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Effect of particle size and compaction on K_0 value of sand by centrifugal model test

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Abstract: The coefficient of earth pressure at rest K_0 is particularly important in the calculation of earth pressure of retaining wall. In this paper, the K_0 value of sand with different particle sizes and compactions was studied by centrifugal model tests. Firstly, soil samples were prepared by sand pourer, and the designed compactions of sand samples under different types of sand outlets and drop distances were measured by self-made sanding device. Then, through reasonable design of earth pressure measurement model structure, the centrifugal model test was used to simultaneously measure the soil compression and the horizontal earth pressure on the aluminum alloy plate. The variation of the K_0 value of sand with different particle sizes and compactions was finally obtained by calculation. The test results showed that, when using the sand pourer to prepare the samples, different types of sand outlets and drop distances should be adopted for different soil samples. In the centrifugal model test on the K_0 value of sand, the order of soil settlement was #1 sand > #3 sand > #2 sand, and the settlement of #1 sand and #3 sand was close to each other. For sand with the same particle sizes, the K_0 value increased gradually with the increase of the relative compaction of soil sample. For sand with different particle sizes, under the same compaction, the larger the sand particle size is, the smaller the K_0 value is.

Keywords: relative density; sand pourer; centrifugal model test; coefficient of earth pressure at rest

1 Introduction

The earth pressure at rest occurs only when the retaining wall is rigid and there is no displacement of the wall, and its magnitude is closely related to the coefficient of earth pressure at rest, K_0. In 1920, Terzaghi[1] conducted the tests to measure the coefficient of earth pressure at rest and obtained that the coefficient of earth pressure at rest K_0 is the ratio of horizontal earth pressure and vertical earth pressure. In addition, many domestic and foreign scholars have carried out a lot of research works on the coefficient of earth pressure at rest of soil, but there is still a lot of controversy. In most textbooks of soil mechanics, there are many relevant descriptions of the coefficient of earth pressure at rest[2–4]. According to the textbook '*Advanced Soil Mechanics*' edited by Professor Li Guangxin, the K_0 value of loose sand is 0.6 and that of dense sand is 0.23. In the textbook '*Soil Mechanics and Foundation*' edited by Professor Yin Zongze, it is pointed out that the K_0 value of loose sand is between 0.5 and 0.6, and that of dense sand is between 0.3 and 0.5. In the textbook '*Advanced Soil Mechanics*' edited by Professor Lu Tinghao, it is believed that the K_0 value of loose sand is between 0.4 and 0.45 and that of dense sand is between 0.45 and 0.5. Thus, the description of the relationship between the K_0 value and the relative density of sand from scholars is not consistent, and the variation of K_0 value with sand relative density and sand particle size even rarely studied.

There are generally three ways to determine the K_0 value: laboratory test, in situ testing and empirical formula method. Commonly used laboratory tests include oedometer test method[5–6] and triaxial test method[7–8]. In the oedometer test method, the soil sample is firstly placed in the lateral pressure gauge, and the horizontal stress is obtained by measuring the water pressure in the rubber film around the sample by applying vertical loading to the sample. Then the coefficient of earth pressure at rest of the soil can be calculated. However, in the process of loading, the deformation of the sample is often inhomogeneous, and the deformation of rubber film and the gas disturbance in the pressure chamber often have a great influence on the measurement of horizontal stress. Triaxial test method refers to the method to obtain the K_0 value of soil sample by in the process of loading with triaxial apparatus, constantly adjusting the confining pressure and vertical stress and controlling the soil sample to avoid lateral deformation. However, this method often has a certain lag when regulating confining pressure and vertical stress, which tends to make the final K_0 value inaccurate. With the rapid development of testing technology[9], the accuracy of measuring K_0 value by triaxial test method is continuously improved, but there are still many uncertainties in the process of specific operation, such as the

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problem of installing radial strain gauge.

