CHAPTER VII
DISCUSSIONS AND CONCLUSIONS

This chapter discusses the adequacy of the test results and the scope, limitations and applications of the mathematical correlations between single and multi-stage triaxial compression testing. Conclusions drawn from the test results and analysis are also presented.

7.1 Discussions

Due to the fact that the $\sigma_{1,f} - \sigma_3$ relations for all tested rocks are not linear, as shown in Figure 6.1, the conventional Coulomb strength criterion is not applicable here. In addition, the criterion is only for intact rock specimens, and hence it is not valid for the multi-stage testing specimens where they are failed after the first loading cycle. Hoek-Brown criterion seems more appropriate for this study as it is capable of describing the compressive strengths of the intact specimens for the single stage tests and the failed specimens for multi-stage testing.

Rock types selected for this study have uniaxial compressive strengths ranging from soft rock (gypsum – 10.8 MPa) to strong rock (basalt – 100.6 MPa). This allows deriving an appropriate mathematical relations between m_m/m_s ratios and the strength (i.e., Equation (6.2)). Missing from this study is the very strong rock specimens (σ_c > 250 MPa), as they are rarely encountered in the geo-engineering projects and mines in Thailand.

Good correlations between m_m/m_s ratio and σ_c and between s_m/s_s ratio and σ_c support that the triaxial compression strengths for the single stage testing that uses several specimens to accomplish can be predicted by the results of the multi-stage testing that uses much fewer specimens. As a minimum the multi-stage testing requires only one uniaxial compression test to obtain σ_c and one multi-stage triaxial testing to obtain m_m and s_m. The three parameters can be used to predict m_s and s_s (always equals to 1) for the single stage testing.

Comparison of the correlation equation obtained from this study with the multi-stage strength results obtained elsewhere by other researchers suggests that the multi-stage strengths are sensitive to the loading path. If a multi-stage testing uses the same loading path that used here the prediction by equation (6.2) can give good correlation with the error of about 2.83%, as shown in Figure 6.4. For multi-stage strengths obtained under different loading paths (i.e., not allowing axial stress to drop from the failure stress to the current confining pressure), as performed by Shi et al. (2016) and Venter, Purvis, and Hamman (2016) and Cain, Yuen, Le Bel, Crawford, and Lau (1986), larger error can be obtained, as shown in Figure 6.4.

Correlations between deformation parameters obtained from multi-stage testing (E_m and G_m) and from single stage testing as performed in this study have never been attempted elsewhere. This is due to the fact that the conventional triaxial cell or Hoek cell with strain gages or clip gages cannot measure the lateral deformations after the specimens have been failed by the first loading cycle. This study uses the polyaxial load frame that allows measuring the lateral deformations by the movement of the four cantilever beams. As a results, comparison of the deformation parameters can not be performed against the results obtained elsewhere. In another word, no one has ever measured the deformation moduli and Poisson's ratios from the multi-stage testing.

Figure 6.6 shows that the Poisson's ratios for all tested rocks decrease with increasing the confining pressures. This behavior has long been observed from other triaxial compression tests. For the multi-stage testing, however, the Poisson's ratios increase with confining pressures. This is due to that the failing specimens are dilated laterally as the loading cycles progress. It also suggests that the dilatation effect is predominant over the increased confining pressures. Note that the correlations of the elastic moduli and shear moduli (e.g., equations (6.5) and (6.6)) have similar form of that proposed by Goodman (1970). However, the parameters E_m and G_m denoted here do not represent those of rock mass as proposed by Goodman.

7.2 Conclusions

Test results and analyses performed in this study can be concluded as follows.

1) Hoek-Brown criterion can be used to correlate the triaxial compressive strengths between single and multi-stage testing.

2) Good correlation between m_m/m_s ratio and uniaxial compressive strength allows predicting the conventional single stage triaxial compressive strengths from the multi-stage compressive strength results.

3) The multi-stage triaxial strengths are sensitive to the loading paths used for each loading cycle. Different sets of compressive strengths would likely be obtained under different loading paths.

4) Polyaxial load frame allows measuring the axial and lateral deformations of the failed specimens from the multi-stage testing. As a result the deformation moduli and Poisson's ratios of the multi-stage test condition can be determined.

5) The elastic moduli, E_m and E_s, and shear moduli, G_m and G_s, can be correlated using equations with similar form of Goodman (1970) for intact and rock mass relation. This allows predicting the deformation parameters of single stage test conditions for the intact rocks from the multi-stage test condition for the failing rocks.

7.3 Recommendations for future studies

The limitations of the numbers of tested rocks used in this study load to the following recommendations for future study, as follows:

1) More rocks with a variety of strengths should be tested, in particular for those with uniaxial compressive strengths of greater than 150–250 MPa. This could enhance the predictive capability of the proposed correlation equations.

2) The effect of loading path remains poorly understanding. More tests should be conducted under different loading paths using the same sets of test specimens.

3) Numerical analysis approach is desirable to study the failure behavior of the specimens after the first cycles of the multi-stage triaxial compression test. The results could reveal how the modes of failure of rocks induced for different strengths.

4) The effect of the range and interval of the confining pressures should be studied. The could be useful to determine the appropriate ranges of confining pressure for different strengths of rocks.