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Void ratio and angle of repose for coral gravel sand mixture

Taux de vides et angle de repos pour le mélange de gravier de corail

Yukio NAKAYA

Department of Civil and environmental engineering, Yamaguchi University, Japan, nakata@yamaguchi-u.ac.jp

ABSTRACT: Coral gravel soil has well known as a problematic soil in Japan. This is because the gravel has large and complicated shape grains. In order to understand the density and shear strength properties of the soils, a series of experimental tests and numerical simulations was conducted to understand the physical and mechanical properties of soil containing coral gravels. These properties were discussed using the coral gravel content as examined in the previous research for mixture of two grain sizes. Then the features of these properties are characterized by two gravel contents. One is the optimum gravel contents in which the mixture has the minimum value of the void ratio. The other is the boundary gravel contents which is recognized as the boundary of replacement-of-gravel process. The coral gravel soil has lower gravel contents which can be considered as a peculiar nature comparing with the other gravel. Such lower gravel contents can be explained by DEM simulation.

RÉSUMÉ : Le sol en gravier de corail est très connu comme un sol problématique au Japon. C'est à cause du fait que le gravier est composé de grains larges et de formes compliqué. Pour comprendre les propriétés sur la densité et la résistance au cisaillement des sols, une série de tests expérimentaux et de simulations numériques ont été conduits avec le sol contenant des graviers de corail. Ces propriétés ont été discutées en utilisant le contenu du gravier de corail examiné dans la précédente recherche sur le mélange de deux dimensions de grain. Ensuite, les éléments de ces propriétés ont été caractérisés par deux contenus de gravier. L'un était au niveau optimum des contenus du gravier dans lequel le mélange avait la valeur minimale du taux de vide. L'autre était à la limite des contenus du gravier qui a été reconnue comme la limite du processus de remplacement du gravier. Le sol en gravier de corail a un niveau de gravier inférieur qui pourrait être considéré comme nature inhabituelle en comparaison avec l'autre sol de gravier. De tels bas niveaux de contenus du gravier peuvent être expliqués par une simulation DEM.

KEYWORDS: coral gravel, gravel content, void ratio, angle of repose.

1 INTRODUCTION

A difficulty of the design of coral gravel soil which exists in the coast in Okinawa Prefecture, Japan has been pointed out (Oyadomari, 2004, Watabe et al, 2016). This is because since it is the remains of coral reefs, the coral gravel is known as porous and fragile materials. Also the gavel has larger and complicated shape grains. So, the sampling of such materials is quite difficult due to disturbance. Then the knowledge on mechanical properties has not been accumulated sufficiently (Lade et al., 2009, Shinjyo, 2015). The other aspect is that the coral gravel soil is a mixture of larger gravel and fine particle. Many researchers have performed experimental and theoretical studies on the density of the mixture of two grain sizes. Those two grain sizes were for example, sand and clay, fine and coarse sands, and gravel and sand. But, there is no research for mixture of coral gravel and fine grain. It is well known that the density (void ratio) must be related to the strength of the mixture. Therefore, it is very important to deepen an understanding of the density changes of the coral gravel soil with variation of gravel content.



Photo 1. Branch type of Coral gravels.

The paper provides the results of experiment for the void ratio and angle of repose of coral gravel soils as mixture of two grain sizes. Firstly, previous research on the mixture will be introduced. Subsequently, the theoretical relation of void ratio

and gravel content will be compared with the results obtained from minimum density tests. Moreover, the tests result of an angle of repose will be examined as influence of gravel content on a strength property. Furthermore, in order to clarify the microscopic structure of a mixture material, the numerical simulation by a distinct element method will be conducted.