In situ testing usually obtains the coefficient of earth pressure at rest of soil K_0 directly through the techniques of field test, such as pressuremeter test (PMT)[10−11] and flat dilatometer test (DMT)[12−13]. In the pressuremeter test, the cylindrical pressuremeter is first placed vertically into the soil, and then the uniform pressure is applied to the surrounding soil by the expansion of pressuremeter. The relationship between radial pressure and radial deformation is measured. Finally, the K_0 value of the soil in the corresponding state is obtained by calculation. In the flat dilatometer test, the flat shovel with the diaphragm is firstly pressed into the soil to a predetermined depth, and then the diaphragm is inflated to expand laterally towards the soil of the hole wall. Finally, the corresponding K_0 value is obtained according to the relationship between pressure and deformation. However, soil disturbance is inevitably caused in the process of in situ testing. It is incorrect to measure the coefficient of earth pressure at rest after the lateral deformation of soil.

The third method to obtain the coefficient of earth pressure at rest of soil is the empirical formula method. In the empirical formula method, the famous Jaky's formula is the most widely used: $K_0 = 1 - \sin\varphi'$, where φ' is the effective internal friction angle of soil[14]. Jaky believed that the K_0 value of soil was only related to the effective internal friction angle of soil, which was obviously not in line with the actual situation. Some studies[15] have shown that for soil with a larger effective internal friction angle, the calculated value based on Jaky's formula would significantly underestimate its K_0 value. In engineering application, the coefficient of earth pressure at rest K_0 is often calculated in reverse after obtaining the Poisson's ratio of soil, but the result is often inconsistent with the actual situation.

In general, the most accurate method to obtain the K_0 value of soil is to truly restore the confined state of soil during the measurement process. Admittedly, those problems above can be effectively solved by conducting centrifugal model tests. Liang et al.[16] calibrated two different earth pressure sensors by using centrifugal model tests. Sekelly et al.[17] studied the relationship between OCR and the K_0 value of soil through centrifugal model tests. Xu et al.[18] developed a new type of earth pressure cell and applied this chamber to the centrifuge test. Based on this, they succeeded in obtaining the K_0 value of fine sand with a relative density of 0.45.

Based on the current studies on the coefficient of earth pressure at rest K_0, no researcher has systematically studied the relationship between the K_0 value of sand, and the particle size and relative density of sand fully considering the real confined condition of soil. Therefore, this paper employs the centrifugal model test to carry out a detailed study on the K_0 values of different sands.

2 Testing materials and methods

2.1 Testing apparatus

The NHRI60 g·t geotechnical centrifuge from Nanjing Hydraulic Research Institute was used in the test (see Fig.1). The effective radius of this geotechnical centrifuge is 2 m. The maximum load of the centrifuge: at 100g, 600 kg; at 200g, 300 kg. Acceleration is controlled by silicon controlled stepless speed regulation. The centrifuge is equipped with 60 silver slip ring channels for signal transmission, which can meet the measurement needs of stress, displacement, and other physical quantities.

Fig. 1 NHRI60 g·t geotechnical centrifuge

The model box used in the test is shown in Fig. 2. The dimension of the model box is 700 mm×350 mm× 450 mm (length × width × height). Before the test, the BW-3 earth pressure cell was embedded into two prefabricated aluminum alloy plates, and the measuring surface of earth pressure cell should be flush with the surface of the aluminum alloy plate. Two rows of earth pressure cells were arranged in parallel on each metal plate, and four earth pressure cells were arranged in the direction of depth. The dimension of the model plate is 450 mm× 350 mm×20 mm (height × width × thickness). In the test, two aluminum alloy plates were fixed on both sides of the model box to simulate the confined state of soil.

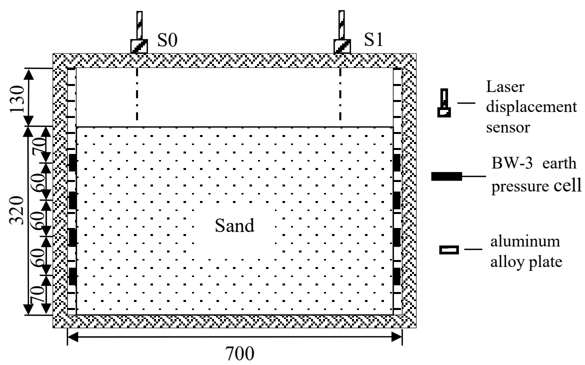


Fig. 2 Layout of model and transducers(unit: mm)

