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Jamming effect of particles through artificial manipulation of the particle distribution

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ABSTRACT

Jamming of soil particles utilizes the Plato's regular polyhedron model and assumes that the soil particles are complete spheres. Placing larger soil particles at each vertex of a regular polyhedron and smaller particles at the center of the voids, in a manner such that all soil particles come in contact with each other, induces the jamming effect. 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. Herein, we investigated this mechanism, first through a numerical analysis and centrifuge test initiating the interlocking effect by distributing gap-graded sized particles and then by conducting a plate-load test to verify its ground reinforcement effect.

1. INTRODUCTION

There are many methods for improving soft soil, including physical, chemical, and electrical methods. However, physical improvement methods are widely applied in consideration of the economic efficiency, technical challenges, and environmental

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pollution. The mainstream methods for the physical improvement of soft ground include the pre-loading, vertical drainage, geotextile reinforcement, and grouting methods. The pre-loading method is one of the oldest and most widely used soft ground improvement methods, which is effective and economical; however, it entails lengthy construction periods. Furthermore, it is economically inefficient because of the complexity of construction and demanding design. The purpose of improving the soft ground while tackling economic and environmental problems is to solve the structural-stability problems caused by the low soil strength and bearing capacity. To maintain the stability of the soil structure, studies have been conducted to increase the internal strength by enhancing the internal physical forces without introducing outside reinforcement (Cho. 2006, Oda. 1977, and Viggiani. 2001). According to Takao (2011), the inner resistance angle increases even with small amounts of sand is added in aggregate. Yagiz (2001) showed that the shear resistance angle measured in the shear resistance test was the largest when the soil was mixed with over 20% of sand. This shows that the interlocking effect of the mixed gravel is better. Taiwan suffers from aggregate shortages because 90% of roads are built with asphalt and aggregate pavements. Therefore, Shen (2005) evaluated the performance of an asphalt pavement using a gap-aggregate gradation to improve the utilization of aggregates. Thus, increasing the contact area between particles aims at achieving as-solid density of soil. This physical process is called jamming (Siemens, 2010). Jamming phenomena are related to the particle-size distribution. The gap-particle size refers to an artificially manipulated particle-size distribution that generates a large number of frictional resistance surfaces and causes horizontal restraint force based on the load, causing lateral jamming between the frictional surfaces. Siemens (2010) demonstrated and explained the jamming point, which is a critical point where jamming occurs, as the density of particles increases. If sufficient balance is achieved between the particle-size distribution and support capacity, it can create a strong ground, despite even if the particle size is not diversified. This study aims to determine and verify the particle-size distribution that causes the jamming effect through numerical analysis of the particle-size distribution.

2. GAP-GRADED PARTICLE DISTRIBUTION

As shown in Fig. 1, loose soil has low contact frequency between particles when the upper force is applied and low frictional resistance because the contact points between particles transfer mostly vertical compression forces. On the other hand, dense soil has high frictional resistance due to numerous contact points transferring vertical and horizontal compression forces, with the latter generating friction. Soils formed with a gap-graded granularity develop well-structured contact points between particle layers. In particular, when a vertical compressive force is applied, the contact frequency between particles is high, and the best frictional resistance is generated by the systematic contact forces acting in the horizontal direction.

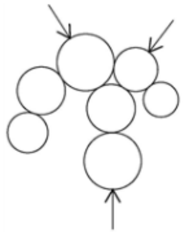
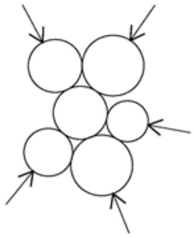
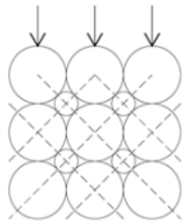
		
