Slope Stability Assessment Using Optimization Techniques: an Overview

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ABSTRACT

Slope stability analysis has received increased attention recently. Slope stability problems may be solved using both deterministic and probabilistic approaches and can be characterized as optimization problems. In the deterministic approach, the factor of safety is the function to be minimized, and for probabilistic analysis, the reliability index is considered the objective function. The search for the minimum factor of safety or the reliability index is a very complicated optimization problem, and many successful optimization methods have been employed to solve this problem. This paper presents a survey of the literature on the various optimization methods applied to solving slope stability problems.

KEYWORDS: Slope stability; Deterministic analysis; Probabilistic analysis; Optimization

INTRODUCTION

The stability analysis of earth slopes is one of the fundamental calculations in geotechnical engineering. Slope stability is a concern in construction projects involving excavation, embankments, earth dams, and the loading or undercutting of existing slopes. The main approach used in slope stability analysis is the deterministic method. This method involves the identification of the critical slip surface and the associated minimum factor of safety. Available analytical methods include limit equilibrium methods, limit analysis methods, rigid element methods, and finite element methods. The most commonly used method for slope stability
analysis is based on the limit equilibrium methods. These methods make use of the limit equilibrium theory to derive the factor of safety against sliding for the slope. The factor of safety is defined as the ratio between resisting and disturbing forces involved in the slope stability problem. When the factor of safety approaches unity, failure is assumed to be imminent. There are a variety of methods of analysis available based on the limit equilibrium principle. Most of them are based on the method of slices, such as Bishop (1955), Morgenstern and Price (1965), Spencer (1967), Janbu (1973), and Sarma (1973). In the method of slices, the potential sliding mass is subdivided into a number of slices. Then a critical slip surface of a predetermined or general shape is sought, for which the factor of safety is minimized. Generally, the problem of locating the critical deterministic surface associated with the minimum factor of safety \((FS)\) may be formulated as a constraint optimization problem as follows:

\[
FS_{\text{min}} = \min FS (Z, X)
\]

Subject to: \textit{some kinematical constraints} \hfill (1)

where \(Z\) is a set of input geotechnical parameters (mean-values of soil parameters) and \(X\) is a set of coordinates defining the shape and the location of the slip surface.

Another approach used in slope stability assessment is the probabilistic method. In deterministic methods, the factor of safety is derived by assuming that the variables involved in the calculations are represented with certainty by a single value. In probabilistic methods, the variability of the factors governing slope stability is taken into account in the design process, and the concept of probability of failure is employed. The results of the probabilistic analysis of the earth slope may be expressed as a probability of failure \((P_f)\) or reliability index \((\beta)\). The aim of the probabilistic method is the search for a critical probabilistic slip surface with the minimum reliability index \((\beta_{\text{min}})\) or maximum probability of failure. The problem of locating the critical probabilistic surface associated with the minimum reliability index is formulated as an optimization problem as follows:

\[
\beta_{\text{min}} = \min \beta (Z, X)
\]

where \(Z\) is a set of input geotechnical parameters (including the statistical properties) and \(X\) is a set of coordinates defining the shape and the location of the slip surface.

An optimization algorithm is a useful and powerful technique in both deterministic and probabilistic slope stability analysis. Generally, optimization algorithms can be divided into two basic classes: deterministic and heuristic algorithms. Deterministic methods, which are based on gradient information, include linear and nonlinear programming, dynamic programming, quadratic programming, mixed-integer programming, and interior-point methods. These methods are based on the gradient information of the objective function and constraints. However, the acquisition of gradient information can be costly or even altogether impossible to obtain. Another kind of optimization algorithm that is known as the heuristic method is not restricted in this manner. Heuristic approaches include several algorithms such as genetic algorithms, simulated annealing, Tabu search, ant colony optimization, and particle swarm optimization. The heuristic methods are derivative-free methods, which are applicable to any optimization problem regardless of the linearity or non-linearity of its objective function and constraints. Another main difference between the two classes is that heuristic methods use stochastic techniques and include randomness in moving from one solution to the next, but deterministic methods follow
deterministic transition rules, which, of course, gives an advantage to heuristic methods in avoiding local minima.