2.2 Testing soil samples

The sands used in the test were Fujian standards sand. Three kinds of sands were numbered #1 sand, #2 sand and #3 sand, respectively based on the particle size of sand. According to the *Standard for geotechnical testing method*[19], the basic physical properties of #1 sand were obtained: ρ_{dmax} = 1.6 g/cm^3, ρ_{dmin} = 1.4 g/cm^3, d_{50} = 0.183 mm, C_{u} = 1.58, C_{c} = 0.99; the basic physical properties of #2 sand were obtained: ρ_{dmax} = 1.64 g/cm^3, ρ_{dmin} = 1.43 g/cm^3, d_{50} = 0.487 mm, C_{u} = 1.97, C_{c} = 0.86; and the basic physical properties of #3 sand were obtained: ρ_{dmax} = 1.71 g/cm^3, ρ_{dmin} = 1.46 g/cm^3, d_{50} = 1.609 mm, C_{u} = 1.41, C_{c} = 0.99. The grading curves of three sands are shown in Fig. 3.

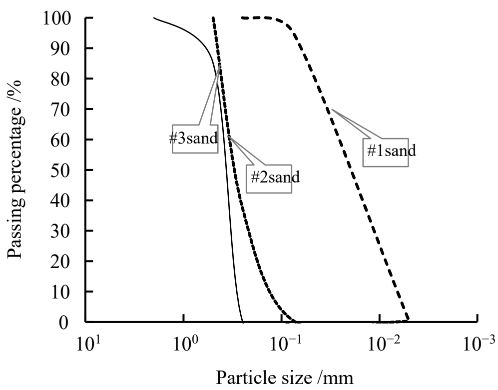
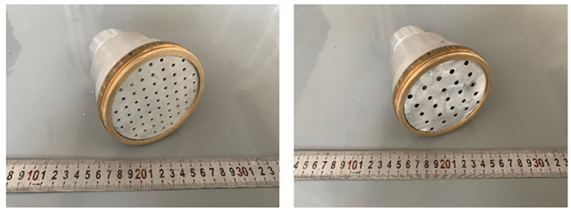


Fig. 3 Particle size distribution curves of three sands

2.3 Sample preparation

In the sample preparation process of sand pourer, the falling distance and relative density (D_{r}) showed a certain regularity. Li et al.[20] and Ma et al.[21] discussed the variation of D_{r} with falling distance, sand spout size, total flow of sand spout and movement velocity, and analyzed the characteristics of spatial uniformity distribution of D_{r}. Referring to previous test methods, four kinds of sand spouts were designed in the test, as shown in Fig. 4. No. 1 and No. 2 are duck-bill spouts, with a width of 3 mm and 5 mm, respectively, and the length of both duck-bill spouts is 10 mm. No. 3 and No. 4 are mesh spouts, with mesh diameters of 3 mm and 5 mm, respectively, and the diameters of both mesh spouts are 100 mm. Nine different falling distances were set in the test, which were 20, 30, 40, 50, 60, 70, 80, 90 and 100 cm, respectively. Through the self-made sample preparation device, the soil samples were uniformly and slowly scattered into the self-made calibration tank by controlling different falling distances, and the relative densities of soil samples from four sand spouts at different falling distances were obtained. During the test, every 2 cm of the thickness of sand in the calibration tank would increase the falling distance once. After finishing scattering sand, the weight of the sand in the calibration tank were weighed. Combined with the known volume of calibration tank, the relative density of sand was calculated. Finally, the relationships between four kinds of sand spouts, falling distance, and relative density were obtained. The internal diameter of the self-made calibration tank is 21.1 cm, the height is 11cm, and the net weight is 3.7 kg.