(a) Loose soil	(b) Dense soil	(c) Gap-graded soil

Fig. 1 Evaluation of particle overlapping

Filling the space systematically with polyhedrons leads to a hierarchical structure in any direction, which increases the rigidity of particle materials. In other words, the rigid base of the hierarchical structure generates a horizontal restraining force, when a vertical force is applied and causes horizontal deformation of the soil particles. The concept of gap-particle size has widely been used in related studies on asphalt pavements. The gap-particle size is defined as the particle-size distribution with one or more intermediate grades omitted (Shen, 2005). In this study, gap-graded particle distribution applied to ground is defined as particle-size ratio between the large and small aggregates between 1.1 and 4.45. The composition ratio of the aggregate used in the tests was calculated according to several principles. As depicted in Fig. 2, the center of a large particle is located at the corner of the regular polyhedron, and the center of the smaller particle is at the centroid of the regular polyhedron. The composition ratio of small particles to large particles in the sample was assumed to be 1:1 by expanding infinitely the arrangement of particles in a regular polyhedron. Since the specific gravity is assumed to be the same, the volumetric ratio corresponds to the weight ratio, thus, the composition ratio of the gap-graded soil can be obtained as follows:

$$\text{Big particle weight ratio} = \text{Big particle volumetric ratio} = \frac{R^3}{R^3+r^3} \quad (1)$$

$$\text{Small particle weight ratio} = \text{Small particle volumetric ratio} = \frac{r^3}{R^3+r^3} \quad (2)$$

R: big particle diameter

r: small particle diameter

This distribution pattern has a large number of contact points, with the symmetrical contact force, so that the geometric friction force is amplified to increase the strength of the ground.

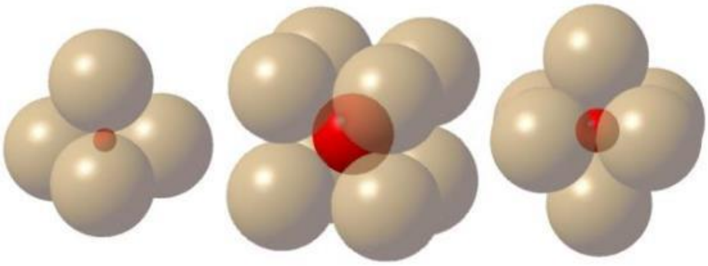


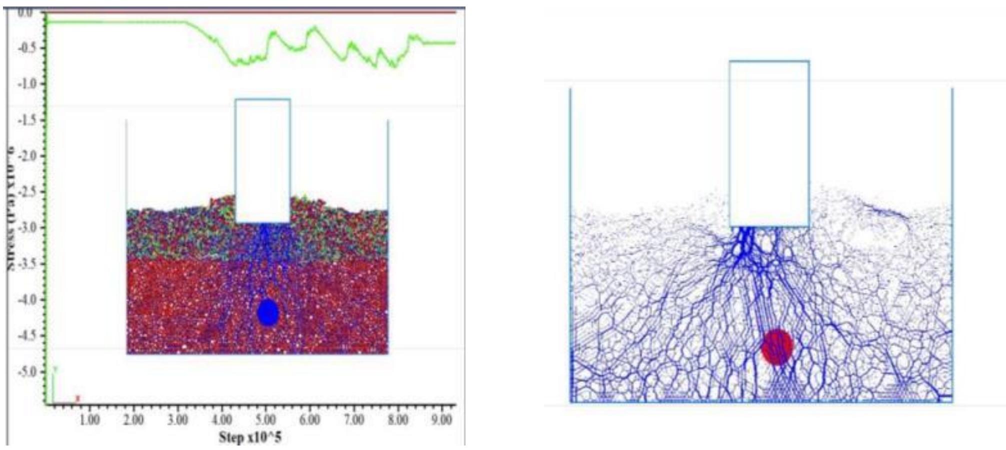
Fig. 2 Gap-particle size soil satisfying the Plato regular polyhedron model

3. EXPERIMENTAL METHOD AND RESULTS

3.1 Simulation of underground stress transfer in upper structure

Theoretically, if the ground has a particle arrangement consisting of polyhedrons, small particles should fit perfectly, like pieces of a puzzle, between the large particles. However, it is almost impossible to form a soil particle without using large mass, such as a rock. Therefore, the particle size and compounding ratio of specimens were decided according to a theoretical formula, and particles were generated and distributed randomly. Numerical analysis conditions were of three types, namely, homogeneous particle size, gap-graded particle size, and multiple particle size, respectively. Homogeneous particles were of 11 different sizes between 1.55 mm and 7.35 mm. The gap-graded particle-size samples comprised 54 cases of the ratio m = R/r of large to small particles of between 1.09 and 4.21 composed of 11 particle sizes.