2 VOID RATIO OF MIXTURE OF TWO GRAIN SIZES

Omne et al. (1992, 1993) has proposed the following formula to the relation of void ratio and fine content of a mixture of clay and sand.

$$e = \frac{e_c \frac{F}{100} + 1}{1 + R \frac{(1 + e_c) - e_s}{1 + e_s}} - 1 \quad (1)$$

F is given by the percentage of the volume for the fines to the whole soil particles. The proposal was assumed as mixing two structures. One is Structure I, in which all coarse particles contact each other. The other one is Structure II, in which any large particles do not contact mutually. Here, R gives the ratio of the volume of Structure I to the whole mixture volume. r is the volume ratio of fine particles to coarse particles in the volume of the structure I. e_s and e_c are the void ratios to coarse particles and small particles, respectively. If the mixture consists of Structures I ($R = 1$), the void ratio is given by the following formulas.

$$e = e_s - (1 + e_s) \frac{F}{100} \quad (2)$$

If the mixture consists of Structure II ($R = 0$), a void ratio is given by the following formulas.

$$e = e_c \frac{F}{100} \quad (3)$$

Figure 1 shows the equation (2) and (3).

Lade et al. (1998) performed a detailed examination to understand the influence of fine grains on mechanical behavior of mixture. They reviewed the theoretical void ratio change with the fine content as equations (2) and (3). Then they paid attention to the intersection of the two equations to be the theoretical minimum void ratio of the mixture. The fine content was defined as the optimum fine content. Then they showed the difference between theoretical and experimental void ratios is related to the ratio of coarse grain size to fine grain size. If the ratio took more than 7, it was shown that the void ratio of the actual soil became close to theoretical value. Gutierrez (2003) suggested an equation to express the relation of void ratio with microscopic point. He showed that the average void ratio of a mixture at F was given by the following formulas.

$$e = e_c \frac{F}{100} + e_s \left(1 - \frac{F}{100}\right) \quad (4)$$

The formula gave the void ratio for the mixture in which two grains does not mixed at all. This means that fines grains do not include any voids to coarser grains at all. So the void ratio varies linearly from " e_s " to " e_c " as fine content increases as shown in Figure 1. Then, he proposed the following formula which gave the decrease of void ratio for coarse grains with fine grains.

$$e = e_c \frac{F}{100} + e'_s \left(1 - \frac{F}{100}\right) \quad (5)$$

Here, e'_s is an effective void ratio for coarser grains. In the case of $e'_s=0$, Equation (5) becomes Equation (2). He proposed the following formulas for e'_s based on the viewpoint of micro mechanics.

$$e'_s = e_s - e_s R_m \frac{F}{100} \quad (6)$$

Here, R_m is a parameter which gives the mixing degree given experientially. Equation (5) for $R_m=0$ becomes equivalent to Equation (4). For $R_m=1$, Equation (5) is $e'_s = e_s(1-F/100)$, and e'_s become e_s at $F=0\%$. Figure 1 shows the relation between F and e obtained by substituting Equation (6) into Equation (5) with $R_m=0.5$ and 1.0 . The void ratio calculated from equation (5) becomes quite large compared with Equations (2) and (3). Cubrinovski and Ishihara (2002) clarified experimentally about the various kinds of the mixture of two grain sizes based on Ladd's examination. Ham and others (2010) studied the compacted density for decomposed granite soils which recognized as a mixture of sand and gravel. They examined the void ratio for decomposed granite soils using Equation (5). Although two grain sizes range from gravel to clay particles, the optimum fine content is about 30%.

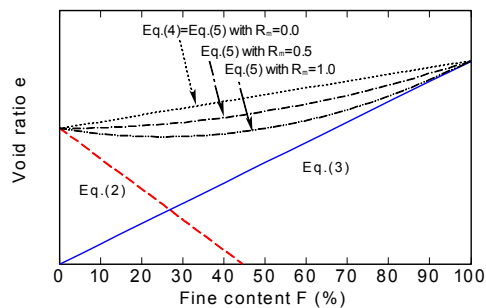


Figure 1. Theoretical line for void ratio and fine content.