(a) Duck-bill spouts



(b) Mesh spouts

Fig. 4 Duck-bill spout and mesh spout

2.4 Measurement of the earth pressure coefficient at rest of sand

Prior to the test of earth pressure coefficient at rest, the standard sand calibration test had been carried out on the earth pressure cell[22]. Firstly, the plastic film was pasted on both sides of the model box, and the wall panels embedded with earth pressure cells were fixed on both sides of the model box to ensure that there was no displacement of wall panels. During the sample preparation, according to the results of sand pourer, the duck-bill spout and mesh spout are respectively used to prepare sand samples with different relative densities by controlling the falling distance. The thickness of scattered sand in the model box was about 30 cm, and four earth pressure cells can be buried in the depth direction. After scatting sand, the laser displacement sensor was fixed on the model box to measure the compression amount of the soil sample during the centrifuge operation. The model of laser displacement sensor is YP11MGVL80 non-contact high-precision laser sensor produced by German Wenglor Company, and its resolution is better than 20 μm. Finally, the model box was lifted into the centrifuge, and the acceleration was gradually loaded to 50g and stabilized for about 30 min. The output voltage of the sensor at different depths in the superheavy field was measured. The vertical stress was calculated by the following formula:

$$\sigma = \gamma z n \tag{1}$$

where σ is the vertical stress; γ is the soil unit weight;

z is the depth of soil layer; and n represents the magnitude of acceleration.

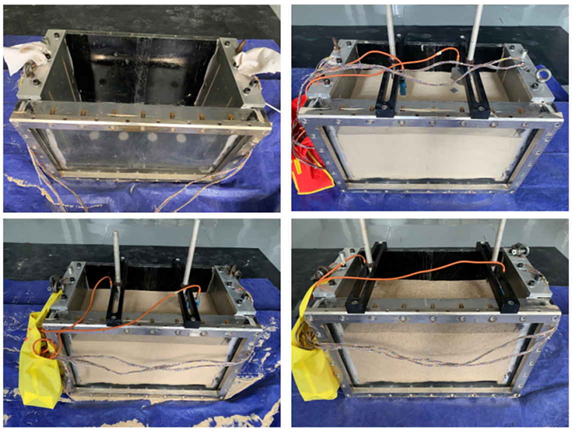


Fig. 5 Tests for the coefficient of earth pressure at rest of different sands

It is worth noting that during the centrifuge operation, the hanging basket containing the model box would be swung up and the distance between the sand sample at different depths and the center of rotation varied, which caused the acceleration of sand in the depth direction to change linearly while the centrifuge was operating. Therefore, when calculating the vertical earth pressure, the value of g should be the acceleration at the depth of earth pressure cell. In addition, since it was difficult to measure the earth pressure, the average value of the earth pressure measured at the same depth was used for accuracy. Finally, the K_0 values of soil samples with different relative densities were obtained by fitting the linear relationship between the vertical stress and horizontal earth pressure of the earth pressure cell at different depths at 50g.

3 Analysis of test results

3.1 Relationship between falling distance and relative density in the sample preparation by sand pourer

Through the analysis of Fig. 6, it can be concluded that, for a specific sand spout, the relative density of sand obtained by sample preparation increased with the increase of falling distance, but the growth rate decreased gradually. That is, in the range of lower relative density, the change of falling distance greatly affected the relative density from sample preparation. While in the range of higher relative density, the change of falling distance had little effect on the relative density from sample preparation. In addition, For different types of sand spouts, the relationship between falling distance and relative density is also different. For mesh spout, when the falling distance was relatively lower, the relative density increased rapidly with the increase of falling distance and then tended to be stable gradually. While for duck-bill spout, in the process of scattering sand, the change of relative density was relatively slower with the increase of falling distance, and loose sand samples were easier to produce by the duck-bill spout. In the subsequent tests of earth pressure coefficient at rest, the sample preparation was carried out based on the relationship between relative density and falling distance for different sand spouts, as shown in Fig. 6. The specific sample preparation scheme is shown in Table 1.