The simulation model is shown in Fig. 3. The size of ground model is 23 m × 17 m. The ground is composed of two layers, namely, the general support layer and the substitution ground, with depths of 2 m and 7 m, respectively. The support ground is homogeneous with the particle size of 8.5 mm, and the substitution ground was simulated with different conditions, i.e., multiple particle size, homogeneous particle size, and gap-graded size, respectively. The superstructure was 5 m × 10 m in size and strata were formed and traveled at 15 cm/s.



(a) Particle generation by strata (b) Particle contact stress distribution

Fig. 3 Ground stress distribution monitoring

From Fig. 4, the stress dispersion effect was the highest at m = 1.37, followed by the homogeneous particle size, while the lowest stress dispersion effect was for the multiple particle size condition. From the numerical results, it is determined that the reduction of ground stress distribution can be up to two times higher than in the multiple grain size condition, when certain gap-graded size conditions are satisfied. If the proportion of small particles that act as a key stone is very small among randomly distributed sizes, the probability of producing jamming effect will be relatively small. Therefore, additional verification will be conducted through experiments, comparing the results with the gap-graded condition that exhibited high strength.

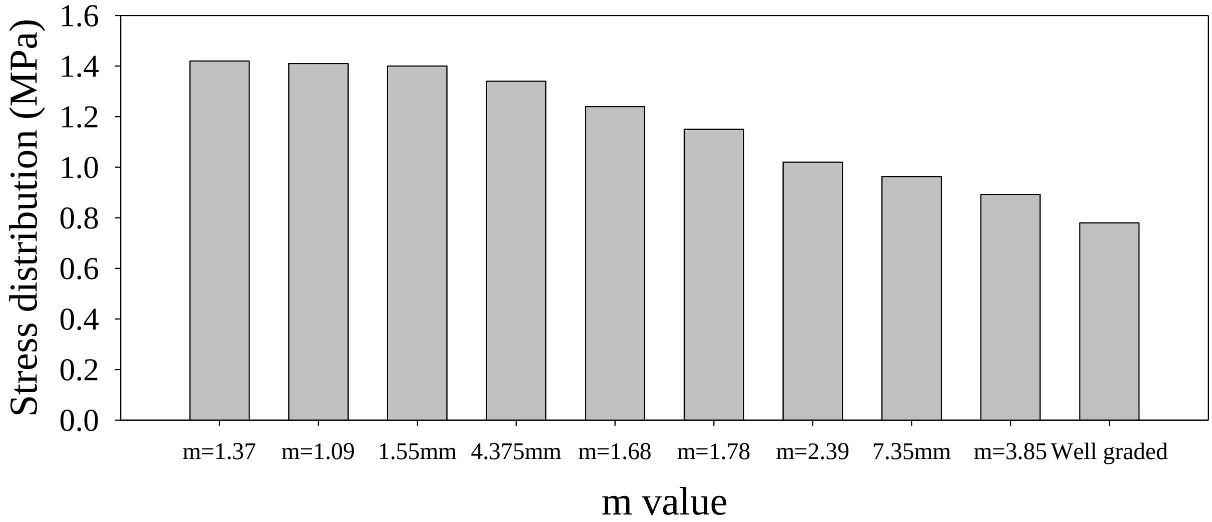


Fig. 4 Ground stress distribution of upper structures

3.2 Finding optimum gap-graded condition through centrifugal model tests

Centrifugal model tests were performed to evaluate the ground stress distribution caused by a structure placed on the soft ground. After scaling the structure at a ratio of 67:1, a centrifugal force of 67 times that of gravity was applied. The stress distribution in the soft ground was thus observed is similar conditions to those that occur for real structures and soils.

