airfield, despite being classified as Poorly-Graded sand (SP) according to the Unified Soil Classification System (USCS) (Park *et al.* 2005). This sand is known to be composed of poor particle-size distribution, according to the particle size distribution curve, however it has been used in the past as a runway for aircraft to take off and land without concrete or asphalt pavement. It is not simply due to the capillary phenomenon, but rather a unique particle distribution and spatial arrangement. The studies of Cho *et al.* (2006), Vashi *et al.* (2014), and Cablar (2016) show that particle size distribution is influenced by soil type, size, and granular shape. There have been many studies to compare the strengths of binary granular samples, such as gravel and sand or sand and another soil. However, there have not been many attempts to affect particle size distribution with composed aggregate.

This study attempts to reinforce the ground by adjusting the particle size distribution through the introduction of aggregate. This methodology was evaluated by creating gap-graded granular soil and conducting laboratory experiments, numerical analysis, and field tests, to investigate a method for ground reinforcement that induces jamming, where the particle size distribution consists of specific gap-graded granular particles. In addition, to

∗Corresponding author, Professor
E-mail: yukim@mju.ac.kr
[a]Ph.D. Candidate
E-mail: jeena97@nate.com
[b]Ph.D. Candidate
E-mail: jekyll99@nate.com
[c]M.Sc.
E-mail: loginmolra@naver.com
[d]Chief Executive
E-mail: kgbsns@daum.net

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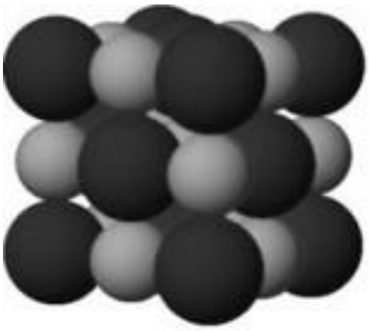


(a) 3D graphic of gap graded model

(b) A scale model of the gap graded

Fig. 1 Gap graded model

confirm the field applicability, namely reproducibility and reliability, a field test was conducted on a larger scale.

2. Gap-graded soil

As depicted in Fig. 1(a) and 1(b), soil composed of two different partial sizes satisfying a specific ratio does not separate easily. The jamming of the soil particles utilizes the platonic regularity model and assumes that the soil particles are complete spheres. To place soil particles at each vertex of a regular polyhedron, and smaller particles in the center of the voids, so as all soil particles come in contact with each other, jamming can be induced. In a three-dimensional model, it is also referred to as the body-centered polyhedral, and when applied to soil, the size distribution is found to be gap-graded.

The composition ratio of the aggregate under the test conditions was calculated according to several principles. As depicted in Fig. 2, the center of the large particle is located at the corner of the regular polyhedron, and the center of the smaller particle is the center of force of the regular polyhedron. The composition ratio of the sample was assumed to be 1:1 of small particles to large particles by infinitely expanding the arrangement of particles in a

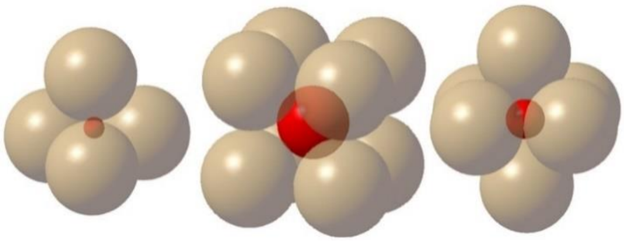


Fig. 2 Gap graded soil satisfying Plato's polyhedral

Table 1 Samples composition ratio of gap graded soil satisfying Plato's polyhedra

Volume ratio (Small & big particle)	Maximum dense Packing (Tetrahedron)	Median dense packing (Hexahedron)	Minimum dense packing (Octahedron)
n=R/r	4.45	1.37	2.41
Small particle volume ratio	1.1%	28.2%	6.6%
Big particle volume ratio	98.9%	71.8%	93.4%

regular polyhedron. Since the specific gravity is assumed to be the same, the volume ratio can correspond to the weight ratio, so that the composition ratio of the gap-graded soil can be obtained from Eq. (1). This distribution pattern is arranged with a large number of contact points, with the symmetrical force varied, so that the geometric friction force is amplified to increase the strength of the ground.