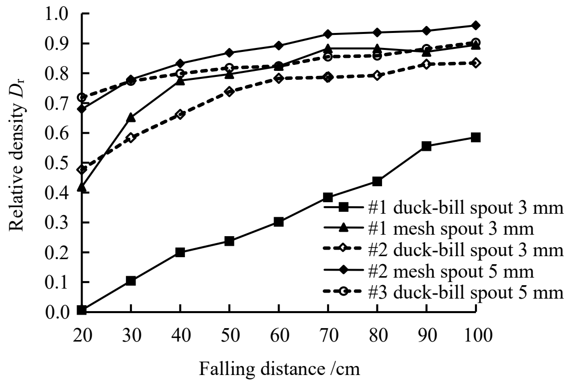


Fig. 6 Paths of sample preparation for sands with different relative densities

Table 1 Summary of sample preparation test scheme

Sample No.	Sand spout		Falling /m	Relative density
	Spout style	Size /mm		
#1	Duck-bill	3	0.60	0.30
			0.70	0.38
			0.85	0.46
			1.00	0.59
	Mesh	3	0.40	0.77
			1.00	0.89
#2	Duck-bill	3	0.20	0.58
			0.50	0.66
			1.00	0.78
	Mesh	5	0.50	0.86
			0.60	0.90
			1.00	0.96
#3	Duck-bill	5	0.20	0.90
			0.50	0.81
			1.00	0.71

3.2 Analysis of soil sample settlement

The deformation of sand under the action of external force is affected by the gradation of soil sample, particle size and particle shape[23]. After the centrifuge ran to 50g and the deformation of soil sample was stable, the vertical deformation (settlement) of sand was measured by the laser displacement sensor as shown in Fig. 7. It can be seen from the Fig. 7 that the deformation of soil sample decreases with the increase of relative density. This is mainly because the porosity of loose sand is higher, and the particles have more space to rearrange when subjected

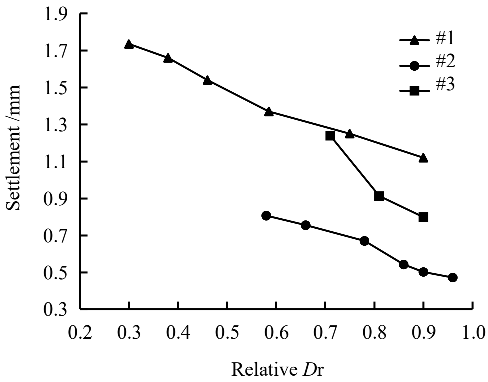


Fig. 7 Compression curves of sand samples

to external forces, resulting in larger vertical deformation. Also, in Fig. 7, The deformation of #1 sand is the largest, the deformation of #2 sand is the smallest, and the deformation of #1 sand is close to that of #3 sand. Minh et al.[24] employed the discrete element method to study the influence of particle size distribution on the one-dimensional compression property of granular soil materials, and found that the soil with good gradation had higher relative density and worse compressibility than that with uniform gradation. After analyzing the influence factors of particle compaction by Weibull function, Chen et al.[25] pointed out that both particle shape and size affect the compaction properties of materials. These studies show that the compression of soil is a complex process at the micro level, and the particle size, particle shape and particle gradation all affect the vertical compression deformation of soil. In the study, when the centrifuge run to 50*g* stable, the maximum compression of sand layer was only 1.735 mm, and the relative density only increased by 0.54% compared to that at the initial state. Therefore, the effect of the compression deformation of soil sample on the relative density can be negligible. But the compression has a certain influence on the relative density of soil sample, and subsequently, the relative density of soil sample after compression will be used to illustrate the test results.

3.3 Analysis of the reliability of earth pressure cell test

In the centrifugal model test, four earth pressure cells were arranged on the soil samples at the same depth during the test in order to ensure the accuracy of the test results. While the centrifuge was running, two rows of earth pressure cells rotated parallel to each other. After the rotational speed was stable, the measured values from the earth pressure cells at the same depth should be the same in theory. However, in the test, it was difficult to measure the horizontal earth pressure of sand. In this paper, after repeated tests, the results with no obvious deviation in measured values were selected from each row of earth pressure cells and the average value was taken. To verify the rationality of this method, two groups of test results (S1 and S2) of #1 sand at three relative densities were selected for illustration in this paper, as shown in Fig. 8. As be seen from Fig. 8, the test results of #1 sand at three relative densities of 0.34, 0.50 and 0.90 were close to each other, with the same trend and good linearity. This demonstrates the repeatability of the measured results of the horizontal earth pressure of sand in the test, and it is also feasible to use the method of average value to deal with the data results.

