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Mechanical Properties of Virtual Block-in-matrix Colluvium

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This paper was prepared for presentation at San Francisco 2008, the 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium, held in San Francisco, June 29-July 2, 2008.

ABSTRACT: The present work attempts to simulate and analyze the mechanical behavior of block-in-matrix (BIM) colluvial materials using virtual specimens. This study carried out a series of numerical simulation as virtual mechanical tests in order to look into the important factors that affect the mechanical properties of BIM colluvium. It was found that (1) the strength of BIM colluvium increases with increasing block proportion, (2) rock-block orientation affects the anisotropy of mechanical properties, raising confining pressure reduces the anisotropy, and (3) the rock-block aspect ratio has a minor influence on the mechanical behavior/properties. The effect of specimen size on the mechanical behavior/properties of BIM colluvium was also evaluated. It was shown that the variation of mechanical behavior tends to converge as the specimen size approaches to a representative elemental volume (REV). Due to the inevitable difficulties in obtaining colluvium specimens close to the REV for laboratory tests, it may be possible to adopt virtual mechanical tests to complement insufficient data of laboratory tests, provided an appropriate calibration can be made.

1. INTRODUCTION

Colluvial materials are often complex mixtures of geo-materials of various sizes, shapes, fabrics, and porosities depending on the parent strata and the slope-failure mechanism. Very often, colluvium from previously failed rock slopes is composed of both hard rock blocks and soft clay matrix, and may be considered as a complex composite geo-material which can be treated as a "blocks-in-matrix (BIM) material [1]. Unlike the common laboratory tests for intact rock or soil, conventional laboratory testing of BIM colluvium specimens (that may contain various sizes of rock blocks) is likely impractical since the specimen size is usually much smaller than the representative elemental volume (REV) of the in-situ BIM geo-material.

Medley (1994)[1, 2] treated the composition of mélange as an example of a "block-in-matrix rock", or "BIMROCK". Medley considered that in a BIMROCK, the mechanical properties of the "blocks" in the BIMROCK have to be at least twice as great as those of the "matrix" in order that failure surfaces be forced to negotiate around blocks. Lindquist (1994) [2] performed a series of triaxial tests using artificial mélange BIMROCK specimens, and concluded that both the strength and stiffness of mélange BIMROCK varied with volumetric block proportion (termed "block proportion" hereafter). He also observed that as the block proportion increased, the failure surface tended to develop along block/matrix contacts interface and the failure surfaces appeared tortuous ("winding" or "zigzag" nature).

Although both are BIM materials, BIM colluvium and mélange BIMROCK differ in the nature of their formation. However, in both forms of mixtures the mechanical properties of block and matrix may differ by several orders (*e.g.*, 100 or 1000 times different). This study aims to simulate and analyze the mechanical behavior of BIM colluvial materials through a series of numerical simulations or "virtual mechanical tests".

2. DESCRIPTION OF COLLUVIUM AT THE STUDY SITE

The study site is within a huge landslide area (about 2.3 km^2) named *Li-Shan* located in the west wing of the central mountain chain of Taiwan with an average elevation near 1900 m. This area has been subjected to repeated and reactivated landslides with various depths of sliding surfaces according to several intensive investigations in the past. The rock formation in this area is mainly Oligocene slate or argillite with well-developed cleavages. Due to the effects of steep landform, valley unloading, faulting, and climate, both the degrees of fracturing and weathering are high. The colluvial deposit in this landslide region is often composed of both rigid slate blocks and soft clay, which is the "BIM colluvium", referred to in this paper.

Depending on the mechanism of slope failure, the orientation of slate blocks may be either randomly distributed or have a preferred alignment. For a colluvial deposit that has experienced intensive mass rotations and mixing during the landslide processes, the slate blocks may tend to be randomly distributed. On the other hand, for rock mass sliding without severe rotation and fragment mixing, the original discontinuity fabrics were roughly retained although somewhat loosened and deformed. After a certain period of time, the remaining slate blocks may be surrounded by clayey matrix from weathering along loosened discontinuities (cleavage or joints) or else from fine soils transported by groundwater. In this case, the slate blocks tend to be aligned more or less along the orientation of cleavage. The maximum size of the slate blocks is about 100 mm.

Good quality colluvial samples HQ cores with high recovery were obtained by wire-line sampling, using micro-fine slurry as the drilling fluid. Fig.1 and Fig. 2, respectively, show typical cores of colluvium with and without aligned orientations of slate blocks. These cores were used for fabric study and subsequent laboratory tests. The volumetric block proportion (block ratio by volume) ranged between 20% and 50%. Following the guidelines of Medley [1], blocks of size smaller than $0.05\sqrt{A}$ were assigned to the matrix, where A denotes the specimen area. In the present work, block proportions were measured by two-dimensional image analysis (2D area block proportion) (see Fig.3 as an illustrated example) as well as by weighing grain composition from the disaggregated specimen (3D volumetric block proportion). The measured results obtained by the two different methods agreed well. In the present work, the 2D area block proportion is assumed to be the same with the 3D volumetric block proportion.