3 VOID RATIO FOR MIXTURE OF CORAL GRAVEL AND SAND

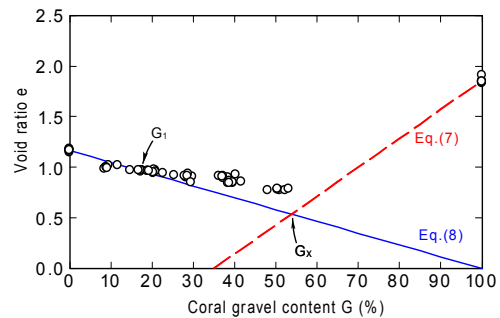
In order to clarify the influence of gravel content on void ratio of the coral gravel soil, the minimum density tests were carried

out. The coral gravel ($G_s=2.845$) was sampled at Urasoe, Okinawa. The sample used in the tests was two types; cylindrical body with 10mm of diameter and 30-50 mm in length (Photo 1(a)), and cylindrical body with protrusion (Photo 1 (b)). The sand used was Chiibishi sand sampled in Okinawa Prefecture. Chiibishi sand is classified as Calcareous sand, and is skeletal remains of marine organisms. So the sand contains angular and platey particles with 90% carbonate content. The average grain diameter of Chiibishi sand ($G_s=2.821$) is 0.61 mm. Then the particle diameter ratio of gravel and sand is about 16. The container used is a cylindrical shape with 175 mm in height, and 150 mm in diameter. The sample which mixed with coral gravel and sand at certain percentage, was supplied to the container using the funnel having about 100 mm of exit diameter.

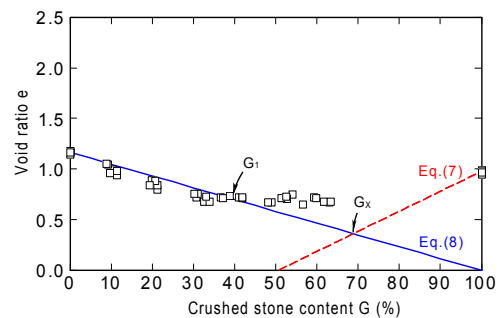
Figure 2(a) shows the relation of the void ratio and gravel content for the mixture obtained from the density test. G is given by the percentage of the weight for the gravels to the whole soils particles. The void ratio at $G=0\%$ is the same as the maximum void ratio of the sand (see Figure 3(a)). The straight lines shown in Figures 2 were drawn by Equations (7), (8) which were rewritten from Equations (2), (3) using the gravel content G .

$$e = e_s \frac{G}{100} - \left(1 - \frac{G}{100}\right) \quad (7)$$

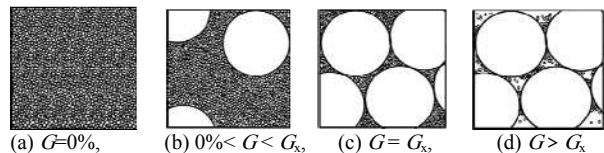
$$e = e_s \left(1 - \frac{G}{100}\right) \quad (8)$$



(a) Result for mixture of coral gravel and sand



(b) Result for mixture of crushed stone and sand
Figure 2. Variation of void ratio with change of gravel content.



(a) $G=0\%$, (b) $0\% < G < G_x$, (c) $G = G_x$, (d) $G > G_x$
Figure 3. Idealized micro-structure of mixture with increase of gravel content.

For the result obtained from the tests, the void ratio of the mixture decreases with increasing in gravel content until gravel content reaches to 50%. The line of Eq.(8) indicates the structure which the coral gravels distributes inside the matrix of

the sand particles and called as the replacement-of-gravel process (see Figure 3(b)). The process is the structure in which the void of coral gravels do not exist. The experimental result mostly coincides with (8) line until gravel content (G_I) reaches to about 18%. That is, the structure II predominates over the inside until gravel content reaches to about 18%. When this gravel content (G_I) exceeds 18%, the void ratio shows a larger value than the line of Eq.(8). It means that the gravel particles were not simply replaced to sand particles. That is, G_I can be called the boundary content defined as the gravel content not to have any effect of gravel structure on the mixture structure.

The line of Eq.(7) shows the condition where coral gravel particles contact each other. This is the structure (Structure I) in which sand particles exist in the void of coral gravel and is called as the void-filling process (see Figure 3(d)). It can be seen that the theoretical optimum gravel content is 55%. It corresponds to 45% of the fine content which is larger value than the previous study.

Moreover, Figure 2(a) shows there are no data for the mixture more than 53% of gravel content. The value is close to the intersection (G_x , see Figure 3(c)) of two theoretical lines.

The result of the density test for crushed stone is shown in Figure 2(b). The particle diameter of crushed stone is about 10 mm. The mixture of crushed stone and sand showed 39% of G_I and 69% of G_x . The values are larger than those of the coral gravel mixture.

