

Lecture Notes in Civil Engineering

Lakshman Nandagiri  
M. C. Narasimhan  
Shriram Marathe  
S. V. Dinesh *Editors*

# Sustainability Trends and Challenges in Civil Engineering

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Editors

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# Preface

N.M.A.M. Institute of Technology, Nitte, Karnataka, India, organized the International Conference on Emerging Trends in Engineering (ICETE 2020) on 22 and 23 December 2020, which is the 10th international conference being organized since 2011. From the year 2019, in an effort to focus on the specific issues associated with various engineering disciplines, the idea of a multi-conference platform has been mooted.

ICETE 2020—a multi-conference platform—was a collection of several international conferences with the themes specific to various engineering streams. Besides, there was an opportunity for the students and research scholars of various branches of engineering and technology, and industrial professionals to present and discuss research papers.

Civil Engineering Trends and Challenges for Sustainability (CTCS 2020) was organized by the Department of Civil Engineering, N.M.A.M. Institute of Technology, Nitte, under the umbrella of ICETE 2020. CTCS 2020 was a platform for the exchange of knowledge from both individual and interdisciplinary researchers pertaining to Civil Engineering Challenges and Sustainability. This international conference aimed to bring together the researchers, scientists, engineers, scholars and students in an international forum for the dissemination of original research results in the domain areas of Civil Engineering.

This proceedings volume contains the full-length research papers, experience reports and empirical study plans. All of these submissions went through a rigorous peer-review process commensurate with their track. In all, 175 research papers were submitted, with each of them being reviewed by a minimum of two experts. Upon peer review, 90 papers were accepted for presentation in the conference. Presentations were reviewed and ranked by the track chairs and discussed with the industry

and practice chairs in order to ensure suitable theme sessions were available. Subsequently, after quality and plagiarism checks, 68 papers were accepted (an acceptance rate of 39%) for the publication in the Lecture Notes in Civil Engineering (Springer).

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# Stability Analysis of Embankments on Soft Consolidating Layered Foundation Soil



P. Radhika Bhandary, A. Krishnamoorthy, and Asha U. Rao

**Abstract** Embankments are being constructed for highways, railways and abutments. Sometimes the foundation soil encountered is soft consolidating soil and can cause settlements due to embankment construction. The method of combining the method of finite elements and the genetic algorithm to evaluate the safety factor of the embankment built on a soft consolidating layered soil is discussed in this paper. The foundation soil has two layers with soil properties weaker than the embankment soil. Two numerical examples are considered for the analysis. In the finite element system, the soil is modeled using the Mohr–Coulomb nonlinear model and the least safety factor is calculated at different time intervals after construction until the consolidation process is completed using the genetic algorithm. The safety factor variant from the study helps to know when the embankment is suitable and safe to use.

**Keywords** Factor of safety · Consolidation · Embankment · Soft soil

## 1 Introduction

The stability of embankment is defined by the critical slip surface and the corresponding safety factor. The embankment can be evaluated using the two techniques, namely the method of limiting equilibrium and the method of finite elements. The finite element method has been used to analyze the embankment stability to find realistic stresses when compared to simplified techniques. In this process, non-homogeneous soil properties and nonlinear conditions of stress are easy to implement.

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The embankment stability depends on the time needed for the complete dissipation of pore pressure when built on soft soils. In the stability analysis of these embankments, consolidation plays an important role. The critical slip surface and the corresponding safety factor define the stability of the embankment. Compared to simplified techniques, the finite element method is used to analyze the stabilization of the embankment to find realistic stresses. The enforcement of non-homogeneous soil properties and nonlinear conditions of stress is simple in this method. During consolidation, the effective stresses change due to dissipation of pore pressure and deformation. This process can be implemented in finite element method by coupling the pore pressure and deformation in soil using the theory proposed by Zienkiewicz [1]. The finite element method has been used to find embankments deformation and behavior has been analyzed and compared to the field measurements [2–4]. As a large number of possible sliding surfaces must be taken into account to determine the critical slip surface, the stability analysis of the embankment is an optimization problem. Compared to the various optimization techniques for finding the global minimum, the genetic algorithm has been found to be more effective in defining the optimum solution for several complex problems [5]. Genetic algorithms can also deliver outcomes more efficiently and can be used to evaluate geotechnical issues involving failures and more decision variables [6]. In the proposed approach the embankment stability study is carried out in terms of safety factor from the construction completion to the end of consolidation. The realistic stresses from the finite element method are obtained for different time intervals and the safety factor is determined by the genetic algorithm. The soil behavior is modified to nonlinear, by adopting the elastic-perfectly plastic satisfying Mohr–Coulomb yield criteria considering the associated flow rule. The present study demonstrates the competence of the finite element to calculate realistic stresses and the combination approach with genetic algorithm in order to find critical slip surface when the foundation soil consolidates softly and has two layers.