Due to the significant variations in samples from even the same borehole and the fact that the specimen sizes could not approach the size of the REV, quantitative characterizations of the mechanical properties of the colluvium through conventional laboratory mechanical tests appeared unreliable and impractical. This difficulty motivated a program of parametric studies using a series of numerical simulations of virtual mechanical tests.

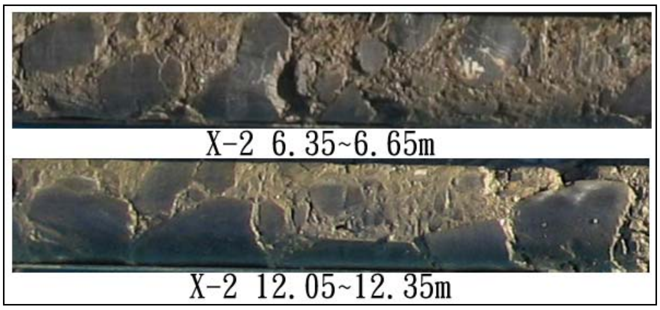

Fig.1. Typical cores of colluvium without an aligned orientation of slate blocks.

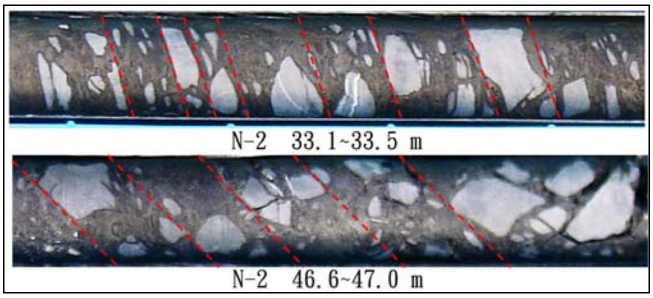

Fig.2. Typical cores of colluvium with an aligned orientation of slate blocks

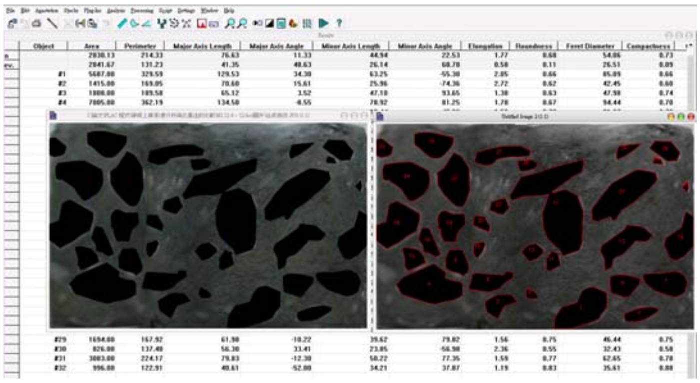

Fig.3. Example of 2D image analysis for measuring block proportion

3. VIRTUAL MECHANICAL TESTS OF BIM COLLUVIUM

As Fig.1 and Fig.2 show, the shapes of most slate blocks are triangle, quadrangle, or pentagonal with different aspect ratios (the ratios of length/width). As a consequence, the shapes of rock blocks were modeled randomly by these three types of polygons with various aspect ratios as shown in Fig.4.

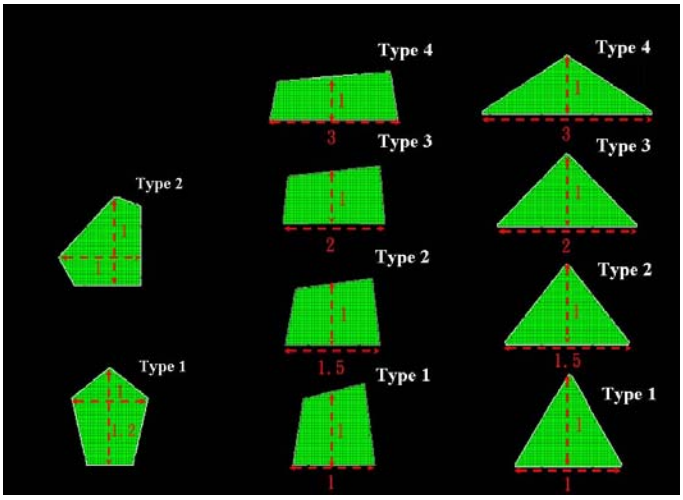

Fig.4. Various types of rock-block elements.

