SPECIMEN RECONSTITUTION AND UNIAXIAL COMPRESSIVE STRENGTH TESTING OF ROCK-SOIL MIXTURES

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In the most mountainous areas of southwest China, the lands, and especially the slope base areas, are covered with colluvial deposits. These colluvial deposits consist of low strength materials like clay or sands and high strength materials like rocks. Such a mixture is an inhomogeneous geo-material with wholly different behavior to that of soil or rock alone. In the laboratory, some samples of this colluvium were reconstituted, and unconfined uniaxial compression tests were carried out on the specimens with volumetric rock content (VRC) varying in the range $0 < \text{(VRC)} < 60\%$. Typical stress-strain curves and relationships between uniaxial compressive strength (UCS) and rock content were analyzed. In addition, ultrasonic tests were carried out on the mixture specimens, and the relationship between wave velocity, rock content and the variation of wave velocity to the loading process were discussed. The results show that the uniaxial compressive strength and elastic modulus of colluvium show a similar linear relationship for specimens with different rock content. Compressive strength and elastic modulus of specimens with VRC of 20%∼30% were found to be the largest, and in the loading process, the wave velocity decreased with increase of vertical stress.

1. INTRODUCTION

An increasing number of transportation projects, especially highways, have been under construction in western China in recent years. Some highway projects have encountered difficulties when constructed in a special geology. This geology is often situated at the foot of steep slopes, widely existed in the ground of quaternary diluvium, colluvium, or eluvium, and always named as a colluvial deposit. Most of these deposits consist of low strength materials like clay mixed with high strength materials like rocks. There is no generally accepted term for such geomaterials, even though a number of researchers have been doing work on it. Some of the commonly used terms include Mélange (French for 'mixture'), Bimrock (Block in matrix, Medley[1]), colluvial rock/soil, gravelly soil, rock-soil mixture (Xu *et al.*[2]) or talus (Zhang[3]). These terms may apply to different geomaterials with different depositional origins. In the current work, we have adopted the pragmatic

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Figure 1. Typical in-situ RSM of Shuima highway project.

term "rock-soil mixture" (RSM) to represent these colluvial deposits found in mountainous areas.

Due to its widespread nature, RSM has attracted much attention among researchers who have focused on characterizing its mechanical properties. Most of the research has focused on the shear strength of RSM applied to slope stability problems. Triaxial tests can be used to test the samples' cohesion and friction angle (Dupla *et al.*[4], Irfan *et al.*[5], Lindquist[6]). In practice, triaxial tests are often limited due to their expense and difficulty. Large direct shear box tests are commonly used to study the mixture's shear strength (Irfan *et al.*[5], Wu[7]). Some researchers performed a lot of in situ shear tests on large size specimens for the scale effect. From test results, it can be shown that the internal structure of RSM and the volumetric rock content (VRC) significantly influence its shear strength. Increase in VRC will lead to an increase in the friction angle and a decrease in cohesion. The increase in the friction angle is correlated to the increase in tortuosity of the failure plane during shearing, while the decrease in cohesion is related to the weakness of the matrix around the block boundaries (Iannacchione *et al.*[8], Coli *et al.*[9]). Due to the complexity of RSM components, the in situ coring process is very difficult. Most of the laboratory tests were carried out with reconstituted samples. Irfan & Tang[5] gave some sample preparation techniques.

As a special geomaterial, the uniaxial compressive strength (UCS) is an important input parameter used in rock/soil engineering designs, as well as the shear strength. Sonmez *et al.*[10] carried out some tests on volcanic bimrock to study the relationship between UCS and volumetric block proportion, and then developed an empirical approach for the determination of the UCS for a volcaniclastic mixture. Liao *et al.*[11] proposed a standard procedure for sample remodeling of RSM and carried out a series of uniaxial compression tests on 100 mm diameter samples. Even though the scale effect has been shown to be an important influence on RSM mechanical properties, a review of the literature indicates that no work has been done to consider the particle distribution and size effect in preparing reconstituted samples.