In the field of slope stability, an extensive number of studies have investigated the application of both deterministic and heuristic optimization techniques to solving slope stability problems. In this survey, a serious attempt is made to summarize and present a comprehensive analysis of various optimization algorithms applied to slope stability analysis, which have been proposed by researchers over the past several decades.

**OPTIMIZATION METHODS FOR DETERMINISTIC SLOPE STABILITY ANALYSIS**

This section reviews the studies that have applied different optimization techniques in the field of deterministic slope stability analysis and have also searched for the critical deterministic slip surface of an earth slope in order of publication date. Figure 1 statistically illustrates the number of the published research papers on the subject of the deterministic slope stability problem during the last 30 years.

![Figure 1: Number of papers published on the subject of the deterministic slope stability problem](image)

The application of optimization in slope stability problems was investigated first by Baker in 1980 (Baker, 1980). Baker (1980) introduced an effective approach that utilized the dynamic programming technique (Bellman, 1957) in slope stability computation. In this approach, Baker (1980) combined an optimization search using the dynamic programming technique with Spencer's method (Spencer, 1967) to locate the critical slip surface and calculate the associate factor of safety. The methodology introduced by Baker (1980) might be applied to slopes of any geometry, layering, pore pressure and external load distribution and could find a more critical slip surface with a lower factor of safety compared to previous methods.

Nguyen (1985) also applied the optimization technique to determine both the minimal factor of safety and the associated critical failure surface. The algorithm treats the factor of safety as an objective function of the N geometrical coordinated defining potential admissible failure surfaces and seeks for the optimum by a simplex reflection algorithm (in conjunction with the Omit equilibrium) (Spendley et al., 1962) through an N-dimensional space defined by these geometrical coordinates. Nguyen (1985) showed that the technique is suitable for virtually all
types of failure surfaces, and compared with the popularly known grid search method, this technique yields lower values of the minimal factor of safety with fewer computations.

In another study, Chen and Shao (1989) explored the feasibility of using optimization methods to search for the minimum factor of safety in slope stability analysis. Chen and Shao (1989) applied three types of the optimization algorithms including the simplex method (Nelder and Mead, 1965), steepest descent method, and Davidson-Fletcher-Powell (DFP) method in conjunction with the Morgenstern-Price method (Morgenstern and Price, 1965) to evaluation of safety factor of earth slopes. The results of a number of test problems and case history analyses supported the feasibility of their proposed methods.

The downhill simplex algorithm (Nelder and Mead, 1965) was applied to systematically locate the critical failure mechanism in slopes and to compute the minimum factor of safety by Bardet and Kapuskar (1989). The methodology proposed by Bardet and Kapuskar (1989) was verified with some numerical examples of circular and noncircular slope stability. Their results revealed that, although the simplex method may not be the fastest and most efficient technique of optimization, it is versatile, robust and simple and may be easily implemented in slope stability programs.

Jade and Shanker (1995) implemented the RST-2 algorithm for deterministic slope stability analysis. This algorithm is a kind of random search global optimization technique. As noted by Jade and Shanker (1995), there are several advantages of the RST-2 algorithm: (1) it attempts to determine the global rather than the local optimal solution, (2) it does not require any continuity and differentiability conditions of the functions appearing in the optimization problem (in this case, the objective function is a discontinuous function), (3) it does not require any initial guess of the slip surface to initiate the algorithm but requires an approximate lower and upper bound of the co-ordinates of the slip domain, and (4) it is easy to program and can be applicable to a wide variety of problems. Jade and Shanker (1995) used Janbu's method of slices (Janbu, 1973) for the determination of the factor of safety equation for a given slope using the co-ordinates of the slip surface. The model developed was successfully applied to three original case studies, and they concluded that the RST-2 algorithm is a very efficient, accurate and convenient algorithm for determining the critical failure surface and its corresponding minimum factor of safety.

Greco (1996) proposed a Monte Carlo method for locating critical slip surfaces of general shape in a slope-stability analysis. The Monte Carlo methods are techniques of random search that are very simple in structure. From a comparative analysis, Greco (1996) showed that the proposed method provides solutions of the same quality as the best nonlinear programming methods. However, the structure of the method is very simple, and it can be more easily programmed, integrated and modified for particular exigencies. The drawback of Greco’s strategy was that it provided a local minimum only. To increase the probability of finding a global minimum, Greco (1996) suggested restarting the iterative procedure from different trial slip surfaces and checking that the critical ones obtained are very similar.