A simulation of the sampling process was designed to model the random sampling of specimen. First, a layout of a virtual (simulated) BIM colluvium was generated by taking into account the random distributions of block proportion, block shapes, aspect ratios, and block orientations. Next, each simulated specimen was sampled randomly within the simulated ground to model the sampling process through ground exploration. Fig.5 illustrates the conceptual procedure for random generation of a virtual specimen.

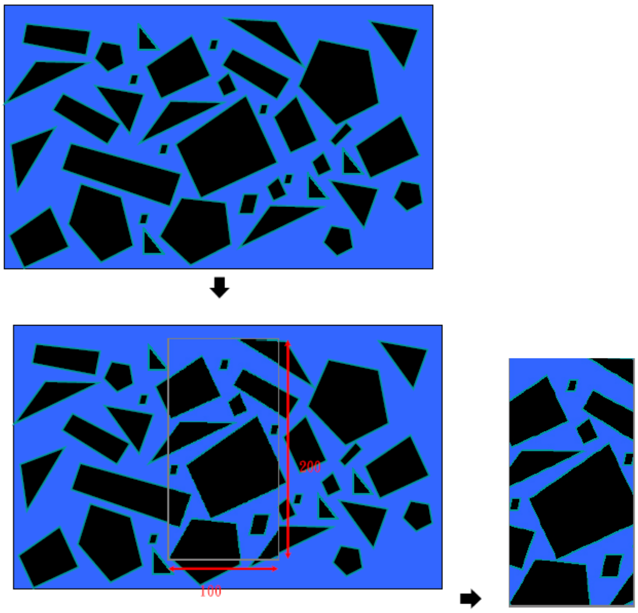

Fig.5. Conceptual procedure for random generation of a virtual specimen.

Fig.6 presents examples of virtual specimens containing blocks with random block orientations for three different block proportions (30%, 45%, and 60%). Fig.7 shows examples of virtual specimens with various (a) block proportions (30%, 45%, 60%, and 75%), (b) block orientations (relative to the vertical axis) (0°, 15°, 30°, 45°, 60°, 75°, and 90°), and (c) block aspect ratios (1:1, 1.5:1, 2:1, 3:1). A series of numerical simulations for the purpose of performing "virtual mechanical tests" on BIM colluvium were carried out using two-dimensional FLAC analysis. All materials are assumed to follow the Mohr-Coulomb model. Typically, a 100 by 200 mesh was used to model a 50mm by 100mm specimen.

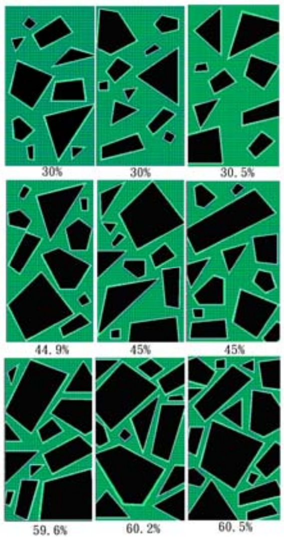

Fig.6. Virtual specimens contain rock blocks with random block orientations.

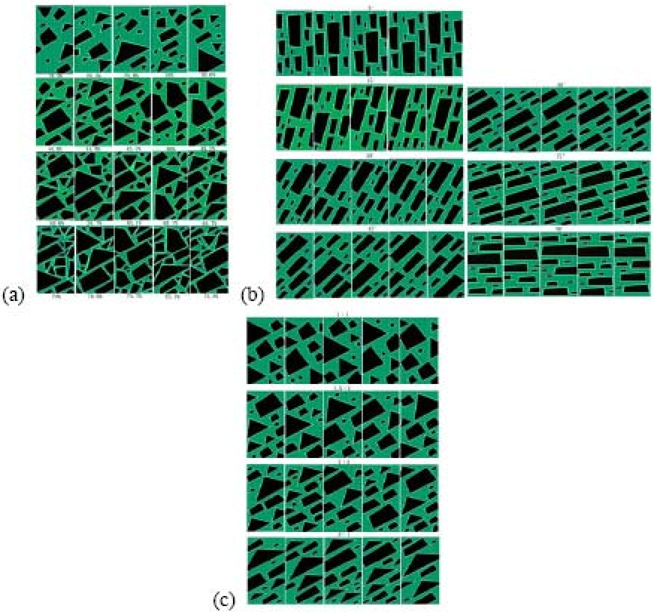

Fig.7. Virtual specimens contain aligned rock blocks with various (a) block proportions, (b) block orientations, and (c) block aspect ratios.