The centrifugal model structure and ground composition are shown in Fig. 5, The internal dimensions of the centrifuge chamber are 46-cm long, 25-cm wide, and 45-cm deep. The lower part of the chamber was filled with 8 cm of clay to form soft ground, and then filled with the Jumunjin standard sand to a height 13 cm above the clay, and, finally, and 8 cm deep aggregate replacement layer was formed above the sandy ground. In the centrifugal model test, displacement and earth pressure gauges were installed on the upper and lower structures to measure the displacement resulting from the upper structure applying vertical load onto the ground. Centrifugal model tests were carried out with the centrifugal acceleration of 67 g for each condition.

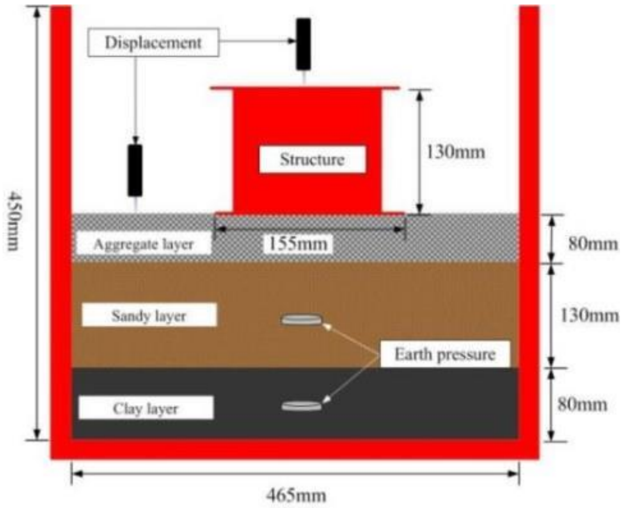


Fig. 5 Cross-section of centrifugal model chamber

The results of the centrifugal model tests are shown in Table 1, When interlocking between aggregates occurs in the gap-graded particle condition, the contact area increases, and friction effect is amplified. It was confirmed that ground stress distribution and settlement were reduced. For the particle size condition, the gap-graded size showed good performance at m = 1.68 and 1.37, and it can be seen that the smaller the particle size of the homogeneous particles, the greater the effect of reducing the ground stress. However, there is a need to further determine the optimal ratio of the large to small particle aggregates via a scaled-up test.

Table 1 Results of centrifugal model tests

m value	Clay layer (kPa)	Sandy layer (kPa)	Ground settlement (mm)	Structure settlement (mm)
m=1.09	407.07	192.31	98.49	349.00
m=1.37	377.26	215.84	93.80	366.96
m=1.68	271.15	167.60	141.37	208.30
m=1.78	380.89	249.87	181.57	381.70
m=2.39	284.98	251.93	106.53	436.96

m=3.85	527.99	358.92	212.39	809.56
m=1, 1.55 mm	260.37	146.22	377.88	1054.92
m=1, 4.375 mm	274.59	182.11	230.48	439.32
m=1, 7.35 mm	561.92	433.84	423.44	839.04
Multi particle sizes	571.76	421.6	414.864	613.50

3.3 Performance evaluation of gap-graded grain ground through plate loading tests

The concrete chamber dimensions were 1.5 × 1.5 × 1.5 m (width × length × depth). To measure the gap-graded aggregate ground stress distribution, as shown in Fig. 6, earth pressure cells were installed at 200 mm intervals from the center of the loading plate. Three gap-graded particle sizes were considered, namely, 13 mm aggregate, 19 mm aggregate, and 13 mm & 19 mm, respectively. The mixing ratios for each aggregate are shown in Table 2, The ground was formed by placing aggregates in layers at an interval of 30 cm and compacting the ground for 10 min with a compactor. The loading plate was 30 cm wide, and the load was applied in 10 steps until it reached 1700 kPa.