## 2 Methodology

### 2.1 Steps in Analysis

There are mainly two steps in analysis:

- (1) Using finite element procedure for stress determination considering nonlinear soil behavior.
- (2) Using the genetic algorithm to define the critical slip surface and the required safety factor.

The discretization is done in order to find the stresses that are realistic using four noded isoparametric plane strain elements with two translational degrees of freedom at each node. The finite element method to obtain stresses at various time intervals developed by Krishnamoorthy and Sanjay [7] is used in the proposed method

with modifications in nonlinear model. The soil behavior, taking into account the associated flow law, is modeled as the elastic-perfectly plastic satisfying Mohr–Coulomb yield criteria. In the finite element process, the staged construction of the embankment and the formulation of the time-dependent material behavior are applied.

## 2.2 Finite Element Method for Stress Determination

The finite element approach is still the most commonly used and potentially the most robust technique in geotechnical engineering. Nonlinear material behavior that can be implemented to analyze the entire structure are the key advantages of using Finite element analysis.

In this technique, even the staged embankment construction and the construction sequences can be easily modeled. In this method, the time-dependent material behavior can also be implemented. Finite element method has been widely used for analysis of consolidating soil for deformation and dissipation of pore pressure.

In the consolidating soil, the displacement  $u$  and excess pore pressure  $p$  have been implemented in the finite element method by relating them to the displacement vector  $\{u\}$  and the pore pressure vector  $\{p\}$  at nodal points using shape functions which defines the displacement and pore pressure distribution of the soil element [7]. Eq. 1 gives the relation between the pore pressure and displacement with the pore pressure vector and displacement vector at each node.

$$p = [Nf]\{p\} \text{ and } u = [Ns]\{u\} \quad (1)$$

$Ns$  is shape function that defines the displacement and  $Nf$  is shape function defining the pore pressure distribution of the soil element.

The coupled consolidation equation suggested in matrix form by Zienkiewicz [1] is given in Eq. 2, which is used to combine the displacement and pore pressure.

$$\begin{bmatrix} k_s & L \\ 0 & H \end{bmatrix} \begin{Bmatrix} u \\ p \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ L^T & 0 \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{p} \end{Bmatrix} = \begin{Bmatrix} f \\ 0 \end{Bmatrix} \quad (2)$$

where  $k_s$  is the matrix of soil stiffness,  $H$  is fluid conductivity matrix,  $f$  is the load vector for externally applied load and the coupling matrix is  $L$ .

The incremental form is given in Eq. 3 to apply the incremental loads so that the staged construction is incorporated in finite element method.

$$\begin{bmatrix} k_s & L \\ 0 & H \end{bmatrix} \begin{Bmatrix} \Delta u \\ \Delta p \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ L^T & 0 \end{bmatrix} \begin{Bmatrix} \dot{\Delta u} \\ \dot{\Delta p} \end{Bmatrix} = \begin{Bmatrix} \Delta f \\ 0 \end{Bmatrix} \quad (3)$$

where  $\Delta u$  is the changes in displacement and  $\Delta p$  is excess pore pressure which changes for load increment of  $\Delta f$ .

Using the elastic-perfectly plastic Mohr–Coulomb model, the nonlinear soil behavior is modeled. To model the behavior of the soil, this model requires only two basic parameters, namely cohesion and the angle of internal friction. The stresses are achieved from the completion of the construction of the embankment to the end of the foundation soil consolidation over different time intervals.

### 2.3 Genetic Algorithm

In order to find the safety factor of the slip surfaces created by the genetic algorithm, the stresses obtained from the finite element method are used. John Holland developed Genetic Algorithms in 1975 to study self adaptivity in natural system processes. The genetic algorithm imitates the principles of biological evolution in order to solve optimization problems. Search algorithms are genetic algorithms that emphasizes on mechanisms of natural selection process and natural genetics [5]. Genetic algorithms are perfect for solving complex problems with optimization and are thus suitable for applications requiring techniques for adaptive problem-solving.

A chromosome is known as a solution generated by a genetic algorithm, whereas a population is known as a chromosome array. A chromosome is composed of genes and, depending on the problem, the value of the chromosome may be either symbols, numerical, binary or characters. To evaluate the suitability of solving the problem generated by genetic algorithms, these chromosomes will be subjected to a process called fitness function. By a mechanism called crossover, some population chromosomes can match, thereby producing new chromosomes which are known as offspring. Their gene composition is the combination of their parent's genes. Some of the chromosomes can even undergo mutations in their genes within a generation. The value of the crossover rate and mutation rate governs the number of chromosomes undergoing crossover and mutation. Chromosomes in the population to be preserved for the next generation will be chosen on the basis of Darwinian theory of evolution, and in the next generation, the chromosome with a higher fitness value will be more likely to be selected again. The chromosome value should converge to a certain value after many generations, which is the best solution to the problem.