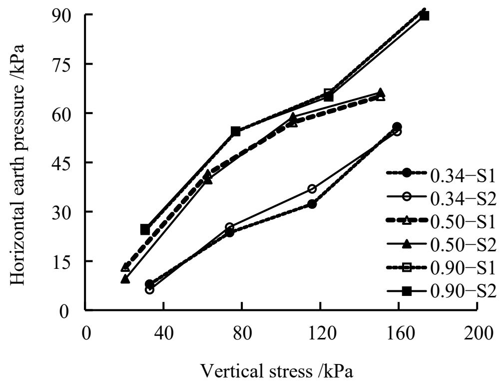


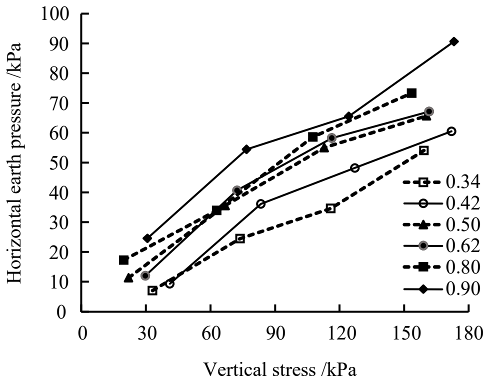
Fig. 8 Distribution of earth pressure along the lateral depth under different compactions after the repeated test on sand #1

3.4 Earth pressure variation in sands

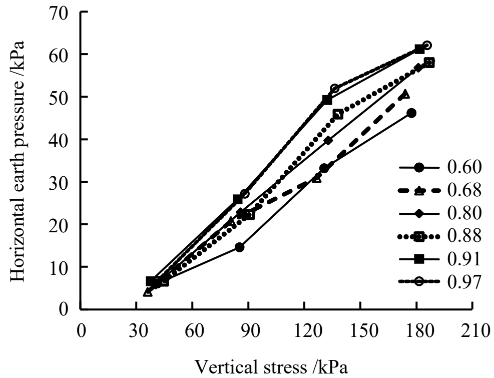
Figure 9 shows the relationship between horizontal earth pressure and vertical stress of soil samples with different relative densities after the centrifuge ran to 50*g* and stabilized. It can be observed from Fig. 9 that the linearity of vertical stress and horizontal earth pressure in the measured results are good, which proves the feasibility of using centrifugal model test to study the coefficient of earth pressure at rest of soil. It is also found from the test results that for the same kind of soil, the soil with a higher relative density of soil represents the greater horizontal earth pressure of soil acting on the aluminum alloy plate. However, when the relative density of soil gradually increased, the regularity of the measureement results of the earth pressure cell placed in the shallow layer of sand was not obvious. This is mainly because during the centrifuge loading process, the surface settlement of sand layer caused the dislocation of sand particles, which changed the contact mode between sand particles and the surface of earth pressure cell, resulting in the instability of the measured values of earth pressure cell.

3.5 Relationship between K_0 and particle size of sand

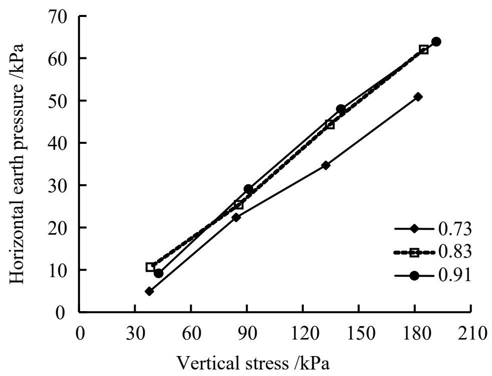
Figure 10 illustrates that when the relative density from sample preparation is 0.9, the coefficient of earth pressure at rest of soil gradually increases with the increase of particle size. Among them, the K_0 values of #2 sand and #3 sand are close to each other, while the K_0 value of #1 sand is significantly different from the former. This



(a) Distribution of earth pressure along the lateral depth under different relative densities of sand #1



(b) Distribution of earth pressure along the lateral depth under different relative densities of sand #2



(c) Distribution of earth pressure along the lateral depth under different relative densities of sand #3

