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Forecasting of landslide disasters based on bionics algorithm (Part 1: Critical slip surface searching)

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ABSTRACT

Two key issues for landslide forecasting include searching critical slip surfaces and determining their parameters. To solve the former aspect of this problem, a new critical slip surface search method based on an immunised continuous ant colony algorithm is proposed. Artificial immune system and evolutionary algorithms are combined with a continuous ant colony algorithm to form a new bionics algorithm (the immunised continuous ant colony algorithm) for continuous optimisation. The new bionics algorithm was then combined with a limit equilibrium analysis to form a new global optimisation algorithm to search critical slip surfaces. Finally, the proposed method is verified through five typical numerical examples and is compared with a continuous ant colony algorithm and previous studies in the literature. The results indicate that the applicability, validity and effectiveness of the new method are all improved over previous studies and over the continuous ant colony algorithm.

1. Introduction

Slopes are very common in geological environments and in engineering studies. Landslides that result from the instability of slopes are serious geological hazards. In China, the geological environment is very complex and unique. At the Qinghai–Tibet Plateau (which is located in the western region), the topography is very complex, and the geological activity is very intense. Rapid economic development has accompanied expanded large-scale engineering construction and resource development in this region. These activities have caused many landslide disasters and the loss of life and property. To prevent landslide disasters, the accurate forecasting of a landslide is important. In forecasting landslides, two key issues include searching critical slip surfaces and determining their parameters [1]. To address the important issue of searching critical slip surfaces, many studies have been conducted.

Critical slip surface searching is a common task in the landslide field. Its initial study involved the grid-mapping method for a hypothesised circular slip surface [2]. Subsequent work considered the complexities of a real slip surface by transforming the critical slip surface search into a typical optimisation problem and subsequently applying different mathematical optimisation methods. For example, optimisation methods such as the Simplex method and the Powell method have been used to search critical slip surfaces [3,4]. The pattern search method was introduced by Lefebvre [5] and Mo et al. [6]. To overcome issues related to traditional optimisation methods, the Monte Carlo method [7,8] has also been used. Some shortcomings of the Monte Carlo method have been identified, such as issues related to random searching and low efficiency; therefore, global optimisation algorithms have been used. For example, Han and Yang [9] proposed a method to search critical slip surfaces of a soil slope using a taboo search algorithm. McCombie and Wilkinson [10] proposed a method to search circle critical slip surfaces using a simple genetic algorithm. Zolfaghari et al. [11], Sun et al. [12] and Li et al. [13] used a genetic algorithm to search noncircular critical slip surfaces. As an alternative approach, Goh [14] used a simple genetic algorithm to search a polygonal critical slip surface. To overcome the shortcomings of simple genetic algorithms, a chaotic mutation operator has been used, and a method to search circular critical slip surfaces was proposed by Li et al. [15]. Gao and Feng [16] proposed a new method to search non-circular critical slip surfaces using immunised evolutionary programming. To avoid the shortcomings of evolutionary algorithms, some new bionics algorithms have also been used. For example, by considering that the critical slip surface search problem can be transformed into a combination optimisation problem, Kahatadeniya et al. [17] proposed a method to search non-circular critical slip surfaces using a traditional ant colony algorithm. A simulated annealing method [18] has also been applied to this problem. Particle swarm optimisation [19,20], artificial fish swarm algorithms [21], shuffled frog leaping algorithms [22], and

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harmony search algorithms [23] have all been used in previous studies.

To overcome the shortcomings of the limit equilibrium method, the finite element method has also been used. For example, Zou et al. [24] determined the initial slip surface and the range of the sliding surface of a slope by using the finite element method and by selecting the critical slip surface using traditional optimisation methods. Wang et al. [25] searched a critical slip surface using an ant colony algorithm and computed a safety factor using the finite element method. In addition, Griffiths and Lane [26] proposed the strength reduction method to search a critical slip surface. Because of its versatility, Zheng et al. [27] recently conducted studies using the strength reduction method. However, when searching critical slip surfaces, the strength reduction method exhibits some unique problems [28].

In this study, the artificial immune system and evolutionary algorithms are combined with a continuous ant colony algorithm to form a new bionics algorithm for continuous optimisation (the immunised continuous ant colony algorithm). In addition, based on the new bionics algorithm and a typical limit equilibrium analysis (the Spencer method), a new critical slip surface search method is proposed. Finally, to demonstrate its applicability and to investigate the validity and effectiveness of the new algorithm, five numerical examples with varying complexity are presented, and the obtained results are compared with those of the continuous ant colony algorithm and those from previous studies in the literature.