In 1997, Kim and Lee (1997) proposed a technique to search for the critical slip surface and to define and calculate the factor of safety for the slope based on the finite element method. To calculate the factor of safety, Kim and Lee (1997) estimated the stresses at each Gaussian point from the finite element analysis. Then the global stress smoothing method was applied to obtain a continuous stress field. Based on this stress field, they evaluated the factor of safety for a specified slip surface by a stress integration scheme. Kim and Lee (1997) proposed a reasonable
optimization strategy on the basis of the Broyden–Fletcher–Goldfarb–Shanno (BFGS) method and the feasible direction method to obtain the critical surface. Their proposed search method for the critical surface could be applied to both the finite element method and the limit equilibrium method. The results obtained by their proposed method were in good agreement with the limit equilibrium solutions for homogenous slopes. In the actual embankment failure application, the location of the critical surface was in better agreement with the actual failure surface, although the failure height of embankment is underestimated.

In the other studies, Goh (1999; 2000) proposed the genetic algorithm methodology (Holland, 1975) for determining the critical slip surface for circular and multiple-wedge stability analysis, respectively. The examples presented by Goh (1999; 2000) demonstrated the effectiveness of the genetic algorithm approach. He found that the search strategy was sufficiently robust to handle layered soils with weak, thin layers and as efficient and accurate as the conventional pattern search method.

In 2001, Malkawi et al. (2001) presented a new search procedure based on the principle of the Monte Carlo method of the random walk type. Several practical examples of known minimum factors of safety and their associated slip surface were examined by Malkawi et al. (2001). The results demonstrated the efficiency and capability of the proposed methodology. In addition, the method produced accurate results of the safety factor and predicted the failure mechanisms. All slip surfaces generated were kinematically admissible.

A simple genetic algorithm (SGA) (Holland, 1975) was applied to the search for the minimum factor of safety in slope stability analysis by (McCombie and Wilkinson, 2002). McCombie and Wilkinson (2002) implemented a simplified Bishop’s method (Bishop, 1955) to the analysis of circular failure surfaces of slopes. The results showed that the SGA can be used to find the slip surface with the lowest factor of safety and can be expected to perform better than either a ‘brute force’ approach or a ‘Monte Carlo’ approach.

Bolton et al. (2003) described the use of a global optimization algorithm in conjunction with Janbu's simplified method (Janbu, 1973) and Spencer's method (Spencer, 1967) to determine the critical failure surface in slope stability analyses. As mentioned by Bolton et al. (2003), an important feature of the new method was that no assumptions were required with regard to the geometry of the failure surface and no restrictions were placed on the positions of the initiation and termination points. As a result, the solution was completely general.

The application of simulated annealing (Kirkpatrick et al., 1983) for slope stability problems investigated by Cheng (2003). Cheng (2003) showed that, although the search for a critical failure surface of a general soil slope is difficult because the objective function of the factor of safety is non-convex and multiple minima exist in general, simulated annealing is effective and efficient in the analysis. The critical failure surface can then be located with high precision with reasonable computation time with his proposed method. Furthermore, the author also proposed a double QR factorization method in the evaluation of the factor of safety. The advantage of this method was that the factor of safety and internal forces with respect to force equilibrium are obtained directly without any iteration analysis. This method requires more computation compared with the classical iteration analysis but possesses the advantage of reducing failure to converge situations. By combining all of the proposed techniques, as suggested by Cheng (2003), the analysis of the slope stability problem can be automated and evaluated easily.

In 2003, the applicability of the dynamic programming method to two-dimensional slope stability analyses was studied by Pham and Fredlund (2003). The only assumption regarding the
shape of the critical slip surface is that the surface is an assemblage of linear segments. They used finite element stress analysis to evaluate the stresses acting along the critical slip surface. The method proposed by Pham and Fredlund (2003) does not require assumptions associated with the limit equilibrium methods of slices related to the shape of the critical slip surface and the relationship between the slices. They developed a computer program named DYNPROG and analyzed numerous example problems. The results obtained using DYNPROG were compared with those obtained using several well-known limit equilibrium methods. The comparisons demonstrated that the factors of safety computed using the dynamic programming method are generally slightly lower than those computed using conventional limit equilibrium methods of slices. Moreover, their results showed that, as Poisson’s ratio approaches 0.5, the computed factors of safety from the dynamic programming method and the limit equilibrium method become similar.

