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Seismic stability and displacement analyses of earth slopes using non-circular slip surface

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Abstract

The seismic stability and deformability of earth slopes are conventionally evaluated by simple, practical methods. Because a multimodal function optimization problem makes it mathematically difficult to search large critical slip surface of earth slopes with complex strata, stability analysis is one of the classical problems of geotechnical engineering. One option is to evaluate the seismic deformability of earth slopes using permanent seismic displacements via Newmark's sliding block analysis in the current seismic design. The advantage of this method is that it is useful in practice and is less time consuming in terms of calculations. However, the calculations require that the critical slip is assumed either linear or circular. This paper proposes two methods for computing safety factors and permanent seismic displacements of earth slopes using an efficient non-circular slip surface search algorithm based on the force equilibrium given by the Spencer method. The validity of these proposed methods is verified by applying them to models with a known safety factor or theoretically calculated permanent seismic displacement and the results obtained compared. Comparative analyses are also conducted in order to demonstrate their efficacy in terms of computation precision and convergence performance. Further, they are utilized to calculate the permanent seismic displacement of a practical earth slope model subjected to seismic motions in both the horizontal and vertical directions. The results obtained indicate that they can calculate the safety factor of earth slopes using a smaller number of simulations than conventional methods and that they can also be applied to calculate the permanent seismic displacement of earth slopes. The results also indicate that the permanent seismic displacement calculated is an important index that can be used to quantitatively evaluate the seismic performance of earth slopes.

IGS: E- 6; E- 8; G- 6; G- 8

Keywords: Slope; Stability analysis; Displacement analysis; Permanent seismic displacement

1. Introduction

In recent years, a number of powerful earthquakes have occurred in various regions in Japan, resulting in severe damage to many embankments and earth slopes. This damage typically involves the burying of private houses and the closure of roads and railways. For example, Koseki et al. (2012) reported several case histories including the collapse of a high cut slope due to the 2011 off the Pacific Coast of Tohoku Earthquake in Japan. Hyodo et al. (2012) reported five slope failures which occurred in a residential area on artificial valley fills due to the same earthquake. Embankments and earth slopes with low seismic stability need be evaluated appropriately, either by field investigation or numerical analysis, to

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reduce such damage to embankments and earth slopes. To comprehensively evaluate the seismic stability of embankments, it is important to consider the construction records and factors such as ground and environmental conditions, in addition to simple field investigations, including cone penetration tests, a practical stability analysis and displacement analysis. Since no simple field investigation method has yet to be established for the seismic stability evaluation of earth slopes, practical stability and displacement analyses are essential.

Methods for evaluating the seismic stability of an earth slope using a safety factor calculated from the ratio of the sliding force and the resistive force of soil mass that follow along the slip surface in a limit equilibrium state are generally known as stability analysis methods. Stability analysis methods can be classified according to the approach they use to search the slip surface and calculate the safety factor. Methods that assume the slip surfaces are circular include the Fellenius and Bishop methods (Fellenius, 1936; Bishop, 1954). These classical methods calculate a safety factor that satisfies the force equilibrium equation under simple assumptions. They are widely used in actual practice because they are considered to generate no major errors in comparison to the exact solutions, and the safety factors that they provide are usually almost the same or slightly smaller.

There are also methods that assume that the slip surfaces are non-circular, such as the Janbu method (Janbu, 1955), the Morgenstern – Price method (Morgenstern and Price, 1965), and the Spencer method (Spencer, 1967, 1973). The Janbu method is mechanically hyperstatic (Sarma and Bhave, 1979). The Morgenstern – Price method and the Spencer method determine the safety factor by satisfying both the force and the moment equilibrium equations by considering the forces in between slices and hence, can be considered exact methods. The similarities of the Morgenstern – Price method and the Spencer method are discussed in detail by Kondo and Hayashi (1997). Although the Morgenstern – Price method is considered to be more general than the Spencer method, the computation processes of both these methods use the same equilibrium condition equations; therefore, the simpler Spencer method is more appropriate for practical applications.

Methods that calculate the permanent seismic displacement of slopes subjected to a strong ground motion using a displacement that integrates the equation of rotational motion of a soil mass contained within the critical circular slip surface are generally known as Newmark's sliding block analysis methods (Newmark, 1965). Newmark's sliding block analysis is a simplified procedure, employed in the design code of railway, road, and dam structures in Japan (RTRI, 2000; JRA, 2010; MLIT, 2005), in which the critical circular slip surface is determined using a conventional stability analysis. Newmark's sliding block analysis requires unit weight, friction angle, and soil cohesion values. The method is useful practically and less time consuming, in terms of calculations, than other methods. Newmark's sliding block analysis will be hereafter referred to as Newmark analysis.

When conducting the seismic stability analysis or Newmark analysis, as mentioned above, the slip surface must be determined. In searching for a conventional circular slip surface, the only parameters required are the arc center and the radius, which enables the easy determination of the slip surfaces. To evaluate the stability or deformability of earth slopes composed of homogenous foundation material, a seismic stability analysis or Newmark analysis using the circular slip surface is highly practical, but in evaluating the seismic stability or deformability of natural slopes that have complex strata with weak layers, the safety factors or permanent seismic displacement obtained by these methods are not always the smallest safety factors or the largest permanent seismic displacements.

On the other hand, for non-circular slip surfaces, the seismic stability or Newmark analysis methods require the setting of constraint conditions and a search for slip surfaces with a minimum safety factor or maximum permanent seismic displacement. However, while a stability analysis or Newmark analysis with non-circular slip surface can obtain reasonable slip surfaces even for natural slopes with complex strata, there are issues in relation to the complexity of its computation algorithm and the high computation cost required to obtain appropriate solutions. These problems arise because of the need to solve a multimodal function with slip surface coordinates as variables when searching the non-circular slip surface of natural slopes, resulting in the optimization of a multimodal function that satisfies the goal of a minimum safety factor.

On the basis of the above background, various optimization methods have been proposed. Early examples include the conjugate gradient method (Yamagami and Ueta, 1988), the pattern search method (Greco, 1996), and the Monte Carlo method (Greco, 1996). These methods can easily converge on local solutions depending on the initial value settings and, in some cases, may not be able to provide an appropriate optimum solution. A genetic algorithm (GA) is a typical example of a method that includes a process for searching for the optimum solution while converging on local solutions. This method has frequently been applied (Goh, 1999). Cheng et al. (2007a) applied simulated annealing, GA, particle swarm optimization (PSO), a simple harmony search, a modified harmony search, and a Tabu search to various slope models. They found that PSO had the highest practical applicability. However, although PSO is easy to implement and robust in performance, it tends to be computationally expensive for high strata earth slopes. Consequently, Shinoda (2013a) proposed an efficient PSO-based critical slip surface search algorithm with high computational precision and convergence performance.

Considering stability analysis in the presence of plain failure and circular failure, many studies have used Newmark analysis to estimate the earthquake-induced slope displacement. Currently, it is well known that Newmark analysis can be used to estimate practical slope displacement, as confirmed by Goodman and Seed (1966) and Wartman et al. (2003, 2005) in laboratory model tests, and Wilson and Keefer (1983) and Pradel et al. (2005) in analyses of earthquake-induced landslides in natural slopes. Yan et al. (1996) proposed a modified Newmark analysis method for a rigid block on an inclined plane, which incorporated the vertical component of the