This paper proposes a new sampling preparation method based on particle fractal dimensions. With more than 18 cubic specimen (with different VRC), the UCS of RSM was tested. For in situ RSM surveying, the acoustic velocity of samples was also tested and analyzed.

Table 1. Sieving test result of RSM samples (with length unit:mm).

No	Sieving results/kg										VRC /%	C_u	C_c	$D_{<2mm}$	$D_{\geq 2mm}$	$\overline{D}$
	>40	20~40	10~20	5~10	2~5	1~2	0.5~1	0.25~0.5	0.1~0.25	<0.1						
1	4.92	1.30	2.05	2.05	2.62	1.12	0.40	1.05	1.55	0.35	0.59	72.73	1.92	2.211	2.656	2.490
2	15.60	3.30	2.90	2.52	2.80	0.30	0.75	0.67	1.15	0.36	0.81	25.00	1.44	2.137	2.485	2.389
3	12.20	7.10	9.90	9.05	11.50	1.05	3.45	2.90	5.95	0.59	0.60	65.00	2.60	2.106	2.565	2.420
4	0.00	2.20	5.90	5.60	7.45	0.20	1.15	1.40	2.60	0.37	0.51	34.00	4.24	2.124	2.477	2.369
5	8.30	3.80	7.60	6.70	9.70	0.30	1.95	2.30	2.50	0.4	0.61	27.39	1.55	2.151	2.478	2.366
6	7.50	3.35	5.90	5.65	8.10	0.20	1.55	2.15	3.05	0.38	0.60	48.46	2.75	2.137	2.522	2.401
7	7.45	2.45	3.95	3.50	5.10	0.15	1.50	1.40	1.85	0.32	0.63	42.50	1.51	2.130	2.543	2.406
8	6.94	2.63	3.77	4.69	6.68	1.08	1.17	0.58	3.46	0.71	0.57	60.00	3.27	2.309	2.585	2.486
9	6.07	1.45	1.50	1.56	1.82	0.33	0.48	0.29	0.56	0.29	0.74	7.83	3.41	2.385	2.522	2.470
10	18.11	3.35	5.85	5.78	9.11	1.31	2.69	1.89	2.25	0.42	0.65	55.33	0.65	2.146	2.557	2.385
11	2.90	0.94	2.36	2.81	4.38	0.42	1.15	0.88	1.11	0.18	0.53	20.50	1.76	2.077	2.554	2.363
Sum	89.99	31.87	51.68	49.91	69.26	6.46	16.24	15.51	26.03	4.37	0.62	20.50	1.22	2.135	2.540	2.403

Remark: $D_{<2mm}$ is the fractal dimension with particle size smaller than 2mm; $D_{\geq 2mm}$ is for particle size equal or bigger than 2mm; $\overline{D}$ is the average value of $D_{<2mm}$ and $D_{\geq 2mm}$.

2. TEST MATERIALS AND METHODS

2.1. *Test materials*

This test material was taken from several on-site places of the Shuima highway in Yunnan, China. As shown in Fig. 1, the rock component of the sample is mudstone or shale with a brown or dark purple color. The stone size is highly inhomogeneous, and there exists a lot of huge piece of stone with irregular geometric shape. The stone strength is apparently higher than soil within the RSM.

To study the mechanical characters of RSM, sieve tests were made first to determine the natural gradation of natural air-drying sample. Table 1 shows the results of screening tests. And Fig. 2 illustrates the cumulative distribution curve of the average particle size. The average non-uniform coefficient (C_u) is 20.50, curvature coefficient (C_c) is 1.22, and the average moisture content of the natural air-drying sample is 2.6%.