A simple genetic algorithm (Holland, 1975) was presented to search the critical non-circular failure surface in slope stability analysis by Zolfaghari et al. (2005). The pseudo-static horizontal and vertical forces due to earthquakes and surcharge loads due to existing buildings and structures on natural slopes are included in their analysis. For the non-circular slope stability analysis with pseudo-static horizontal and vertical forces due to earthquake loading, Zolfaghari et al. (2005) applied a simple computation format of the Morgenstern and Price method (Morgenstern and Price, 1965). Important features of their study were that no assumptions were required with regard to the geometry of the failure surface and no restrictions were placed on the positions of the initiation and termination points of the failure surface. The simple genetic algorithm method presented can be applied to find the non-circular failure surface with the lowest factor of safety very quickly compared to random or simplex method approaches.

In the upper bound approach to limit analysis of slope stability based on the rigid finite element method, Chen et al. (2005) formulated the search for the minimum factor of safety as a non-linear programming problem with equality constraints based only on a yield criterion, a flow rule, boundary conditions and an energy-work balance equation. Chen et al. (2005) employed a non-linear mathematical programming algorithm because of the non-linear properties of the resulting optimization problems. Moreover, the relationships between the numbers of nodes, elements, interfaces, and subsequent unknowns and constraints in this approach were investigated in their research. The results showed that, in large-scale problems, the unknowns are subject to a highly sparse set of equality constraints. Because of the existence of non-linear equalities in the approach, Chen et al. (2005) applied a special sequential quadratic programming (SQP) algorithm, feasible SQP (FSQP), to obtain solutions for such non-linear optimization problems. In the FSQP algorithm, the non-linear equality constraints are turned into inequality constraints, and the objective function is replaced by an exact penalty function that penalizes only non-linear equality constraint violations.

Wan et al. (2005) proposed an improved genetic algorithm for the calculation of the integral stability of a slope based on the slice method of the non-circular slip surface, which can freely search for the most dangerous slip surface of the slope and the corresponding minimum safety factor for the general shape of the most dangerous slip surface. The improved genetic algorithm suggested by Wan et al. (2005) is capable of simulating the genetic evolution process of organisms and avoiding the local minimum value compared with the classical methods. The results of their study showed that it is a global optimal algorithm and has many advantages, such as higher efficiency and shorter time, than the simple genetic algorithm for slope stability analysis.
Cheng et al. (2007c) proposed a modified particle swarm optimization method together with a simple termination criterion for the solution of slope stability problems. Through modification, a pre-determined number of trials are not required, and the refinement of the search depends on the tolerance of the search as specified by the engineer. As mentioned by Cheng et al. (2007c), although their modification to the original PSO method was not major, the advantages of their algorithm were clearly illustrated by the numerical examples. Through the examples, Cheng et al. (2007c) demonstrated that the original and modified PSO methods are stable in complicated slope stability problems and that the results using these methods are also satisfactory. To demonstrate that the global minimum was obtained with PSO or MPSO, the pattern search used by Cheng (2003) was adopted, and the results showed that the global minimum obtained with the pattern search was virtually the same as the results of PSO/MPSO for every example in their study.

The application of six heuristic optimization algorithms was investigated by Cheng et al. (2007b). These heuristic methods included simulated annealing (Kirkpatrick et al., 1983), the genetic algorithm (Holland, 1975), particle swarm optimization (Kennedy and Eberhart, 1995), harmony search (Geem et al., 2001), Tabu search (Glover, 1989; Glover, 1990) and the ant colony algorithm (Dorigo, 1992). These methods were implemented for some simple and complicated slope stability problems. From the results, Cheng et al. (2007b) concluded the following points. First, no single method could outperform all of the other methods in all cases because different methods had different behaviors in different types of problems. Second, for normal cases, the particle swarm method appeared to be effective and efficient in various conditions, and this method was recommended for general use. Third, for special cases where the objective function was highly discontinuous, the simulated annealing method appeared to be a more stable solution.