Fig. 9 Distribution of earth pressure along the lateral depth under different relative compactions

can be explained by the composition of soil samples. In the particle composition of #3 sand and #2 sand, particles with a size between 0.5 mm and 2 mm constitute the vast majority of the specimens and the properties of particle size are similar, so the K_0 values of two soil samples are close to each other. But in the particle composition of #1 sand, particles with a size between 0.075 mm and 0.25 mm accounts for 94.5% of the soil sample, and the composition of #1 sand is quite different from those of #2 sand and #3 sand, which directly results in a significant difference in K_0 values between #1 sand and #2 sand, #3 sand.

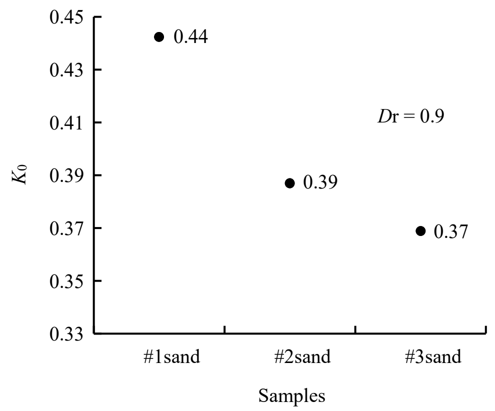


Fig. 10 Relationship between K_0 of sand and particle size

3.6 Relationship between K_0 and relative density of sand

As be seen from Fig. 11, as the relative density of soil sample increases, the K_0 value of soil sample also presents a gradual increasing trend, and basically exhibits a linear growth. The maximum K_0 value of #1 sand is 0.442 and the minimum is 0.367. The maximum K_0 value of #2 sand is 0.396 and the minimum is 0.306. The maximum K_0 value of # 3 sand is 0.369 and the minimum is 0.315. It can also be inferred from these results that even if when the relative density of #1 sand is small, the K_0 value of #1 sand in that relatively loose state is close to the K_0 values of #2 sand and #3 sand in a relatively dense state. Therefore, when determining the coefficient of earth pressure at rest K_0 of sand, it is necessary to determine the relative density of sand first.

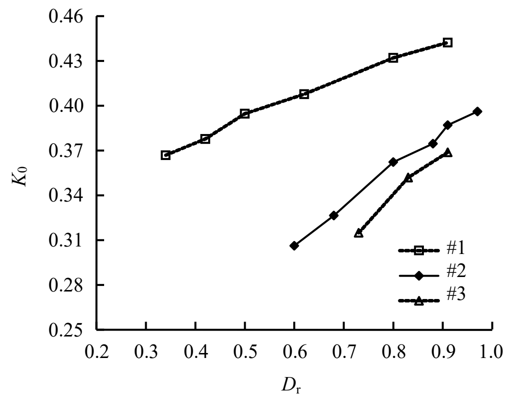


Fig. 11 Curves of K_0 changing with relative density

4 Conclusions

In this paper, through the centrifugal model test, the coefficient of earth pressure at rest K_0 of sand with different particle sizes at different relative densities was systematically studied, and the following conclusions were drawn:

(1) Sample preparation is very important for the measurement of geotechnical test results. When using the sand pourer to prepare the samples, in order to obtain

the desired relative density, different types of sand spouts should be used for sand with different particle sizes and different falling distances should be selected according to different test conditions.

(2) In the centrifugal model test for determining the K_0 value of sand, the settlement order of soil sample is #1 sand >#3 sand >#2 sand, and the settlements of #1 sand and #3 sand are close to each other. In addition, for the model with a height of about 30 cm, the maximum compression of sand is 1.735 mm, which has little influence on the relative density of soil sample and can be negligible.

(3) The K_0 values of sand with different particle sizes at different relative densities present a certain regularity. For sand with the same particle size, the K_0 value gradually increases with the increase of the relative density of soil sample. For sand with different particle sizes, at the same relative density, the larger the particle size of sand is, the smaller the K_0 value is. Moreover, in the test, at the same relative density the K_0 values of #2 sand and #3 sand are close to each other, while the K_0 value of #1 sand is quite different from other two sands.

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