Table 2 Composition of gap-graded aggregates

Aggregate	Ground composition
13 mm aggregate	13 mm aggregate 100%
19 mm aggregate	19 mm aggregate 100%
13 mm & 19 mm aggregate	40% of 13 mm aggregate & 60% of 19 mm aggregate

The aggregate type classification by uniform classification is shown in Table 3, The data logger measured the displacement and earth pressure generated by increasing load, and the ground stress transmitted from the earth pressure to each soil strata.

Table 3 Aggregate type classification by uniform classification

Aggregate size	*Cu*	*Cg*	USC
13 mm	1.83	1.06	GP
19 mm	2.27	1.08	GP
13 mm & 19 mm	1.98	0.98	GP

The Boussinesq equation for calculating the stress in the ground due to a concentrated load is as follows. The Boussinesq equation is used to determine the increment of vertical stress that occurs below the center of the foundation under a circular distribution load. If the radius of the loading surface is *B*/2, and the load is uniformly distributed, the soil stress changes with depth as shown in Fig. 6, To find the stress increment at depth *z* below the center of the loading area, the load on a small area can be assumed to be point load and can be expressed as $q_0 r d\theta dr$. The total stress increment caused by the loading area can be obtained by integration, as shown in Eq. (3)

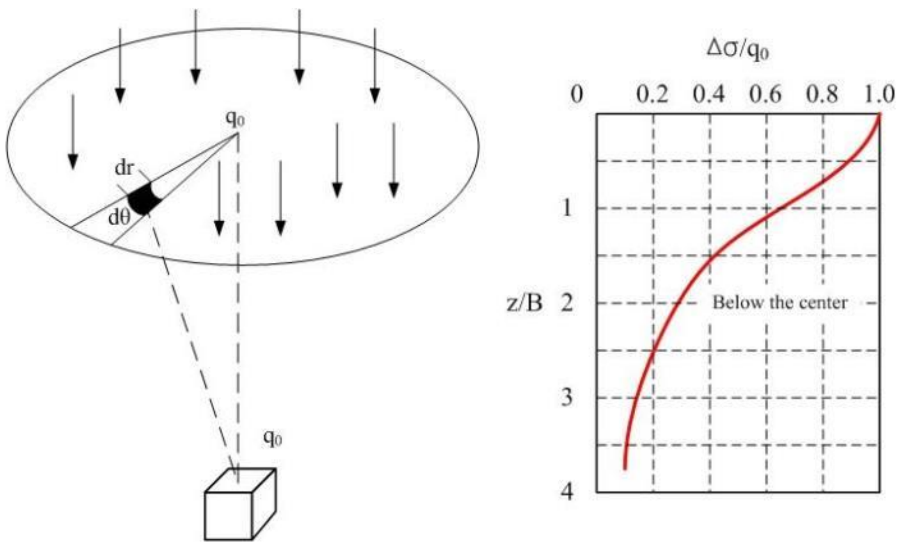


Fig. 6 Increase of vertical stress due to circular distributed load

$$\Delta\sigma = \int d\sigma = \int_{\theta=0}^{\theta=2\pi}\int_{r=0}^{r=B/2}\frac{3(q_0 r d\theta dr)}{2\pi z^2\left[1+\left(\frac{r}{z}\right)^2\right]^{\frac{5}{2}}} = q_0\left\{1-\frac{1}{\left[1+\left(\frac{B}{2z}\right)^2\right]^{\frac{3}{2}}}\right\} \qquad (3)$$

Fig. 7, shows the depth corresponding to the stress reduction below the center of the loading area measured for the various ground conditions in the plate loading tests. In addition, the depth under the center was also calculated from the Boussinesq equation, and the measured earth pressure for each depth was converted into transmission rate. As can be seen, the ground stress transfer rate rapidly decreases with depth. From the plate loading tests, the stress at a given depth was substituted into the Boussinesq formula to compare the stress transfer rate with the experimental results. The reason why the stress transfer rate exceeds 100% is due to the self-weight of the ground aggregate.