In another study, Cheng (2007) proposed the new version of simulated annealing (Kirkpatrick et al., 1983) for slope stability analysis. In his method, the control variables were controlled within dynamic domains instead of the conventional static domains. Cheng (2007) also proposed a simple transformation technique for slopes with a soft band domain (equivalent to a Dirac function). With these improvements, the minimum factor of safety for complicated problems might be determined with high accuracy and reasonable computation time, and his proposed algorithm was demonstrated to be efficient and effective for various difficult problems.

To overcome the problem of being trapped by the local minima encountered when applying the simple genetic algorithm (Holland, 1975) to search for the critical slip surface of the slope, Li et al. (2008) proposed an improved procedure based on the harmony search algorithm (Geem et al., 2001). In the searching computation, the new solutions are obtained from all of the information of the current generation. Their proposed method was applied to calculate the minimum factors of safety of two complicated soil slopes. Comparison of the results showed that the method proposed by Li et al. (2008) is feasible for the stability analysis of soil slopes.

The stability of a soil slope is usually analyzed by limit equilibrium methods, in which the slip surfaces are defined by a series of straight lines. Sun et al. (2008) used spline curves in conjunction with a genetic algorithm (Holland, 1975) to search for the critical slip surface, and Spencer’s method of slices (Spencer, 1967) was employed to calculate the factor of safety. Three examples were presented to illustrate the reliability and efficiency of the method. Sun et al. (2008) compared the slip surfaces defined by a series of straight lines with those defined by spline curves, and their results indicated that the use of spline curves renders better results for a given number of slip surface nodal points compared to the approximation using straight line segments.
An improved harmony search algorithm was proposed by Cheng et al. (2008a), which was found to be more efficient than the original harmony search algorithm (Geem et al., 2001) for slope stability analysis. The effectiveness of their proposed algorithm was examined by considering several published cases. Cheng et al. (2008a) applied the improved harmony search method to slope stability problems with five types of procedures for generating trial slip surfaces. Finally, they concluded that the improved harmony search algorithm was efficient and effective for the minimization of factors of safety for various difficult problems and that the method for generating the trial failure surfaces might be important in the minimization process.

In another study, Cheng et al. (2008b) developed an effective method for normal problems based on the artificial fish swarm algorithm (Li et al., 2002). Cheng et al. (2008b) adopted the artificial fish swarm algorithm coupled with the slip surface generation method by Cheng et al. (2007a) to search for the minimum factor of safety of earth slopes. Based on extensive trial tests on normal problems, Cheng et al. (2008b) found that the method is highly effective and insensitive to the optimization parameters and can be applied to general slope stability analysis.

Kahatadeniya et al. (2009) developed an ant colony optimization algorithm (ACO) (Dorigo, 1992) to solve the factor of safety minimization problem. The factors of safety of slip surfaces were found using the Morgenstern and Price method (Morgenstern and Price, 1965), which satisfies both force and moment equilibrium, and the slip surface is represented as a piecewise-linear curve. Kahatadeniya et al. (2009) solved the nonlinear equations of the Morgenstern–Price method numerically by the Newton–Raphson method. In the proposed ACO algorithm, the initiation point and the shape of the slip surface are treated as the search variables. Kahatadeniya et al. (2009) compared the results of the ACO, which is a global search algorithm, with some local search algorithms (DFP, BFGS, Powell, simplex and pattern search) and some global search methods (Monte-Carlo, fish swarm and genetic algorithm). The results obtained showed that the global search algorithms always performed much better than the local search ones. In general, there is a higher chance for local search algorithms than global search algorithms to be trapped in local optimum points. Furthermore, the ACO technique is one of the best methods for slope stability analysis.

Li et al. (2009b) found that the harmony search algorithm is sensitive to the parameters used in the algorithm. Although there was no theoretical method for the determination of the values of the parameters used, Li et al. (2009b) proposed a dynamic procedure for the values of parameters and a new substitution method in the original harmony search algorithm. They applied their suggested method to slope stability problems. The improvement was demonstrated to be efficient for the location of critical slip surfaces of soil slopes through the case studies.

As mentioned by Sengupta and Upadhyay (2009), locating the critical failure surface of a soil slope can be erroneous and cumbersome due to the existence of local minima points, especially in the case of large soil slopes. Therefore, Sengupta and Upadhyay (2009) proposed a genetic algorithm (Holland, 1975) to locate the critical surface under general conditions with general constraints. The method used in their study was based on Bishop’s method of slices (Bishop, 1955) for the circular slip surface of a soil slope. They compared the results obtained by the genetic algorithm with the results of the Monte-Carlo method and the grid-points approach and found that the genetic algorithm is computationally superior.

