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A chart-based seismic stability analysis method for rock slopes using Hoek-Brown failure criterion

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ABSTRACT

The parameters of rock mass structures, strength and seismic effect are critical factors for the seismic stability analysis of rock slopes. This paper demonstrates the use of a new form of a chart-based slope stability method that satisfies the Hoek-Brown (HB) criterion. The limit equivalent method is used to assess the stability of rock slopes subjected to seismic inertial force. First, stability charts for calculating the factors of safety (FoS) with a slope angle of $\beta = 30°$ in static and pseudo-static states were proposed by using Slide 6.0 software. Next, scaling factors of the horizontal seismic acceleration coefficient (f_{Kh}) and slope angle (f_β) were established to illustrate the influence of the horizontal seismic load and slope angle on the stability of rock slopes, respectively. Using regression analyses of f_{Kh} and f_β, a fast calculation model was proposed to solve the slope safety factors based on the stability charts. Finally, the stability charts analysis method (SCAM) was verified against the numerical solutions; the results showed that 70.63% of the data had discrepancies of less than $\pm 10\%$, and the data with discrepancies greater than $\pm 10\%$ were associated with high values of geological strength index (*GSI*) and horizontal seismic acceleration coefficient (K_h). The proposed model calculating the FoS of rock slopes is simple and straightforward to use for seismic rock slope design and stability evaluation.

List of symbols

α	Hoek-Brown input parameter
c	Cohesion
D	Disturbance factor of rock mass
f_β	Scaling factor of slope angle
f_{Kh}	Scaling factor of horizontal seismic acceleration coefficient
f_D	Disturbance weighting factor
F_D	Driving force
F_N	Normal force
FoS	Factor of safety
FoS_{LEM}	Factor of safety in limit equilibrium method
FoS_{LAM}	Factor of safety in limit analysis method
GSI	Geological strength index
H	Slope height
HB	Hoek-Brown criterion
$JCond_{89}$	Joint condition
K_h	Horizontal seismic acceleration coefficient
K_v	Vertical seismic acceleration coefficient
LAM	Limit analysis method
LEM	Limit equilibrium method
m_b	Hoek-Brown input parameter
m_i	Hoek-Brown constant
MC	Mohr-Coulomb
N	Stability number
PS	Pseudo-static method
RQD	Rock quality designation
S	Hoek-Brown input parameter
SCAM	Stability charts analysis method
SR	Non-dimensional strength ratio
β	Slope angle
φ	Friction angle
γ	Unit weight of rock mass
σ_1	Maximum principal stress
σ_3	Minimum principal stress
σ_{ci}	Uniaxial compressive strength of the Intact rock
σ_n	Normal stress
τ	Shear stress
λ	Number of discontinuities per meter

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1. Introduction

In seismically active areas, earthquakes are a major trigger factor for the failure of natural and man-made slopes (Li et al., 2009). Hence, predicting the dynamic stability of rock slopes is a significant task for civil engineers with respect to dams, open pit excavations, roads and other engineering projects. Determining the factor of safety (FoS) is the most common way to assess the stability of rock slopes (Michalowski, 2010). The limit equilibrium method (LEM) is the most extensive means for evaluating slope stability; however, the rock masses are inhomogeneous and characterized by several discontinuities including joints, fractures, bedding planes and faults. However, most commercial software and theoretical formulas based on the LEM require the conventional Mohr-Coulomb (MC) shear strength parameters cohesion c and friction angle φ to estimate the FoS of slopes, which completely ignore the non-linear nature of the rock mass strength; therefore, the linear MC criterion do not agree with the rock mass failure envelope (Sheorey et al., 1989; Jimenez et al., 2008; Zheng et al., 2009; Fu and Liao, 2010; Shen et al., 2012).

The application of the Hoek-Brown (HB) criterion surmounts the shortcomings of the conventional MC criterion. Hoek and Brown (1997) and Hoek et al. (2002) proposed a method for converting the rock mass strength parameters into the equivalent MC parameters. However, Li et al. (2008, 2011) found that this conversion could produce inconsistent estimates; the difference between using equivalent parameters and the native yield criterion was found to be up to 64% for slope stability. This suggests that the best way to address the rock and rock mass problems is to use the HB failure criterion directly in the calculations. Over the past 30 years, the HB criterion has been applied successfully to a wide range of intact and fracture rock types. The latest version of the HB criterion proposed by Hoek et al. (2002) is written as follows:

$$\sigma_1 = \sigma_3 + \sigma_{ci}(m_b\sigma_3/\sigma_{ci} + S)^{\alpha} \tag{1}$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively; σ_{ci} is the uniaxial compressive strength of the intact rock; and m_b, S, and α are the HB parameters, which represent the fracturing degree of rock masses.