$$\text{Big Particle Weight Ratio} = \frac{R^3}{R^3 + r^3};\ \text{Small Particle Weight Ratio} = \frac{r^3}{R^3 + r^3} \quad (1)$$

3. Verification procedures and results

3.1 Laboratory experiment

The direct shear tests were performed and their results as shown in Fig. 3, where the ratio of the particle size R of large particles to the particle size r of small particles is expressed by the formula n = R / r. The solid line shows the internal friction angle of standard sand with a uniform particle size of 0.6 mm. In addition, the circle mark shows the internal friction angle according to the Gap particle size (Particle Size Ratio, n), from the results of direct shear test, it can be found that the internal friction angle trend to increase with the particle size ratio.

3.2 Numerical simulation

The direct shear test results show that the internal friction angle increases with particle size ratio, and DEM simulation was performed using PFC2D program to monitor jamming effect with particle distribution. Ground conditions were designed with a homogeneous grain size and a grain size ratio n=1.37, and other conditions remain the same. The micro properties of the gap graded and homogenous granular particles used in the numeric simulation can be seen in Table 2. Through the analysis of the program, the underground stress transfer analysis was carried out according to the particle size distribution when the load was applied. As shown in Fig. 4(a) and 4(b), when the same constant load was applied, the ground, which was designed with a homogeneous particle size was overburden and severely damaged, while the gap-graded distribution ground was stable. This is because the gap-size ground

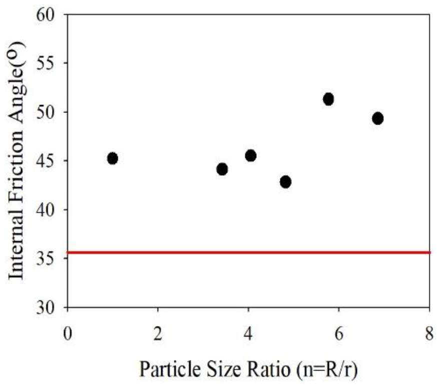
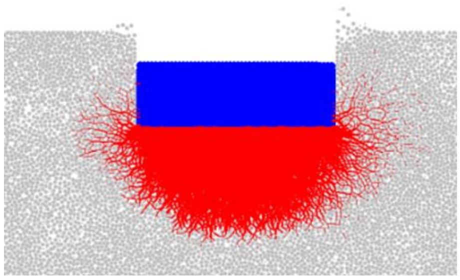


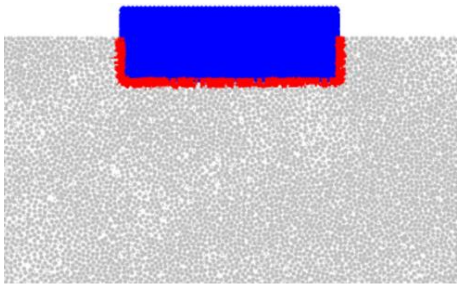
Fig. 3 Internal friction angle with particle size ratio, n

Table 2 Properties of the granular particles used in simulation

Properties	Gap graded condition	Homogeneous condition
Ball radius (mm) R & r	0.85 mm & 0.71 mm	0.71 mm
Volume fraction (%) R & r	71.8% & 28.2%	100%
Ball to ball contact modulus (GPa)	42	42
Ball Stiffness ratio	2.0	2.0
Ball friction coefficient	0.7	0.7
Ball density (kg/m^3)	2500	2500



(a) Failure state with uniform size soil



(b) Safety state with gap graded soil

Fig. 4 DEM analysis

shows a systematic interlocking effect between the particles and effectively disperses the force, and the friction effect is exerted from the surface of the foundation.