In another study, Li et al. (2009a) proposed a mixed search procedure based on the particle swarm optimization (Kennedy and Eberhart, 1995) and harmony search algorithm (Geem et al.,
They applied the mixed search in the determination of the minimum factor of safety of soil slopes. The comparison the results provided by the mixed procedure along with the results of the harmony search algorithm and particle swarm optimization demonstrated the efficiency of the mixed method.

A new version of particle swarm optimization (PSO) called discontinuous flying particle swarm optimization (DFPSO) was proposed by Li et al. (2010a). In the new method, not all of the particles refresh their positions and velocities during each iteration step, and the probability of each particle refreshing its position and velocity is dependent on its objective function value. Li et al. (2010a) applied the DFPSO to find the minimum safety factor of earth slopes and concluded that the results obtained by DFPSO had an average difference of 6% compared with those by PSO, whereas DFPSO requires much fewer evaluations of the objective function than PSO.

A real-coded genetic algorithm was employed by Li et al. (2010b) to develop a search approach for locating the noncircular critical slip surface in slope stability analyses. In the method proposed by Li et al. (2010b), limit equilibrium methods and the finite-element-based method are incorporated with the proposed search approach to calculate the factor of safety. Geometrical and kinematical compatibility constraints are established based on the features of slope problems to prevent slip surfaces from being unreasonable. The results demonstrated the successful application of a real-coded genetic algorithm to noncircular critical slip surface search problems.

**OPTIMIZATION METHODS FOR PROBABILISTIC SLOPE STABILITY ANALYSIS**

This section lists recent publications in the area of probabilistic slope stability analysis that implement a different optimization algorithm to evaluate the minimum reliability index and locate the critical probabilistic slip surface of an earth slope. Figure 2 statistically presents the number of the published research papers on the subject of the probabilistic slope stability problem during the last 20 years.

![Figure 2: Number of papers published on the subject of the probabilistic slope stability problem](image)

reliability index as the first order reliability method (FORM) via constrained optimization. The optimization method used by Low and Tang (1997) was the generalized reduced gradient algorithm, which is one of the most robust nonlinear programming methods to solve optimization problems. Despite the fact that the factor of safety expressions and the performance function are not explicit, Low and Tang (1997) automated a search for the critical deterministic slip surface and the critical probabilistic slip in their proposed method.

In another paper, Low and Tang (1997) proposed a same methodology for the reliability assessment of embankments on soft ground. In this study, they used Spencer’s method of slices (Spencer, 1967) to evaluate the factor of safety and performance function. As mentioned by Low and Tang (1997), the advantages of the new method were simplicity, transparency, versatility, accuracy, and the ease of implementing stochastic reliability analysis in the ubiquitous spreadsheet platform, notwithstanding the implicit and iterative nature of the limit state functions.

Bhattacharya et al. (2003) presented an optimization based search algorithm for locating the critical probabilistic surface of the minimum reliability index for earth slopes. Their procedure uses a formulation similar to that used to search for the surface of the minimum factor of safety in conventional slope stability analysis. Bhattacharya et al. (2003) developed a computer program based on Spencer’s method of analysis (Spencer, 1967) for deterministic slope stability and extended the program with an efficient Monte-Carlo technique (Greco, 1996) for probabilistic slope stability analysis. Their proposed algorithm does not make any a priori assumptions regarding the shape of the slip surface. The advantage of the formulation lies in enabling a direct search for the critical probabilistic surface by utilizing an existing deterministic slope stability algorithm with the addition of a simple module for the calculation of the reliability index. Applications to several cases verified the success of the procedure.

The application of the genetic algorithm (Holland, 1975) for reliability-based slope stability analysis was proposed by Xue and Gavin (2007). In their study, the soil properties were considered to be random variables, and the factor of safety was found using Bishop’s simplified method for noncircular slip surfaces to evaluate the limit state function. By considering the variability of the soil properties, Xue and Gavin (2007) determined the probability of failure from the reliability index. To overcome the complexities associated with defining the limit state function, Xue and Gavin (2007) transformed the variables, such as the soil strength parameters, into polar coordinates. In their study, the determination of the reliability index and associated slip surface was solved by utilizing a powerful and efficient genetic algorithm environment. The results indicated that the new approach provides reasonable and consistent estimates of the reliability index and critical slip surface.

