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Investigating the critical slip surface of soil slope based on an improved black hole algorithm

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Abstract

Analysing the stability of soil slopes and investigating critical slip surfaces present an important and very complicated optimisation problem. In this paper, we solve this problem by introducing and modifying a new global optimisation (black hole algorithm) technique to form a new global optimisation algorithm for continuous optimisation (the improved black hole algorithm). By combination with typical mature limit equilibrium analysis (the Spencer method and the Morgenstern-Price method), the improved black hole algorithm was used to find the critical slip surface of soil slope. Thus, this paper proposed a new method for finding the critical slip surface of soil slope. Finally, the proposed method was verified through two typical numerical soil slope cases and was compared with the black hole algorithm and other extant studies. The results indicated that the applicability, validity and effectiveness of the improved black hole algorithm showed an improvement over previous studies and over the black hole algorithm. Moreover, the proposed method was applied for one highway landslide, and the determined critical slip surface was well agreement with the real one.

Keywords: Soil slope; Critical slip surface; Improved black hole algorithm; Safety factor

1. Introduction

Soil slopes are very common in geological environments. The instability of slopes can cause some serious geological hazards, such as landslides and debris flow. Therefore, studying the stability of the soil slope is very important. Searching for the slip surface with minimum safety factor called the critical slip surface is the key task in stability analysis of soil slopes (Huang, 1983). Hence, nowadays, many studies have focused on this topic.

These studies can be divided into two groups, namely, the analytic methods and the numerical methods. Due to its simplicity and effectiveness, the limit equilibrium method is one of the most widely used analytic methods. The grid-mapping method for a hypothesised circular slip surface was among the initial methods studied (Huang, 1983). Given the complexities of a real slip surface, the critical slip surface search is transformed to a typical optimisation problem, and then, different mathematical optimisation methods are applied. For example, Yamagami and Ueta (1988) located the critical slip surface of soil slope by using the Simplex method, the Powell method, the Davidon-Fletcher-Powell (DFP) method, and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. Chen and Shao (1988) also used the Simplex method and the Powell method. Lefebvre (1971) studied the pattern search method to locate the critical slip surface. Arai and

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Tagyo (1985) applied the conjugate gradient method. Yamagami and Jiang (1997) focused on the dynamic programming method. Previous study (Chen and Shao, 1988) showed, the objective function for this optimisation problem was a complicated non-linear multiple hump function existing multiple local minima. Moreover, for the complexities of real soil slope, generally, this objective function was not a continuous function (Cheng and Lau, 2008). However, the classical mathematical optimisation methods are applicable mainly to continuous functions, but they are limited by the presence of the local minimum, as the local minimum close to the initial trial will be obtained in the analysis. The presence of the global minimum will not be obtained by the classical methods unless a good initial trial is adopted, but a good initial trial is difficult to be established for a general problem. Therefore, for the existence of multiple local minima, the applicability of the classical optimisation methods is very poor. However, if the good initial trial can be given, the efficiency of the classical optimisation methods is very good. Unfortunately, this is a very hard work for a general soil slope problem. Moreover, for the existence of discontinuous function, the robustness of the classical optimisation methods is also very poor. To overcome issues related to traditional optimisation methods, such as poor performance, poor robustness, and hard to be used, a few improved optimisation methods were also applied. For example, Chen (1992) applied the random method to locate the critical slip surface. Greco (1996), and Malkawi et al. (2001) researched the Monte Carlo method in their studies. Recently, Bai et al. (2014) improved the Monte Carlo method, and used it to locate the critical slip surface. To overcome the shortcomings of Monte Carlo method that include random searching and low efficiency, global optimisation methods such as evolutionary algorithms, were applied. For instance, McCombie and Wilkinson (2002) used a simple genetic algorithm (GA) to locate the circular critical slip surface of the soil slope. Zolfaghari et al. (2005) and Goh (1999) utilised a simple GA to locate a noncircular critical slip surface. Sun et al. (2008) and Li et al. (2010) applied a modified GA to locate the critical slip surface. Gao (2015) extended evolutionary programming (EP) and immunised evolutionary programming (IEP) to locate the critical slip surface of complicated soil slopes. Recently, new bio-inspired global optimisation algorithms have also been used. For example, Cheng et al. (2007) applied particle swarm optimisation (PSO) and their modified particle swarm optimisation (MPSO) to locate the critical slip surface. Mohammad et al. (2012) also applied PSO and their MPSO to search for the critical slip surface. Bolton et al. (2003) utilised the leap-frog method to locate the critical slip surface. Cheng et al. (2008a) utilised artificial fish swarm algorithm (AFSA) to locate the critical slip surface. Moreover, they (Cheng et al., 2008b) studied the applicability of the harmony search algorithm to locate the critical slip surface. Kang et al. (2013) applied artificial bee colony algorithm (ABC) to search for the critical slip surface. Gao (2014) proposed the continuous ant colony algorithm (CACA) and immunised continuous ant colony algorithm (ICACA), and used them to search for the critical slip surface of soil slope. Gandomi et al. (2015) studied the applicability of some swarm intelligence algorithms for finding the critical slip surface of soil slope, which included PSO, firefly algorithm (FA), cuckoo search (CS) and levy flight krill herd algorithm (LKH). Kashani et al. (2016) applied the imperialistic competitive algorithm (ICA) to locate the critical slip surface. Transforming the critical slip surface search problem as a combination optimisation problem, separate from the fore-mentioned studies. Kahatadeniya et al. (2009) applied ant colony optimisation (ACO) to locate non-circular critical slip surface. Rezaeean et al. (2011) employed four ant colony algorithms to find the critical slip surface, which were termed ant system, elitist ant system, ranked ant system and max-min ant system. Gao (2016) proposed a new meeting ACO, and applied it to locate non-circular critical slip surface of soil slope.

Compared with the analytic method, the numerical method has some advantages (Alejano et al., 2011). For example, the stress and strain can be used to analyze the slope stability. And the complicated geological environment can be considered in the numerical method. Moreover, the instability process and instability mechanism of slope can be analyzed by the numerical method. Therefore, the numerical method has been used to locate critical slip surface. For example, Zou et al. (1995) employed the finite element method to determine the probable location of the critical slip surface and the corresponding safety factor, and hence used the traditional optimisation method which was the dynamic programming method to locate the critical slip surface. Wang et al. (2003) also employed the finite element method to determine the probable location of the critical slip surface, but used ACO to locate the critical slip surface. To overcome the mesh requirements of the finite element method, Shahrokhabadi et al. (2014) employed the natural element method to determine the probable location of the critical slip surface, and hence used GA to locate the critical slip surface. Different from above studies, Griffith and Lane (1999) proposed the strength reduction method based on the finite element method. In this method, the possible location of the critical slip surface could be determined automatically without optimisation. To improve the strength reduction method, Zheng et al. (2009) proposed one method to find the critical slip surface based on the determination of the points (composed the critical slip surface) at which the equivalent plastic strain arrived at the maximum in the vertical direction in the strength reduction method.

A previous study showed that when the slope had a complicated geometry with major differences in the soil parameters between different soils, the solution was sensitive to the precise location of the critical slip surface (Cheng and Lau, 2008). Then, the effectiveness and efficiency of the solution algorithm and the capability of the optimisation algorithm to escape from the local minima became very important. However, the optimisation meth-