3.3 Field experiment

In previous research, the improved bearing capacity of the sandy soil due to the alteration of the particle distribution was confirmed through the shear resistance test,

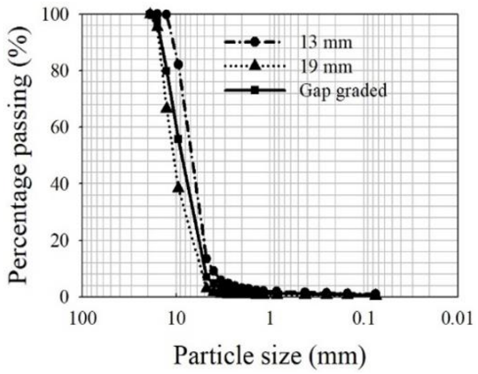


Fig. 5 Particle size distribution

Table 3 Classification of aggregate through unified classification

Aggregate type	Cu	Cg	Unified classification	Gap graded soil degree of precision
13 mm	1.83	1.06	GP	28.3%
19 mm	2.27	1.08	GP	34.7%
13+19 mm	1.98	0.98	GP	87.8%

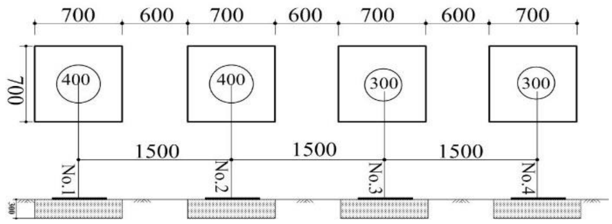
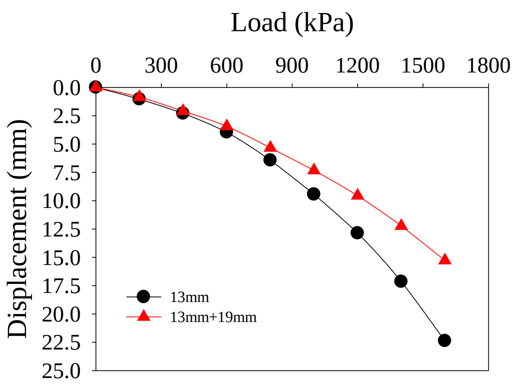


Fig. 6 Field plate load test

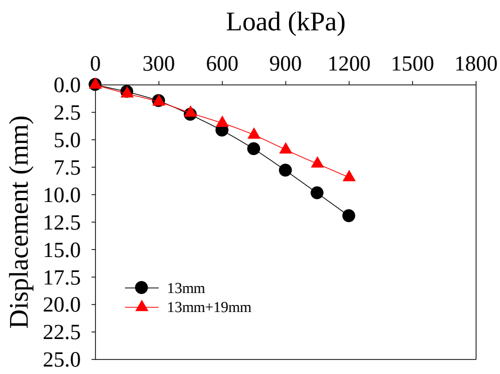
and the stress transfer mechanism was confirmed through a DEM simulation and analysis. In order to verify the interpretation of the program analysis, we carried out a plate loading test through model trenching to confirm the strength change according to the field application.

The aggregate used in the substituted soil condition was 13mm aggregate, 19 mm aggregate, and 13 mm + 19 mm aggregate. The particle size distribution of the aggregates used in the test was confirmed through a sieve analysis. Table 3 shows that poor gravel (GP) can be classified as aggregate used in the unified classification method. The aggregates used in the tests from Table 3 can be classified as GP (Gravel poor) and sieve analysis results are shown in Fig. 5. The ratios of 13 mm aggregate, 19 mm aggregate, and 13 mm + 19 mm aggregate satisfying the gap graded conditions of Plato's polyhedral were evaluated by using the theoretical formula, and the error ranges were summarized in Table 3.

Actual site conditions were simulated to test the bearing capacity performance of a general soil sample as a control and a gap-graded soil sample. This consisted of four test sites, as shown in Fig. 6, where aggregate filled an area of 700 mm × 700 mm × 300 mm, and with a minimum of 600 mm between the test sites. Test sites 1 and 3 were filled with various aggregates of general soil with the maximum size of 13mm and tested with a Φ400 mm and Φ300 mm loading plate, respectively. Sites 2 and 4 were filled will