In a virtual triaxial compression test, each specimen was subjected to three confining pressures (200kPa, 400kPa, and 800kPa) to model a full set of triaxial tests. For each set of fixed parameters (*i.e.*, block proportion, block shapes, aspect ratios, and block orientations, etc.) to be discussed in the following context, at least four different virtual specimens were generated and subjected to further virtual triaxial compression. In other words, each set of virtual triaxial compression tests made use of at least four distinct specimens for each set of fixed parameters. This numerical simulated approach may be regarded as an analogy of the laboratory experimental work as conducted by Lindquist [2] for the testing of artificial mélange. In Lindquist's tests, the strength and deformability of artificial BIMROCKs with various combinations of block size, block alignment, and block proportion were compared to examine the dominant factors for the mechanical properties of BIMROCK. The trend of strength and deformability obtained through the virtual triaxial compression tests appeared in agreement with Lindquist's results.

To account for the influence of the contact interface between slate blocks and clayey matrix, an interface material was modeled between the virtual blocks and matrix, similar to the approach adopted by Lindquist [2]. To account for the frictional nature of interface material, the interface material was assigned a lower cohesion than that of the clayey matrix, but a higher frictional angle and modulus than those of clayey matrix. Material properties are listed in Table 1. Numerically simulated and experimental results (Lindquist, 1994) [2] were compared to examine the role of the interface material. It was found, with the interface material selected, the numerically simulated results agreed reasonably well with Lindquist's experimental results.

Table 1. Material Properties for BIM colluvium model

Material	Blocks	Clay	Interface
cohesion (kPa)	300	20	0.02
Frictional angle (deg)	33	22	30
Density (kg/m3)	2800	1600	2200
Shear Modulus (MPa)	30000	40	2000
Bulk Modulus (MPa)	15000	24	1200
Tensile Strength (kPa)	200	0	0

Fig. 7 displays the location of strain concentration inside the specimen at failure for two virtual specimens with block proportions 18% (left) and 50% (right), respectively. As observable in this figure, a BIM colluvium with a low block proportion tended to develop smooth and continuous failure plane across the clay matrix. However, the failure plane in a BIM colluvium with a relative high block proportion was forced to negotiate around blocks tortuously in order to deform and yield. Similar trends were reported by Medley[3, 4] as well as Irfan and Tang [5].

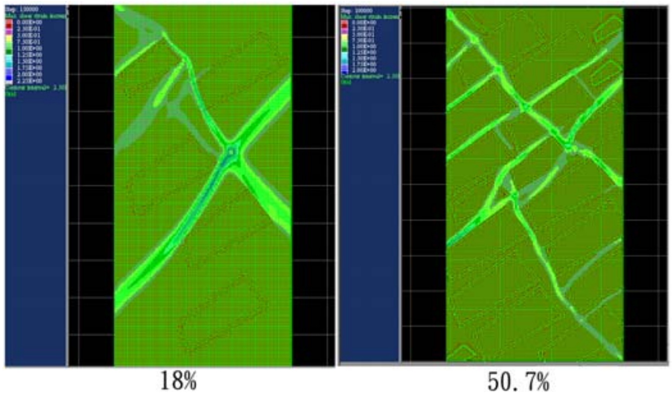

Fig.7. Strain concentration inside specimen at failure for two virtual specimens with block proportions 18% (left) and 50.7% (right).

4. PARAMETRIC STUDIES

4.1 Effect of Block Proportion

(i) Variation of Stress-strain Curve

A series of virtual triaxial compression tests for different virtual specimens (four for each block proportion) were conducted to investigate the effect of block proportion on the variation of stress-strain curve and mechanical properties. Fig. 8 shows the stress-strain curves obtained from virtual mechanical tests for block proportion at 30%, 45%, and 60%, respectively. The confining pressures from the left to right columns correspond to 200kPa, 400kPa, and 800kPa, respectively. For those presented in Fig. 8, the block orientation of the virtual specimens is randomly distributed. Difference in the arrangement of rock blocks within the BIM specimen results in the variation of the stress-strain curve and the ultimate deviator stress. It is noted that, as confining pressure increases, the variation among stress-strain curves for different virtual specimens with a same block proportion reduces notably. BIM colluvium with a medium block proportion appears to show a larger variation in stress-strain curves as well as peak strength. This is understandable, since the variation of the path and the length of the developed failure surface in each individual BIM specimen with various block arrangements, may vary with a higher deviation compared to a BIM colluvium with either a lower and higher block proportion.