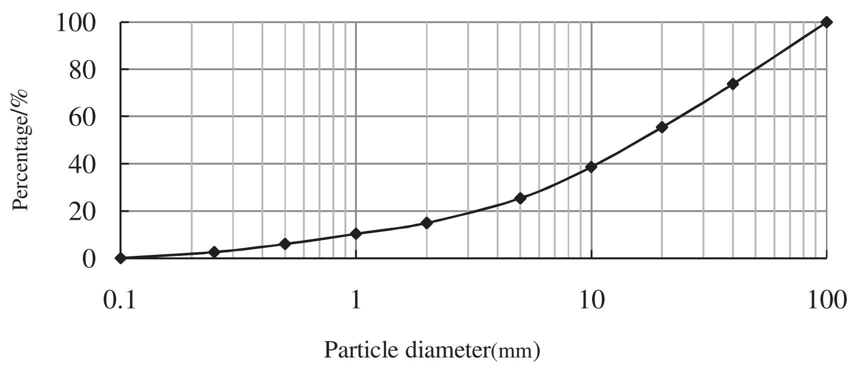


Figure 2. The particle size cumulative distribution curve of RSM.

2.2. Fractal dimension of the particle size distribution

The structural characteristics of RSM can be represented in terms of VRC, particle size distribution (PSD), rock shape and compactness. The RSM particle size distribution satisfies the fractal law, therefore has a scale-independent range (Mandelbrot[12] , Medley[1], He[13]). Fractal dimension is used to describe the PSD quantitatively, therefore is used for specimen reconstitution such that the same geometric structure is kept under in-situ condition.

Fractal dimensions of PSD for the RSM samples were estimated using the procedure proposed by Tyler & Wheatcraft[14], which used the mass distribution of particles in substitution of the cumulative number of particles based on the following relationship,

$$\log \frac{M(r<R)}{M_t} = (3 - D) \log \left(\frac{R}{R_t} \right) \tag{1}$$

where $M(r<R)$ represents the percentage of mass of RSM grains of radius r smaller than a characteristic radius R ; M_t is the total RSM mass; R_t is the maximum particle size, and D is the fractal dimension of the particle distribution.

Figure 3 shows that the particle distribution of RSM samples has fractal character. Each sample has two scale-independent ranges, which is consistent with the existing results (He[13]). The dividing particle size or the rock/soil dividing threshold of these two ranges of RSM is usually set to 5 mm in the literature. However, the reasonable value should be set to 2 mm after a careful analysis of the curve geometric character. The PSD fractal dimension can be calculated through least square linear regression of the curves. The fractal dimension results were listed in Table 1. The average fractal dimension over the entire samples $\overline{D} = 2.403$ ($D_{<2\,mm} = 2.135$ *for* $R<2$ mm and $D_{\geq 2\,mm} = 2.540$ *for* $R \geq 2$ mm).

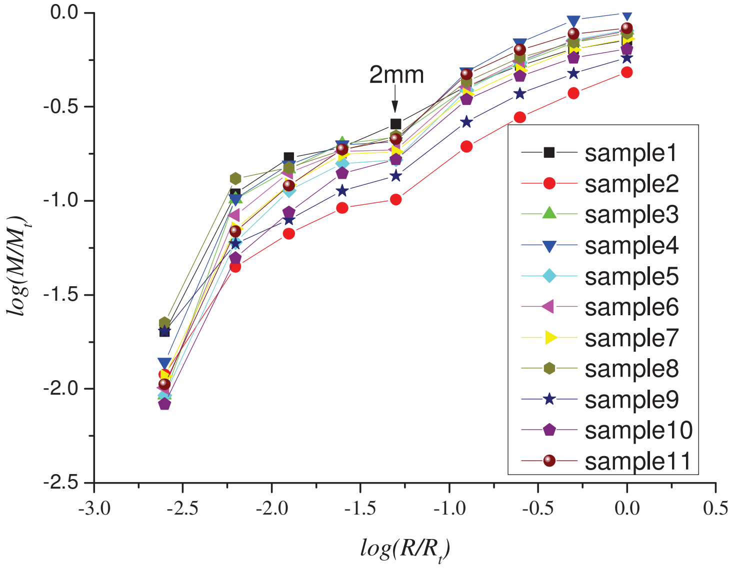


Figure 3. Log-log histograms of particle-size and mass.