Since G_x and G_I are considered to be dependent on grain shape (Yoshimura and Ogawa, 1994), G_I is plotted against void ratio width as shown in Figure 4. Clearly, the boundary content is depend on the void ratio width. The figure also shows the result obtained from the density test of crushed stone and glass bead. The coral gravel material whose shape is irregular and complicated has larger void ratio width. Then such material has the lower gravel content G_I , which the gravels have an effect on the soil structure. It can be called one of the peculiarity of the coral gravel mixture.

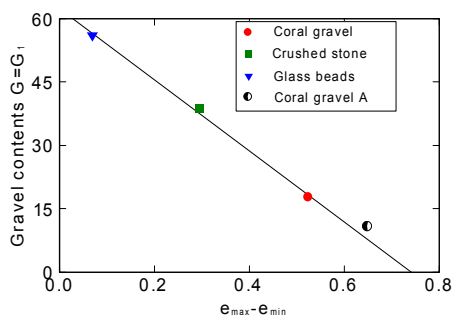


Figure 4. Relationship between boundary gravel content and width of void ratio.

4. ANGLE OF REPOSE FOR MIXTURE

As explained in the earlier section, an ordinary laboratory test such as triaxial compression test is difficult. In order to understand the shear characteristics of the coral gravel mixture, the angle of repose was measured. The angle of repose is considered to be a shear resistance angle of the material with 0% of the relative density under low confining pressure (Miura et al, 1997). Since a clear standard was not provided in the measuring method for the angle of repose, the flowing-out method was adopted as shown in Photo 2.

The flowing-out method measures the angle of the slope formed as follows. Firstly, a sample was filled in a container. In this experiment, the container prepared was cylindrical shape with 164 mm in diameter ($=2r$). The space of the cylinder was loosely filled up with the mixture at a predetermined gravel content. And the wall of the container was removed. Then the

sample was flowed out from the container and formed a slope. The angle of the slope formed was regarded as the angle of repose. After the slope stabilized (Photo 2), conical height h was measured and an angle of repose was calculated using the following equation.

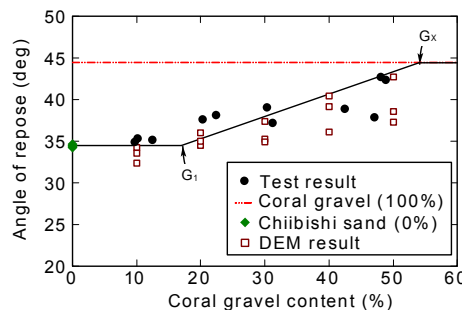


Photo 2. Angle of repose test for coral gravel soil of 10% of gravel content.

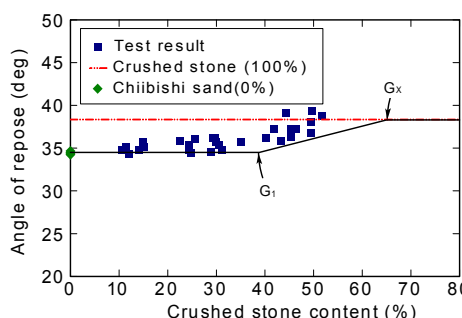
$$\phi_{rep} = \tan^{-1} \frac{h}{r} \tag{9}$$

The angle measured is the average angle of the slope and is not a maximum value due to non-linearity.

Figure 5(a) shows the relation between coral gravel content and angle of repose. For 10% of G_I , the angle of repose for coral gravel mixture showed the same angle of the sand. The angle of repose showed the clearly higher value than the result of only Chiibishi sand from 20% of coral gravel content, G_I . The content indicated the angle has the effect of coral gravel structure. From 20% to 50% of G_I , the angle becomes higher with the increase in coral gravel content. The straight line in Figure was connected from the angle for Chiibishi sand at G_I , to the angle for coral gravel at G_x (Ueda et al, 2011). Figure 5(b) shows the experimental result for crushed stone. The gravel content G_I' is about 40%. So, G_I' of coral gravel is lower than G_I' of crushed stone.