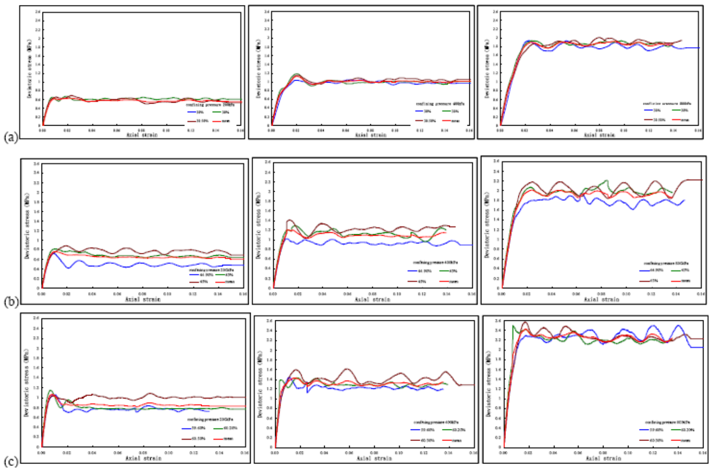

Fig.8. Stress-strain curves obtained from virtual mechanical tests for various block proportion (a) 30%, (b) 45%, and (c) 60%.

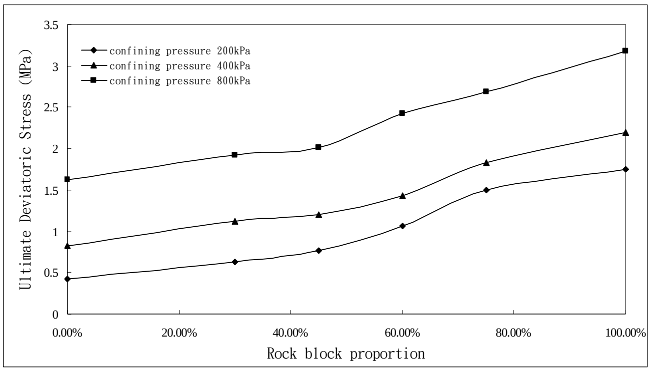

Fig.9. Ultimate deviator stress versus block proportion for virtual specimens containing rock blocks without preferred orientation.

(ii) Effect on Strength and Stiffness

Fig. 9 and Fig. 10 show the strength of simulated BIM colluvium specimens versus block proportion for virtual specimens containing rock blocks without preferred orientation (Fig. 9) and with aligned rock blocks (Fig. 10). The strength of the specimen was defined as the ultimate (peak) deviator stress on the stress-strain curve. When the block proportion is low, the strength is close to the strength of the pure matrix (clay), indicating the failure mechanism for BIM colluvium with a low block proportion probably has a failure surface that remains more or less planar, much as would occur for pure matrix. As the block proportion increases larger than 50%, the failure surfaces in the specimens near failure become tortuous, as shown in Fig.7. Inter-block contact resistance also becomes prevalent and further raises the strength of the specimen. This tendency is more obvious when the block proportion is greater than 50% or so for virtual specimens containing rock blocks without a preferred orientation. For virtual specimens containing aligned rock blocks, the strength increase is more obvious as block proportions increase beyond 70% or so.

Fig.11-12 shows the Young's moduli for various block proportions of virtual specimens containing rock blocks without preferred orientation (Fig.11) and with aligned rock blocks (Fig.12). The Young's modulus of a virtual BIM colluvium was determined from the initial slope of stress-strain curve. Due to the large difference in stiffness of slate blocks and clayey matrix (a difference of three orders of magnitude), the Young's modulus of BIM colluvium increases with block proportion; and especially rapidly as the block proportion increases such that influence of inter-block contacts dominate the overall mechanical behavior. The trends for BIM colluvium containing rock blocks with or without preferred orientation appear quite similar.

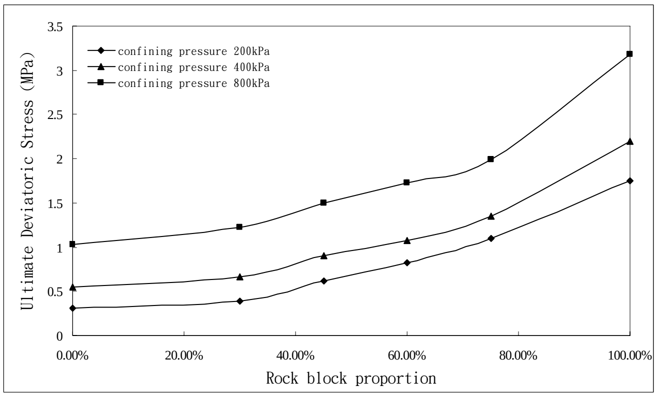

Fig.10. Ultimate deviator stress versus block proportion for virtual specimens containing aligned rock blocks.