2.3. *Preparation of test samples*

For the acoustic velocity testing during the uniaxial pressing process, the samples were made in cubic shapes. The size of specimens was 100 × 100 × 100 mm. Considering the size effect, the maximum particle diameter was limited to 20 mm. Due to the small samples of rock and soil mixture, the particle geometric character may have a strong effect on the mechanic properties, therefore it is important to control the effect. Since the RSM geometric character can be presented by its particle-size fractal dimension, the fractal dimension and the particle maximum diameter can be used to calculate the weight ratio of different size rock or soil,

$$M(r < R) = M_t \cdot \left(\frac{R}{R_t}\right)^{(3-D)} \tag{2}$$

where M_t can be calculated by specimen volume (V) times density (ρ, the density will change with different VRC); $R_t = 20\,\text{mm}$; Fractal dimension D may take the average value $\overline{D} = 2.403$. Assuming the soil density is ρ_s, the rock density is ρ_r, then specimen's density can be evaluated as,

$$\rho = (\rho_r - \rho_s \cdot V) \cdot VRC + 1 \tag{3}$$

When preparing for the test samples, the compactness must be controlled to achieve high quality samples. Liao *et al.*[11] made a series of tests and found the relationship between stamping numbers and sample density. The least stamping number should be more than 50. The samples preparation procedure can be summarized as,

1. Sieving soil and rock. The raw material sampled from Shuima highway construction work place was dried naturally at first; then it was sieved into different particle size group. Water content has a significant effect on mechanical properties of RSM, and particles of different diameters have different water absorbability. To keep the samples with same water content, the amount of water added to the samples was calculated according to the soil content, and is limited to about 9.7% (Fig. 4(a)).
2. Preparing mold. The 100×100×100 mm concrete specimen standard mold was used, and the inner surfaces were lubricated and wrapped with cling film (Fig. 4(b)).
3. Multi-layer filling and tamping. Rock and soil were mixed uniformly, and then put into the mold by layers. A hammer was used to tamp the sample. Each layer was hammered with the same times. There were three layers in a specimen. Tamp each layer and make the specimen surface flat (Fig. 4(c)).
4. The mold was detached 24 h later and the cling film was removed after a 5–7 days curing (Fig. 4(d)).

2.4. *Testing set-up*

Servocontrol rigid material test equipment Instron-1345 was used for uniaxial compressive strength tests. This machine has the maximum axial compression 1000 kN, unique closed-circuit control system whose servo error can be confined to 0.1%. The uniaxial compression test can be carried out on it in displacement-control, load-control and strain-control modes.

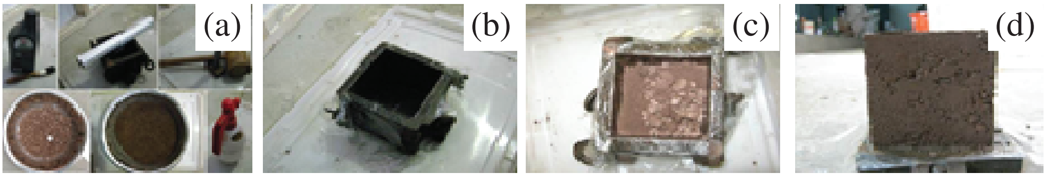
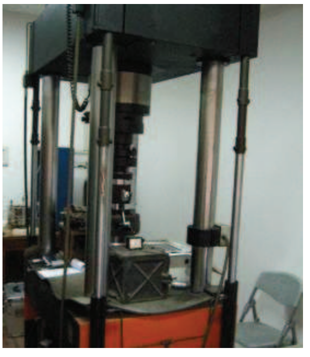


Figure 4. Procedure for the sample remodeling of RSM.