$$m_b = m_i \exp^{((GSI-100)/(28-14D))} \tag{2}$$

$$S = \exp^{((GSI-100)/(9-3D))} \tag{3}$$

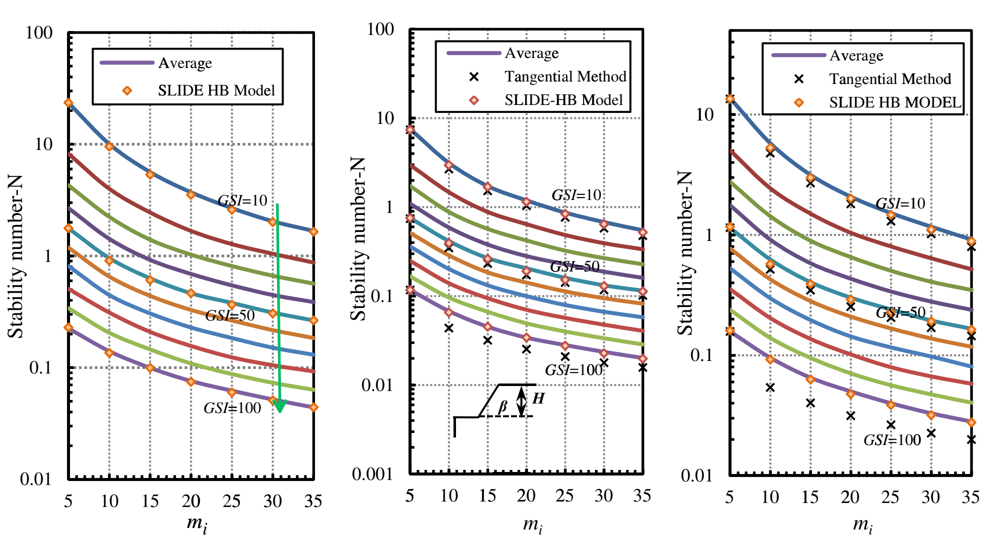
$$\alpha = \frac{1}{2} + \frac{1}{6}\left(\exp^{(-GSI/15)} - \exp^{(-20/3)}\right) \tag{4}$$

From Eqs. (2)–(4), we can see that parameters m_b, S, and α all depend on the geological strength index (GSI), which ranges from 5 (for highly fractured and poor rock masses) to 100 (for intact rock masses); m_i is the HB constant for intact rock, and its value (1.0–35.0) reflects the hardness of the rock mass. D is the disturbance factor; its value ranges from 0 (for undisturbed rock masses) to 1 (for disturbed rock masses). The values of GSI and m_i can be estimated using the method introduced by Hoek and Bray (1981); Marinos and Hoek (2001) and Hoek et al. (2013).

The SCAM is a technique for rapid or preliminary analysis of slope stability, and it has been broadly used to estimate the stability of slopes; examples include the works of Taylor (1937); Hoek and Bray (1981); Zanbak (1983); Gens et al. (1988); Michalowski (2002); Siad (2003); Loukidis et al. (2003), and Li et al. (2008, 2009). However, developing suitable stability charts to estimate the slope FoS directly from the HB criterion is challenging because at least six parameters (GSI, m_i, σ_{ci}, γ, H and β) must be considered for a dry slope with $D = 0$ (Shen et al., 2013).

Hoek and Bray (1981) and Zanbak (1983) proposed charting solutions for stability and toppling problems for rock slopes, respectively. However, these methods were based on statistical analyses, and none considered seismic effects. The pseudo-static (PS) method is a popular technique for evaluating seismic slope stability and has been used by many researchers, such as Newmark (1965); Ling et al. (1997); Hong et al. (2005) and Baker et al. (2006). In the PS method, the earthquake effects are simplified to horizontal and/or vertical seismic coefficients (K_h and K_v). Terzaghi first applied the PS method to assess seismic slope stability (Hong and Xu, 2005), and Newmark (1965) applied and extended the PS method to estimate the ground displacements caused by earthquakes. Subsequently, the PS method has been accepted and extensively used for the study of earthquake-induced landslides and rockslides (Huang et al., 2001; Sepúlveda et al., 2005). Although this method is generally considered to be conservative, due to the simplicity of the PS approach, it is still used in research.

The slope stability charts proposed by Carranza-Torres (2004) and Li et al. (2008, 2009, 2011) are among the few charts that can be used to estimate the FoS directly from the HB failure criterion. Li et al. (2009) put forward the seismic stability charts for rock slopes via the limit



(a) β=30°, K_h=0.1 (b) β=30°, K_h=0.2 (c) β=30°, K_h=0.3

Fig. 1. Slope stability charts based on limit analysis method (Based on Li et al., 2009).