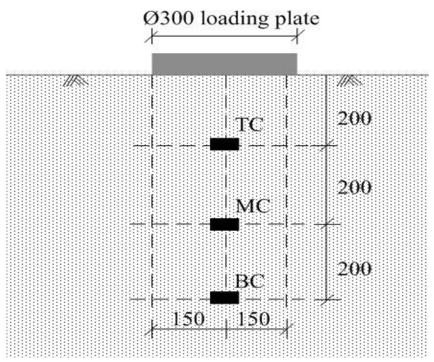


(a) Plate load test with ø300 plate



(b) Plate load test with ø400 plate

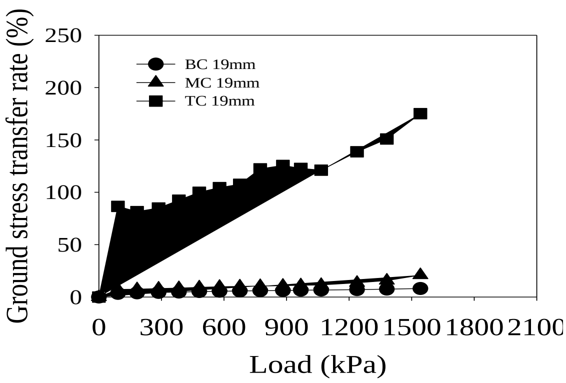
Fig. 7 Results of plate load test



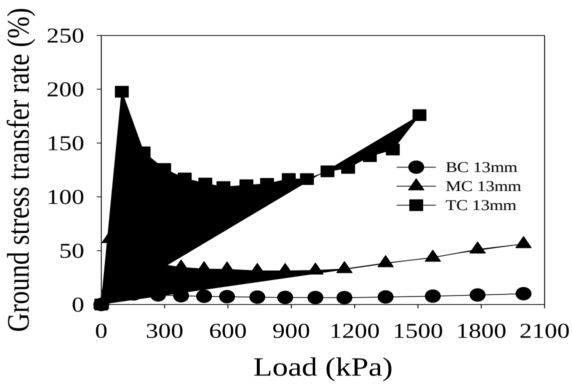
(a) Installation of earth pressure gauge

(b) Earth pressure gauge

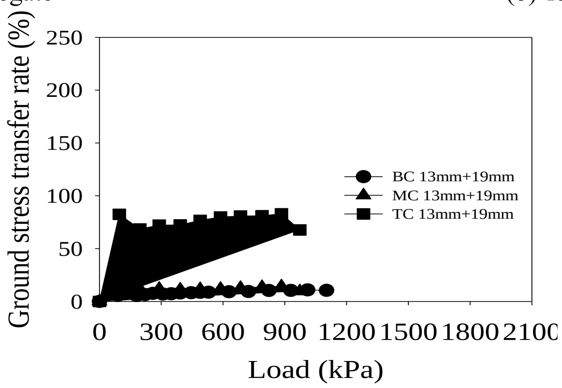
Fig. 8 Stress transfer test



(a) 19 mm aggregate



(b) 13 mm aggregate



(c) 13 mm+19 mm aggregate

Fig. 9 Underground stress distribute with aggregate artificially manipulated gap-grade soil of 13 mm and 19 mm aggregates and tested with a Φ400 mm and Φ300 mm loading plate, respectively. The results can be seen in Fig. 7(a) and 7(b). These results show an increase in bearing capacity in the gap-graded soil 1.75 times higher than general soil. Gap-graded soil settlement was also reduced by about 30% in comparison to the general soil. The experimental results show that the larger the loading plate and tested area, the smaller the settlement in the gap-graded soil; this indicates that a larger area amplifies the jamming effect of the artificially manipulated gap-graded soil.

In order to measure the distribution of underground stress, three soil pressure gauges were installed vertically in intervals of 200 mm from the center of the load plate as Fig. 8(a)-8(b). The soil pressure gauges readings were transferred to a data logger and recorded in real time. The ground stress distribution results for the general soil sites and the gap-graded test results are seen in Fig. 9(a)-9(c). Underground stress distribution test results showed that the underground stress transfer rate decreased in the upper layer of the gap-graded soil in comparison to the 13 mm general soil. Additionally, the stress thickness was reduced corresponding to the accuracy of the gap-graded soil's internal structure, Plato's polyhedral model.