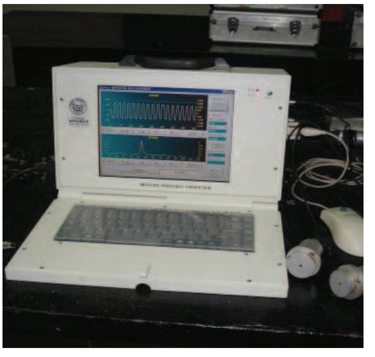


Figure 5. The testing set-up (left is Instron-1345, right is U-Sonic).

The computer was used to facilitate loading and measuring. The ultrasonic instrument U-Sonic was used in acoustic wave test. The testing set-up shows in Fig. 5.

2.5. *Testing procedures*

A specimen was placed on the rigid loading platform, and the load was applied by driving loading platform at a constant speed of 0.2 mm/min. Stress-strain curves of the specimen were obtained using the data-acquisition system.

Acoustic test is often used in rock media, and seldom in soil. In this research, acoustic wave velocity was used to detect the sample structure and its change law during the pressing process. The acoustic test was taken from the beginning till the sample failure by every 0.5 kN loading change.

3. TEST RESULTS AND ANALYSIS

3.1. *Test results*

Total 18 specimens were tested, and the test results were shown in Table 2.

3.2. *The relationship between UCS and VRC*

Figure 6 shows the stress-strain curves of specimens at different CRV. The failure law of soil specimen is obvious subject to ductile failure with around 3% strain corresponding to the maximum stress. However, the failure law of RSM specimens is closer to rock, and its peak strength is much higher than that of soil.

Table 2. Specimen parameters and test results.

NO.	Stone content /%	Density /10^3.kg.m^{-2}	UCS /MPa	Elastic modulus /MPa	Wave velocity without load /m.s^{-1}	Wave velocity with the max load /m.s^{-1}
T1-1	0	2.10	0.340	-	935.5	738.0
T1-2	0	2.02	0.318	15.55	794.3	562.1
T1-3	0	1.90	0.271	13.28	875.8	693.0
T2-1	20	2.19	0.708	29.57	1001.0	691.1
T2-2	20	2.16	0.802	59.56	908.3	624.6
T2-3	20	2.10	0.728	51.25	865.8	740.2
T3-1	30	2.13	0.523	26.29	958.8	676.1
T3-2	30	2.15	0.804	51.18	977.5	684.5
T3-3	30	2.10	0.701	66.31	820.3	597.7
T4-1	40	2.13	0.637	35.99	805.8	582.4
T4-2	40	2.15	0.550	32.84	773.4	562.8
T4-3	40	2.15	0.776	46.25	747.9	465.3
T5-1	50	2.12	0.596	38.69	873.4	526.6
T5-2	50	2.14	0.616	46.84	735.8	492.9
T5-3	50	2.12	0.731	52.94	740.2	499.6
T6-1	60	2.15	0.631	48.65	774.6	475.1
T6-2	60	2.16	0.597	32.97	935.5	738.0
T6-3	60	2.16	0.638	47.65	794.3	562.1

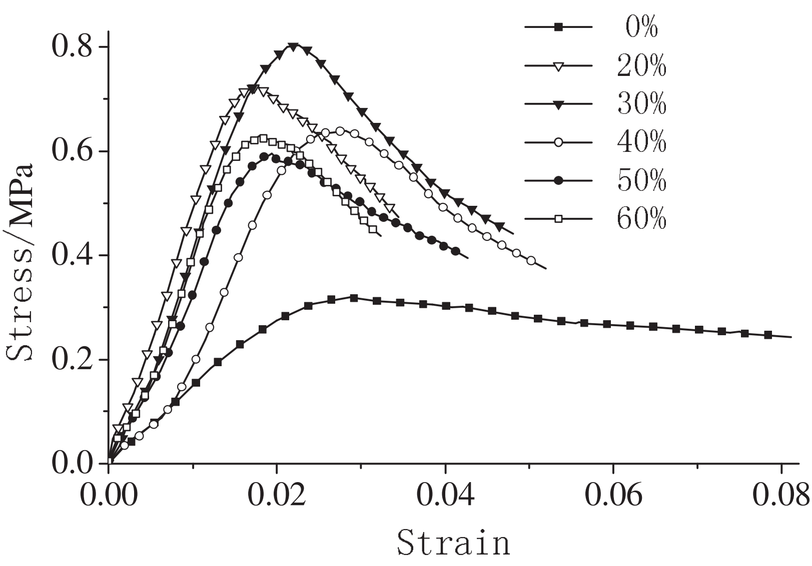


Figure 6. Stress-strain curves at different stone content.