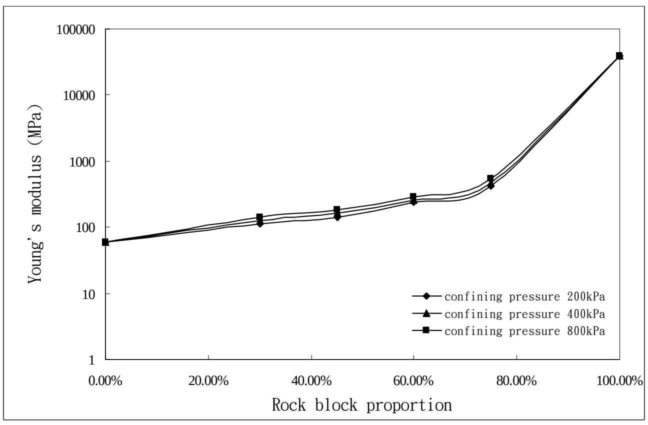

Fig.11. Young's Modulus versus Block Proportion for virtual specimens containing rock blocks without preferred orientation.

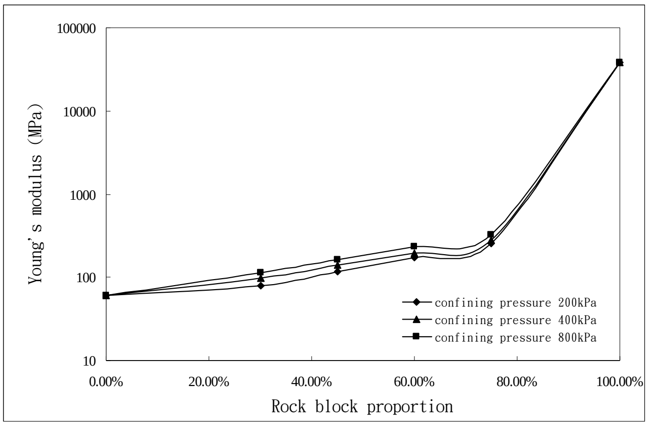

Fig.12. Young's Modulus versus Block Proportion for virtual specimens containing aligned rock blocks.

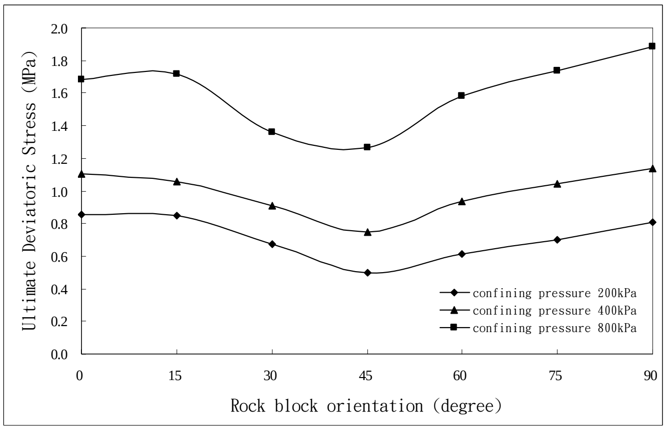

Fig.13. Effect of block orientation on the strength of virtual BIM colluvium.

4.2 Effect of Block Orientation

For virtual specimens containing aligned rock blocks, the block orientations influenced the material's mechanical properties, similar to the effects of aligned discontinuities in a jointed rock mass [6]. To demonstrate the effect of block orientation, a series of virtual specimens with a fixed 45% block proportion, aligned quadrangle blocks, and block aspect ratio 3:1 were generated such as shown by Fig. 7(b). The ultimate deviator stress and Young's modulus obtained from the results of virtual triaxial compression tests are presented in Fig. 13 and Fig. 14, respectively. Regardless of confining pressure, the lowest strength occurs at orientations near 45 degrees, which appears reasonable since the failure surfaces are easier to develop along inclinations somewhat between 30 and 60 degrees. Anisotropy in strength is a feature of coherent rock masses with a single set of discontinuities [6]. It is also noticeable that the anisotropy tends to decrease as confining pressure increases.

The anisotropy in Young's modulus is also apparent (Fig. 14) although the trend is different from that of the strength anisotropy. It appears the Young's modulus monotonically decreases with block orientation within 15-45 degrees, and does not exhibit large change afterward.

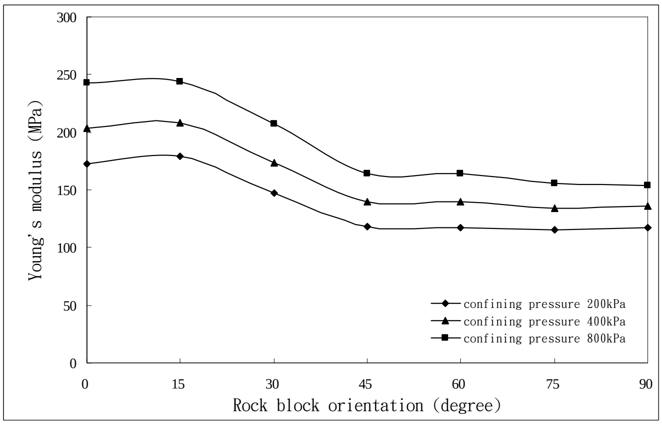

Fig.14. Effect of block orientation on the Young's Modulus of virtual BIM colluvium.