Cho (2007) proposed a numerical procedure for a probabilistic slope stability analysis based on a Monte Carlo simulation that considers the spatial variability of the soil properties. The approach adopts the first-order reliability method to determine the critical failure surface and to conduct preliminary sensitivity analyses. Cho (2007) formulated the factor of safety using Spencer's limit equilibrium method to evaluate the performance function and calculate the reliability index. The problem of locating the critical surface is formulated as a constrained optimization problem, and the feasible direction method is used to solve the problem. As examples, Cho (2007) formulated the probabilistic stability assessments to study the effects of uncertainty due to the variability of soil properties on the slope stability in layered slopes. The examples provided insight into the application of uncertainty treatment to the slope stability and
showed the importance of the spatial variability of soil properties with regard to the outcome of a probabilistic assessment.

Hong and Roh (2008) considered the first order reliability method for estimating the probability of failure or reliability index of earth slopes. The system aspect of the slope in the reliability analysis is handled by defining a limit state of the system as a function of the minimum of the ratio of the shear strength to the mobilized shear strength for each potential slip surface. Hong and Roh (2008) evaluated ratios for a given slip surface using the extended generalized method of slices given by Chen and Morgenstern (1983), which is an extension of the well-accepted Morgenstern and Price method (Morgenstern and Price, 1965). In their study, the sequential quadratic programming (SQP) method presented by Schittkowski (1986) was implemented to compute the minimum factor of safety, reliability index and associated critical deterministic and probabilistic slip surfaces. The numerical results suggested that the reliability of a slope might be sensitive to the assumed or adopted probability distribution types for the input parameters. Moreover, the results suggested that a decrease in the positive spatial correlation of soil properties leads to a decrease in the probability of failure.

Recently, the authors (Khajehzadeh et al., 2010a; Khajehzadeh et al., 2010b) applied the harmony search algorithm (Geem et al., 2001) and particle swarm optimization (Kennedy and Eberhart, 1995) to calculate the minimum reliability index and corresponding critical probabilistic slip surface of earth slopes. In their studies, the performance function formulated by Spencer’s method (Spencer, 1967) of slices for general shape of slip surface and the reliability index defined by Hasofer and Lind (1974) was employed to estimate the reliability index. Khajehzadeh et al. (2010a; 2010b) demonstrated the effectiveness and robustness of their proposed algorithm by considering a number of published cases, and the results showed that both HS and PSO algorithms may successfully be applied for probabilistic slope stability analysis. Moreover, the obtained results showed that the searched critical probabilistic surfaces have different locations than the critical deterministic surface, especially for layered soil.

Gavin and Xue (2010) proposed a hybrid method of assessing the stability of unsaturated soil slopes. The method utilized the benefits of the rational treatment of the variability of input parameters provided by reliability-based design and the simplicity afforded by deterministic approaches. As noted by Fourie et al. (1999), in most slope failures caused by infiltration, the failure plane forms parallel to the existing slope surface. Therefore, Gavin and Xue (2010) considered an infinite slope model to formulate the factor of safety and the performance function. They considered the soil properties as random variables, transferred them to polar coordinates and applied the genetic algorithm to calculate the Hasofer and Lind reliability index. Gavin and Xue (2010) presented the results in design charts from which a designer could choose the safety factor value required to ensure a given target reliability index for a slope.

CONCLUSIONS

This paper attempted to present a bibliographical survey and a list of published references on the application of different optimization techniques used to solve the earth slope stability problem. As shown in this review, in deterministic analysis, the optimization methods may be applied to automate the search for the minimum factor of safety and associated critical failure surface. However, in probabilistic analysis, optimization algorithms could be applied to search for the minimum reliability index and the critical probabilistic failure surface. The survey of previous studies indicated the successful application of optimization to the solution of slope stability problems. Moreover, it showed that the heuristic methods are capable of finding better results.
compared with gradient based methods because of the complexity of the objective function in slope stability analysis. Considerable research has been performed on the application of different optimization algorithms to the deterministic analysis of slopes, but a few studies have been done on the probabilistic aspects. The application of heuristic methods in this area is recommended as future work.

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