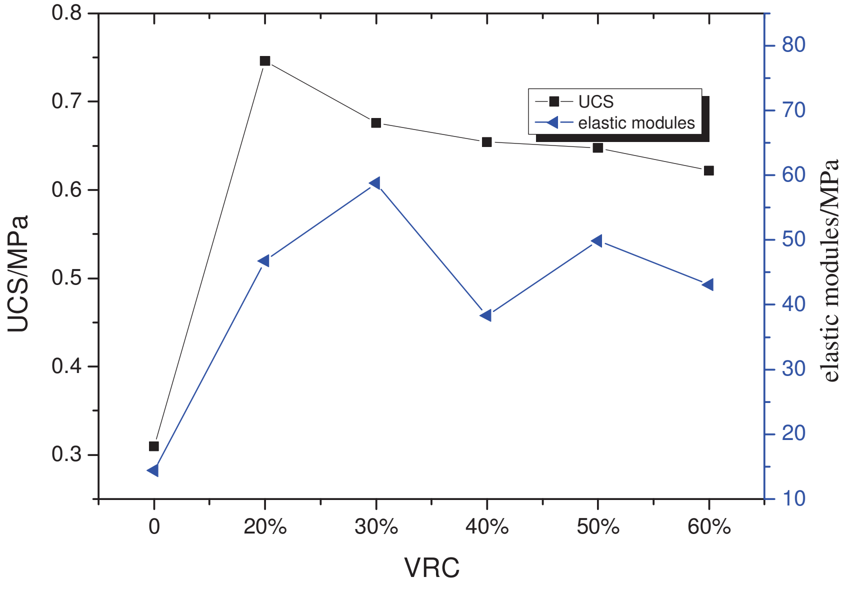


Figure 7. Relationship between VRC and elastic modules and UCS for RSM.

Table 3. Values of C_u, C_c at different VRC.

VRC/%	0	20	30	40	50	60
C_u	24.0	24.0	23.9	23.4	28.0	20.0
C_c	1.04	1.70	2.98	5.12	4.12	3.55

Figure 7 shows the development trend of modulus of elasticity and UCS with the increasing of VRC. The soil specimens have the lowest UCS of 0.31 MPa. The UCS increases rapidly when VRC increases from 0 to 20%. The UCS reached to maximum when the VRC is between 20% and 30%. After that, with the increasing of VRC, the UCS decreased steadily. The samples' uniaxial compressive strength is improved about 100%∼140% due to the rock. These results are opposite to that by Liao *et al.*[11], but consistent with other research conclusions (Han *et al.*[15]). The main reason may be due to the specimen shape and water content which can affect the stress situation and degree of consolidation significantly. On the other hand, the rock shape also has great effect on specimen mechanical behavior. The development tendency of elastic modulus with VRC increasing is similar to UCS.

According to soil mechanics and related research results (Chen *et al.*[16]), a sample will be consider as well-graded when its nonuniform coefficient is larger than 5 and curvature coefficient is between 1 and 3. Well-graded samples can have a good compaction degree and mechanical properties.

The nonuniform coefficient (C_u) and curvature coefficient (C_c) of specimens with different VRC are calculated and listed in Table 3. It shows that a specimen with a VRC between 20% and 30% is well graded. When VRC exceeds 30%, the C_c will be larger than 3 and specimen become poorly graded.