4.3 Effect of Block Aspect Ratio

The aspect ratios of rock blocks can also affect the anisotropy of a BIM colluvium. In the present work, the block aspect ratio is defined as the ratio of block length to block width. To demonstrate the effect of block aspect ratio, a series of virtual specimens with a fixed 45% block proportion and with fixed block orientation 60 degrees, were generated with various block aspect ratio such as shown Fig.7(c). The ultimate deviator stress and Young's modulus obtained from the results of the virtual triaxial compression tests are presented in Fig. 15 and Fig. 16, respectively. As seen from these figures, block aspect ratio does somewhat affect the strength and stiffness of a BIM colluvium. However, as block aspect ratio is greater than 1.5, its influence becomes insignificant.

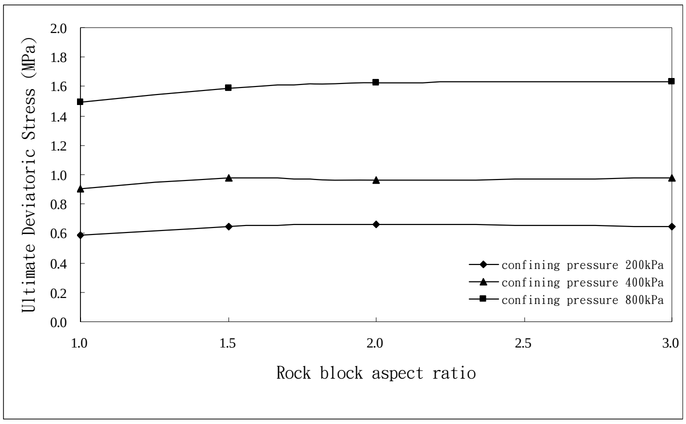

Fig.15. Effect of block aspect ratio on ultimate deviator stress of virtual BIM colluvium.

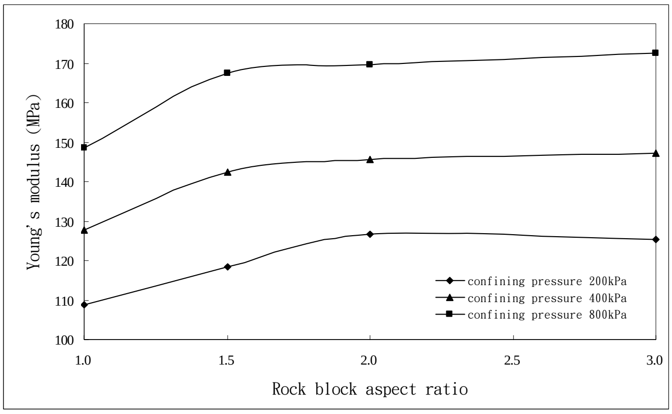

Fig.16. Effect of block aspect ratio on Young's Modulus of virtual BIM colluvium.

4.4 Effect of Specimen Size

The BIM colluvium of the present study contains rock blocks of sizes ranging from a few mm to 100 mm. When the size of the specimen is not significantly larger than the maximum size of rock blocks in the BIM colluvium, the obtained mechanical properties may vary considerably. To investigate the effect of specimen size on the mechanical properties and on the stress-strain relation of the BIM material, a series of virtual triaxial compression tests on sequentially enlarged sizes of virtual specimens were conducted. The specimens have four different sizes: 50mm x 100mm, 70.5cm x 141mm, 100mm x 200mm, and 200mm x 400mm, as Fig.17 displays (not in scale). All the virtual BIM specimens have a fixed block proportion 45% and block orientation 45 degrees. The largest rock block in the 50mm x 100mm specimen occupies 16% of the whole specimen volume; the largest rock block in the 200mm x 400mm specimen occupies only 1% of the whole specimen volume.