3.4 Onsite feld test

In order to further verify the applicability of the gap-graded soil, a field test was conducted on a soft foundation at a new construction site. The gap-graded soil used in the field construction was comprised of a 19 mm aggregate and 25 mm aggregate and is classified as GP according to the USCS. The field test ground is composed of a top layer of sand mixed with silt for 10 meters. Beneath that, there is a 0.7 m layer of clay followed by a weathered residue of bedrock for 8.8 m below the clay layer. As shown in Fig. 10 the standard penetration test value per stratum is shown.
As shown in Fig. 11(a)-11(b) the aggregates were layered in an alternating pattern, starting with aggregate A, 25 mm, and followed by aggregate B, 19 mm, which was then blended vertically and horizontally with an excavator sieve bucket. The test sites consisted of three 5 m × 5 m × 0.5 m areas. Two of the field tests sites were constructed with the manipulated gap-graded soil, while one was filled with general soil consisting of crushed stone aggregate layers with the maximum size of 19 mm. The field sites were deposited with the specialized gap-graded soil then twice compacted.

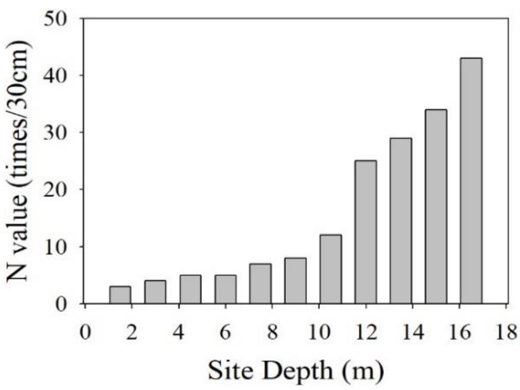


Fig. 10 Standard penetration test

(a) Substitute ground

(b) Compact

Fig. 11 Filed construction

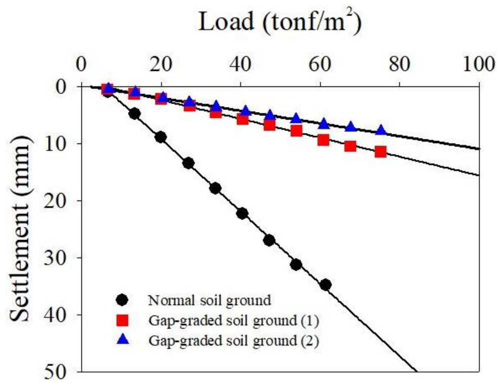


Fig. 12 Results of plate load test of onsite

The plate-loading test results are shown in Fig. 12 The supporting capacity of the general soil was improved by about 200~300 kPa in comparison to the gap-graded soil. Soil settlement of the general soil was reduced by 34.8 mm, while the gap-graded soil settled 9.4 mm and 6.7 mm, a difference of about 73% and 80.7%, respectively, in comparison to the general soil. As seen from the results, the soil settlement decreased and bearing capacity increased remarkably. This is indicative of successfully inducing the jamming effect in a gap-graded soil using a single gap-size aggregate to maximize the interlocking effect.

4. Conclusions

By conducting, a laboratory experiment we investigated the internal friction angle and stress transfer efficiency by forming gap graded soil satisfying Plato's polyhedral. These factors were examined through a direct shear test and DEM analysis. In order to confirm the results of the laboratory tests, a gap grade granular soil composed of crushed stone aggregate was prepared and the plate load tests were conducted. To evaluate the performance of the gap graded ground characteristics the field experiment was conducted. The applicability in the field was verified by increasing the scale and confirmed the reproducibility and the reliability in a field construction.

From the laboratory experiment results, it is shown that the gap size particle ground, which is an arrangement with many contact points, is formed and the path of the force is systematically varied. When the consistent load is applied, the geometric friction force is amplified and the soil strength is increased.

In the laboratory experiments, the gap-graded soil increased the bearing capacity by 1.75 times in comparison to the general soil. When the underground stress transfer rate was compared and analyzed, it was found that there was a decrease in the upper layer of the gap-graded soil due to the jamming effect. It can also be seen that the stress thickness was reduced in the gap-graded soil in response to the level of accuracy of the internal structure, Plato's polyhedral.

In conclusion, the introduction of artificially manipulated gap-graded soil for ground reinforcement has several distinct advantages, when compared with the current methods. When assessing productivity, gap-graded soil is able to be produced and artificially manipulated without the use of factories or specialized equipment. Concerning the materials needed, gap-graded soil is composed of only one aggregate, which is inexpensive and easily obtainable. When compared to the ground injection method and the small diameter bored pile method, gap-graded soil is a greater than 50% cost reduction, while having a smaller environmental impact than that of typical chemical solution injection methods.

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