(a) Result for mixture of coral gravel and sand



(b) Result for mixture of crushed stone and sand

Figure 5. Variation of angle of repose with change of gravel content.

In order to consider the microscopic structure of a mixture with the gravel content, the simulations to the flow-out test were carried out for mixture of cylindrical shaped particles and ball particles. As shown in Figure 6, cylindrical-shaped particles were formed by overlapping five spherical elements with 10mm in diameter. Then the cylindrical-shaped particles

clumped has 30 mm of length. On the other hand, smaller particles were modelled as a spherical element of 10 mm in diameter. The container used in analysis is the same size as an experiment. The procedure of the simulation was carried out so that an experiment was reproduced faithfully, as shown in Figure 7(a)-(d).

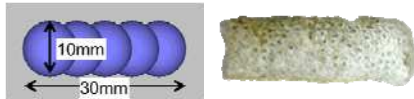


Figure 6. Cylindrical shaped grain modelled.

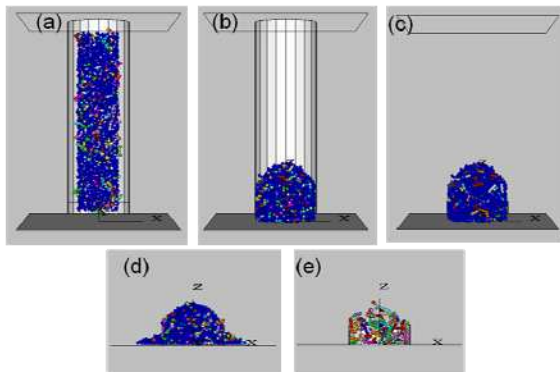


Figure 7. Procedure of simulation for angle of repose test.

Figure 7 is a situation result for 20% of content of cylindrical particles. The angle of repose in the simulation was calculated in accordance with the experiment by measuring the height of the vertex of a mixture which became cone-like. Moreover, the numerical simulation of each content was conducted 3 times. Figure 6(a) shows the angle of repose for the simulations. Although the particle shape and size are simplified considerably, the angle of repose of analysis has caught the tendency measured by the experiment.

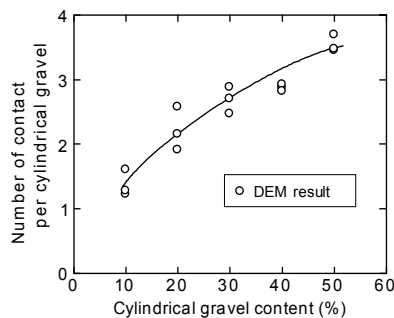


Figure 8. Coordination number for cylindrical particles in DEM result.

Figure 7(e) is the result of Figure 7(d) drawn as deleting spherical particles. So only cylindrical particles are drawn. The coordination number for cylindrical particles obtained in Figure 7(e) is shown in Figure 8. The coordination number of the cylindrical particles varies as cylindrical particle content increases. With the content of 10%, the coordination number becomes about 2.3, while 1.3 of the number is for 20% of the content. If the number is 1.0 two cylindrical particles simply contact each other. For more than two the number, all cylindrical particles contact at any cylindrical particles. The simulation indicates that the coordination number becomes less than two at less than 20% of cylindrical particles content. So, there does not exist any cylindrical grains structure which can transmit the external force.

5 CONCLUSIONS

A series of experimental tests and numerical simulations were conducted to understand the physical and mechanical properties of soil containing coral gravels.

Firstly, minimum density test for coral gravel and sand mixture was carried out to understand the variation of the void ratio with increasing gravel content. The optimum gravel content G_k was observed at 50% as being the minimum void ratio of the mixture. The boundary gravel content G_l was recognized as the boundary of replacement-of-gravel process and was 18% for coral gravel. The G_l was found to be related to the void ratio width. Having such lower G_l and G_k , the coral gravel was considered as a peculiar nature comparing with the other gravel.

Secondly, tests to measure the angle of repose were conducted to understand the shear strength properties. For 10% of G , the angle of repose for coral gravel mixture showed the same angle of the sand. Furthermore, the micromechanical structure for such lower gravel content was explained by DEM simulation. Then, for such lower gravel content, no cylindrical grains structure was existed which could transmit the external force.

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