2. The search model

The problem of searching a critical slip surface can be simplified into a problem of searching key points of the critical slip surface, which can be transformed into a typical multi-parameter optimisation problem and a typical continuous optimisation problem. Because of the complex characteristics of a real slope, the above optimisation problem is a very challenging constrained optimisation problem [28]. In a 2D model, this problem involves the selection of a plane curve of which the corresponding safety factor is minimal. The model for searching the critical slip surface is shown in Fig. 1.

The function $y = f(x)$ is the assumed slip surface, which is not known, and $y = g(x)$ is the known surface curve. The key control points on the slip surface are A_1, A_2, A_{n-2}, A_{n-1}, and so on, whose coordinates are (x_1, y_1), (x_2, y_2), (x_{n-2}, y_{n-2}), (x_{n-1}, y_{n-1}), and so on. The coordinates of the two endpoints are (x_0, y_0) and (x_n, y_n). The entire slip surface can be determined using only these points. Therefore, the search over a slip surface can be transformed into the search for the coordinates of key control points. The values of

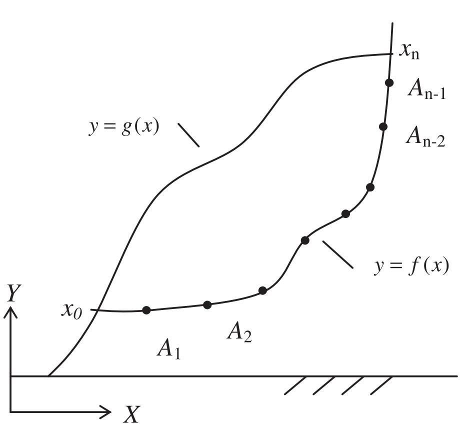

Fig. 1. Computational model for searching a critical slip surface.

y_0 and y_n can be determined using known values of x_0 and x_n from the function $y = g(x)$, and thus, the problem of slip surface searching can be cast as an optimisation problem

$$f = \min F(x_0, x_1, y_1, x_2, y_2, \ldots, x_{n-2}, y_{n-2}, x_{n-1}, y_{n-1}, x_n). \tag{1}$$

The coordinates of the key control points must be in the effective search space, and the slip surface must be rational. Therefore, the following constraint conditions apply:

(1) The horizontal ordinate must be an increasing or decreasing sequence.
(2) The entrance and exit points must be on the surface of the slope.
(3) The range of the horizontal ordinate is the horizontal border of the slope, and the vertical ordinate is restricted to the bottom hard layer by the range of the slope surface.
(4) The dip of the exit line should be in the range of 0°–45°.
(5) Generally, the slip surface should be concave but not convex or jagged, that is, $\alpha_{i-1} \leqslant \alpha_i$, where α_i is the angle between the horizontal line and the slip surface whose order is i. Generally, these angles should be continuous, that is, $\alpha_i - \alpha_{i-1} \leqslant \Delta\alpha$.

Therefore, the slip surface search problem can be considered as a typical complex constraint optimisation problem. To solve this problem efficiently, a new bionics algorithm (the immunised continuous ant colony algorithm) is proposed.

3. The search algorithm

Ant colony optimisation (ACO) is a computational algorithm proposed by the Italian scholar Dorigo in the 1990s [29] that mimics the behaviour of ant colonies. ACO was originally developed to solve complex combination optimisation problems, such as the traveling salesman problem (TSP). Therefore, traditional ACO is a very efficient combination optimisation method.

By imitating information exchange among the ant colony, ACO can solve complex combination optimisation problems more efficiently than traditional methods [29]. Therefore, based on the information exchange of an ant colony, a continuous optimisation method based on the principles of an ant colony should be feasible [30,31].

In this study, a new continuous ant colony algorithm (CACA) is proposed, which is shown as a flow chart in Fig. 2.

As shown in the flow chart for the CACA, there is only one operation in the internal cycle, which is the probability to move of an individual ant. Therefore, if an individual ant cannot effectively explore in the internal cycle, the efficiency and precision of the algorithm will be negatively affected. To improve the CACA, some mature methods, such as those that are used in evolutionary algorithms and artificial immune systems, are introduced into the CACA, and a new immunised continuous ant colony algorithm (ICACA) is proposed.

In detail, the modification is that the self-adaptive mutation operation and immunised selection operation are used after the probability move is computed in the internal cycle. With this modification, the individual ant can move more effectively, and the effectiveness of the search can be significantly improved.

The detailed procedure of the ICACA is described in the following.

3.1. Creation of the initial ant colony

In the solution space of the optimisation problem, the ant colony is randomly created such that the initial ant population