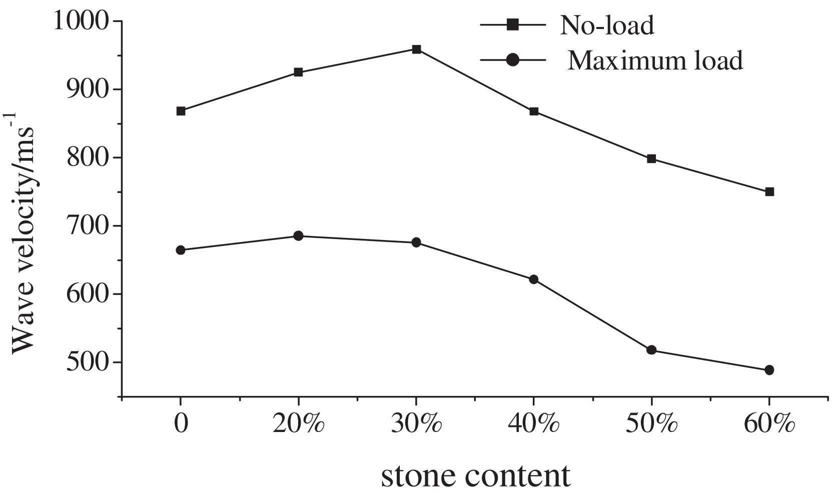


Figure 8. Relationship between stone content and acoustic wave velocity.

3.3. *Wave velocity characteristic analysis*

Acoustic wave velocity (especially means longitudinal wave) was used to test and analyze the material inner compactness or continuity. In order to analyze the relation between the mechanics characteristic and the wave velocity of RSM, wave velocities at no-load and maximum load condition were plotted in Fig. 8. The results may be different with our common view. The velocity in high stress state is slower than that without any stress. From the compression process and fragment of failure specimen, it can be found that with the compressive stress increasing, the compactness of specimen increased steadily; when the compressive stress reached at about 80% of the peak stress (Fig. 6), the specimen will create more cracks, and the rock will break away from soil, all these will result in wave impedance increases and wave velocity decreases. The wave velocity reaches the peak at 20% to 30%.

During the pressing process, the rocks in the mixture have tendency to roll with their long axials parallel to the main stress direction. This rolling will result in void in another vertical direction (Fig. 9). Local stress concentration in inhomogeneous samples is easy to occur even in the low stress situation. This can result in plastic deformation, and then hinder the acoustic wave propagation (Fjar *et al.*[18]). At the same stress situation, specimens with VRC of 20%∼40% have higher acoustic wave velocity than others.

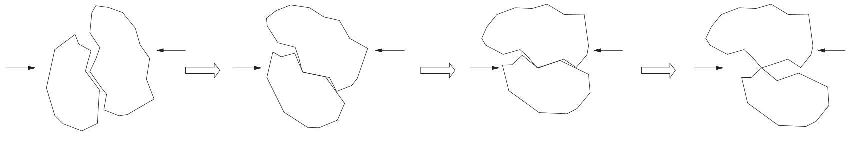


Figure 9. The rolling of rock results in void.

4. CONCLUSIONS

This paper proposed a new approach for rock-soil mixture sample remodeling to analyze the RSM mechanical behavior affected by volumetric rock content (VRC), particle-size distribution (PSD), structure character, rock and soil categories. It considers the particle-size distribution character and structural consistence, and gives guidance on selecting a Representative Volume Element (RVE) for the in situ tests. The test results show that there exist a linear relationship between the elastic modulus and the uniaxial compressive strength (UCS) of RSM, and the UCS and elastic modulus increase as VRC increases. The specimen reaches to peak strength for VRC at 20% to 30%, and the UCS decrease steadily with the increase of VRC.

The acoustic wave testing for the RSM characteristic shows interesting and inspiring results. The wave velocity is shown to have a good relation with the internal structure geometrical characteristic (particle-size fractal dimension used in this paper), volumetric rock content, stress situation and compressive strength. It is expected that the acoustic wave testing may be very valuable for RSM in-situ investigation.

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