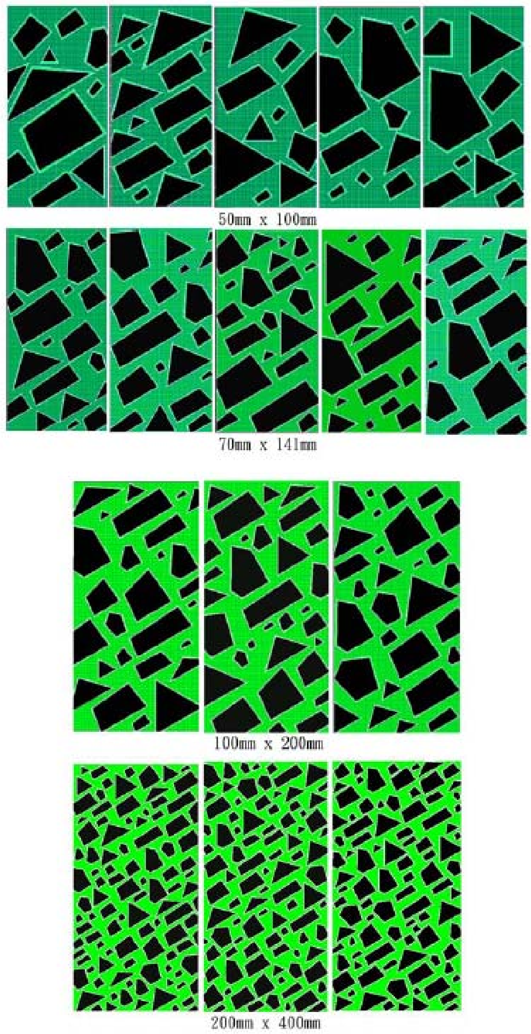

Fig.17. Specimens with various sizes (not in scale).

The stress-strain curves in Fig.18 are the results obtained from virtual triaxial compression tests under the confining pressure 200kPa. As the virtual specimen size gradually enlarges, the obtained stress-strain curves appear less varied among curves. The stress-strain curve gradually converges to the mean stress-strain curve (shown in red) when the specimen size approaches to a certain representative elemental volume (REV). With virtual mechanical tests, it is possible to identify the size of the REV. However, it is likely this REV may be much larger than the common size of cored specimens from geotechnical exploration. As a result, it may be unreliable and impractical to carry out mechanical tests with ordinary cored specimen sizes in real world. On the other hand, there should be no big problem for performing virtual mechanical tests instead.

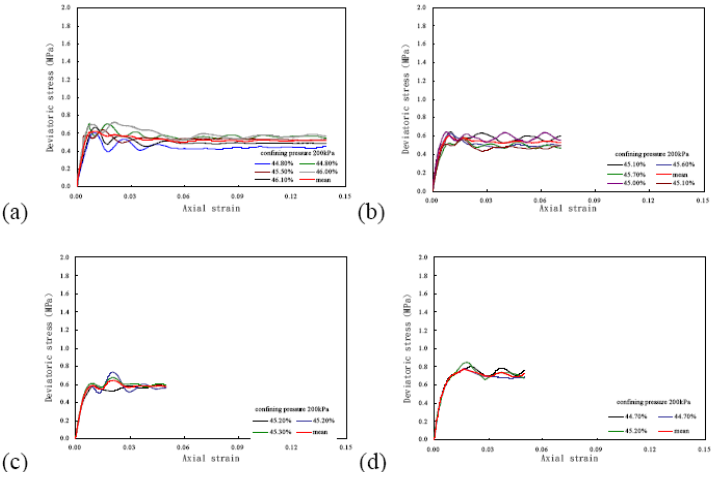

Fig.18. Stress-strain curves for different sizes of virtual specimens of the sizes (a) 50mm x 100mm, (b) 70.5mm x 141mm, (c) 100mm x 200mm, and (d) 200mm x 400mm.

5. SUMMARY AND CONCLUSIONS

It is usually difficult to obtain the mechanical properties of BIM colluvium through conventional mechanical laboratory tests owing to the specimen size limitations. This study attempted to simulate and analyze the mechanical behavior of BIM colluvial materials using virtual specimens. We conducted a series of numerical simulations as virtual mechanical tests and investigated the important factors that affect the mechanical properties of the BIM colluvium. Factors taken into account in the present work included block proportions, block inclinations (with random directions or a preferred direction), and block aspect ratios. Through numerical simulation, it was found that (1) the strength of BIM colluvium increases with increasing block proportion, (2) rock-block inclination results in the anisotropy of mechanical behavior/properties, (3) higher confining pressures reduce the anisotropies, and (4) the block aspect ratio only has a minor influence on the mechanical behavior/properties. Furthermore, the effect of specimen size on the mechanical behavior/properties of BIM colluvium was also evaluated through a series of virtual mechanical tests. It was demonstrated the variation of mechanical behaviors tend to converge as the specimen sizes gradually approach the certain representative elemental volume (REV). Due to the inevitable difficulties in obtaining colluvium specimens for laboratory tests and the specimen size limitation, it may be possible to adopt virtual mechanical tests to complement insufficient data of laboratory tests instead, providing an appropriate calibration can be made. When it is difficult to test BIM material in a large enough specimen, virtual mechanical tests may be able to estimate the variance of mechanical properties obtained from "small specimens" and to examine the effect of scale-independent block-size distribution.

ACKNOWLEDGEMENT

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