模型尺寸與粒徑分布對 PFC3D 模擬結果之影響

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摘要

本研究利用三維顆粒流程式碼(Particle Flow Code, PFC)探討模型尺寸與粒徑分布對宏觀力學性質，包括無圍壓強度(Unconfined Compressive Strength, UCS)、楊氏模數及泊松比的影響。研究考慮了四種最大與最小粒徑比(d_{max}/d_{min})，且皆採用連續均勻粒徑分布，並針對每種粒徑比分析了七種不同模型尺寸，各圓柱體直徑與中位數粒徑比(L/d)。結果顯示，隨著模型尺寸(L/d)增加，模擬所得的力學性質變異係數(COVs)顯著下降。使用 PFC3D 預設設定時，隨著模型尺寸增大，UCS 與楊氏模數皆上升，增加幅度趨緩，主要因為在未固定孔隙率條件下，隨模型尺寸愈大，整體孔隙率下降，顆粒之間鍵結分布更為均勻所致。若固定孔隙率以排除影響，平均 UCS 仍隨模型尺寸(L/d)上升，但幅度減緩；楊氏模數反而隨模型尺寸(L/d)增大而略微下降，泊松比則變化不大，仍呈下降趨勢。此外，粒徑分布也顯著影響模擬結果，當粒徑比愈大，所得 UCS 與楊氏模數平均值愈高，而泊松比隨之下降，且力學性質變異程度趨於穩定。因此，在 PFC3D 模擬中適當考量模型尺寸與粒徑分布極為重要。

關鍵字： 顆粒流程式碼(PFC)、模型尺寸、粒徑分布、模型孔隙率、校正參數。

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ORIGINAL PAPER

Effect of Model Scale and Particle Size Distribution on PFC3D Simulation Results

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Abstract This paper investigates the effect of model scale and particle size distribution on the simulated macroscopic mechanical properties, unconfined compressive strength (UCS), Young's modulus and Poisson's ratio, using the three-dimensional particle flow code (PFC3D). Four different maximum to minimum particle size (d_{max}/d_{min}) ratios, all having a continuous uniform size distribution, were considered and seven model (specimen) diameter to median particle size ratios (*L/d*) were studied for each d_{max}/d_{min} ratio. The results indicate that the coefficients of variation (COVs) of the simulated macroscopic mechanical properties using PFC3D decrease significantly as *L/d* increases. The results also indicate that the simulated mechanical properties using PFC3D show much lower COVs than those in PFC2D at all model scales. The average simulated UCS and Young's modulus using the default PFC3D procedure keep increasing with larger *L/d*, although the rate of increase decreases with larger *L/d*. This is mainly caused by the decrease of model porosity with larger *L/d* associated with the default PFC3D method and the better balanced contact force chains at larger *L/d*. After the effect of model porosity is eliminated, the results on the net model scale effect indicate that the average simulated UCS still increases with larger *L/d* but the rate is much smaller, the average simulated Young's modulus decreases with larger *L/d* instead, and the average simulated Poisson's ratio versus *L/d* relationship remains about the same. Particle size distribution also affects the simulated macroscopic mechanical properties, larger d_{max}/d_{min} leading to greater average simulated UCS and Young's modulus and smaller average simulated Poisson's ratio, and the changing rates become smaller at larger d_{max}/d_{min}. This study shows that it is important to properly consider the effect of model scale and particle size distribution in PFC3D simulations.

Keywords Particle flow code (PFC) · PFC2D · PFC3D · Model scale · Particle size distribution · Calibration study · Model porosity

1 Introduction

Two types of numerical methods are available for analysis of intact rock mechanical behavior: continuum and discontinuum methods (Jing 2003; Fu 2005). An important difference between these two types of methods is how the damage (degradation and failure) process is represented, indirectly or directly (Potyondy and Cundall 2004). The continuum (indirect) methods use average measures of material degradation in constitutive relations to represent micro-structural damage, while the discontinuum (direct) methods idealize the material as a collection of separate units such as particles bonded together at their contact points and use the breakage of the bonds to represent damage (Potyondy and Cundall 2004). In general, rock can be treated as a granular material whose micro-mechanical behavior is discontinuous and heterogeneous. Thus the

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