The problem of slope stability is formulated as a constrained minimization problem to evaluate the critical slip surface and its lowest safety factor. The critical slip surface profile is created as part of the minimization process and is not predefined. The present study uses a computer program implementing genetic algorithms for optimization developed by Deb [8]. The objective function is coded in this program to locate the critical slip surface for the present analysis. The parameters of the genetic algorithm taken for the analysis are: population size 12–20, generation number 2000, 0.4–0.9 crossover rate, and 0.001–0.01 mutation rate. The safety factor is the objective function that needs to be decreased in the stability analysis of the embankment, and the slip surface shape represents the design variables.

## 2.4 Factor of Safety

The stresses obtained from the finite element method and the slip surface produced by the genetic algorithm are used for the determination of the safety factor. The safety factor is the ratio of the shear strength to the shear stresses developed along the considered slip surface. For each of the slip surfaces generated by genetic algorithms, the factor of safety is determined. The slip surface created is divided into 'n' number of segments with increasing length  $\Delta L$  to determine safety factor. Then the aggregate safety factor is determined using the following equation.

$$\text{Safety factor} = \frac{\sum \tau_f \Delta L_i}{\sum \tau_i \Delta L_i}$$

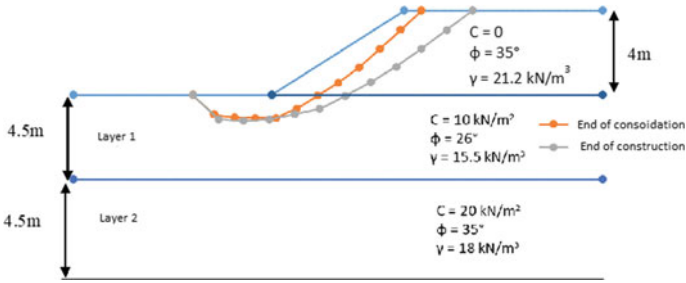
where  $\tau_i$ —shear stress that is mobilized and  $\tau_f$ —shear strength of material.  $\Delta L_i$ —ith segment length.

## 3 Numerical Examples

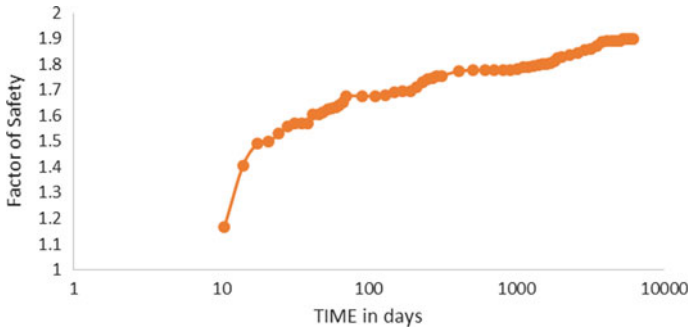
When the embankment is constructed on consolidating soil, the effective stresses change with the time. The excess pore pressure dissipates and the soil deforms thus causing a change in the slope geometry. In the present analysis, for two numerical cases, the minimum safety factor for the embankment on consolidating soil is found for different time periods from completion of construction to the end of consolidation. For various time periods, the safety factor is determined from 10 to 6200 days. The numerical examples considered are embankments constructed on foundation soil with two layers.

### 3.1 Example 1

The embankment details of example 1 is shown in Fig. 1. The embankment is constructed on two-layered foundation soil of thickness 4.5 m each. The foundation soil below the embankment in layer 1 is softer than the soil in layer 2 and the embankment soil. The soil in layer 2 is stiffer than the soil in layer 1. The soil is stiffer as the depth increases. Poisson's ratio and modulus of elasticity of layer 1 considered are 0.2 and 5000 kPa respectively and that of embankment are taken as 0.3 and 30,000 kPa respectively. However, Poisson's ratio and modulus of elasticity of layer 2 considered are 0.3 and 10,000 kPa respectively. The construction of embankment is completed in 10 days. The stability analysis is carried out and, as shown in Fig. 1, the critical slip surface for the slope is calculated using the proposed method. The



**Fig. 1** Numerical example 1 details and critical slip surface for end of construction and end of consolidation



**Fig. 2** Variation of factor of safety for example 1 from end of construction to end of consolidation

safety factor is 1.17 for the embankment at the end of construction and 1.89 for the end of consolidation.

The stability of the embankment with time is observed to be increased and the factor of safety variation with respect to the days is as shown in Fig. 2. The safety factor rises up to 100 days at a faster pace and then confirms at around 3810 days to 1.89. After this time interval, the variation in safety factor is insignificant. The variation of safety factor with time provides information about the time when deformation due to consolidation process is negligible.

### 3.2 Example 2

The numerical example is shown in Fig. 3. The embankment is constructed on two-layered foundation soil. The foundation soil below the embankment that is layer 1 is softer than the soil in embankment. The soil in layer 2 is softer than the soil in layer 1. Poisson’s ratio and the modulus of elasticity of layer 1 considered are 0.3 and 3000 kPa respectively and that of embankment are taken as 0.3 and 10,000 kPa respectively. However, Poisson’s ratio and the modulus of elasticity of layer 2 considered