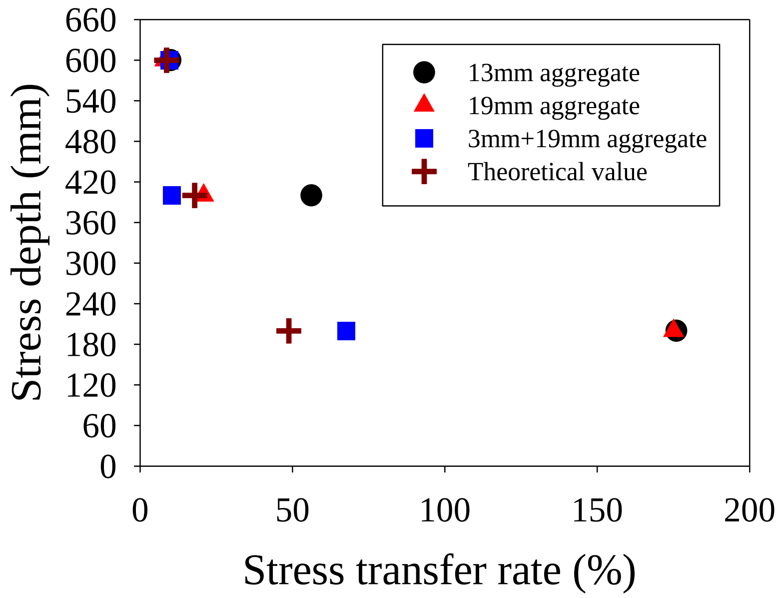


Fig. 7 Depth according to underground stress distribution

The results are summarized in Table 4, The relative error of stress transfer rate between the plate loading test and theoretical calculations in the ground with 13 mm aggregate is 127.15% at a depth of 200 mm, 38.29% at 400 mm, and 1.30% at 600 mm, respectively. The relative error of stress transfer rate between the plate loading test and theoretical calculations in the ground with 19 mm aggregate is 126.27% at 20 mm, 2.98% at 40 mm, and 0.58% at 60 mm, respectively.

The relative error of stress transfer rate between the plate loading test and theoretical calculations in the ground with 13 mm & 19 mm aggregate is 18.82% at 20 mm, 7.47% at 40 mm, and 0.91% at 60 mm, respectively. In the evaluation of the plate loading tests for different ground conditions, the 13 mm particle size aggregate stress transfer rate was the largest the test, and the gap-graded particle-size ground was the closest to the result of theoretical value in the aggregate ground. From the experimental results, the closer to the gap-graded particle-size condition, the stronger the jamming effect due to interlocking, the smaller the stress bulb, and the smaller the stress limit depth.

Table 4 Underground stress distribution results

Ground condition	Stress transfer rate with depth		
Particle size	200 mm depth	400 mm depth	600 mm depth
13 mm	175.95%	127.15%	56.20%
19 mm	175.07%	20.89%	8.11%
13 mm & 19 mm	67.62%	10.44%	9.6%
Theoretical result	48.8%	17.91%	8.69%

4. CONCLUSIONS

In general, it can be expected that ground having large strength has a good particle-size distribution. However, even if the particle-size distribution is poor, the strength of ground can be significant in the gap-graded particle condition. In this study, the characteristics of ground composed with a gap in granularity were investigated.

From the numerical analysis and the centrifugal model tests, the gap-graded particle-size ratio that shows the best performance is determined as m = 1.37.

In the evaluation of ground stress transfer through plate loading tests, the stress transfer rate is closest to the theoretical value for the 13 mm & 19 mm aggregate soil, and the ground stress distribution effect is superior to other conditions. The closer the ground particle-size distribution is to the gap-graded particle-size condition, the more jamming effect is caused by the interlocking and the smaller the stress limit depth.

Gap-graded aggregates rearrange themselves systemically from loose soil to dense soil when the loading is applied. If the gap is reduced uniformly, the jamming effect is exerted due to the interlocking effect between the particles. Due to this action, the settlement of the gap-graded granular ground is small, and the bearing capacity is enhanced.

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