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Research Paper

Mesh-free analysis applied in reinforced soil slopes

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ABSTRACT

One of the most applicable geotechnical structures whose analysis is carried out through iterative procedures is the reinforced soil slope. In this regard, the most successful method for the reinforced slope analysis through numerical methods is the finite element method whose updating mesh may result in some difficulties. In this study, the Natural Element Method (NEM), which is a mesh-free method, in conjunction with conventional limit equilibrium is implemented to find the slip surface in the reinforced slopes. Results demonstrate the convergence and preciseness of the present method in comparison with the other numerical methods and conventional limit equilibrium method.

1. Introduction

Over the past decades, the application of polymer grid to enhance soil properties has increased in civil engineering structures such as slopes, embankment, and retaining walls [1,2]. Among these geotechnical structures, slopes are the most critical, since soil slopes sliding in mines, roads, and dams have occasionally contributed to heavy casualties or great financial losses. Therefore, the safety of slopes has always been a challenge for slope designers [3]. Several researchers have studied slope stability topics and terms affecting the performance under different stress state conditions [4,5]. Engineers primarily use the factor of safety (F.S.) to evaluate whether slopes are away from failure or not. In general, the factor of safety is defined as the ratio of resisting force divided by the driving force [6]. In reinforced slopes, reinforcing elements impose additional resisting forces that should be added to the resisting force due to natural soil strength. The most widely used definition of factor of safety for reinforced slope stability is determined as the ratio of both the reinforcing force and the soil strength divided by shear stress required for equilibrium [7].

One of the earliest techniques exploited to analyze slope stability was the limit equilibrium method (LEM), in which slip surface and its factor of safety were obtained using an iterative procedure [8]. The concepts of LEMs are simple to understand and use. However, LEMs bear some disadvantages such as (1) implementing the effect of reinforcement (i.e. geogrid) and soil stiffness, (2) the effects of backfill soil compaction and sometimes soil cohesion, and (3) LEMs use the ultimate strength of reinforcements and soil [9]. Duncan [8] carried out a general review on the limit equilibrium methods and the position of finite element slope stability analysis. Nowadays, in order to overcome LEMs drawbacks, researchers combine numerical methods such as the finite element method (FEM) and the finite difference method (FDM) with LEM for reinforced slope analysis [8]. FEM has been extensively used in slope stability analysis [10–12]. In the analysis phase of a slope using FEM aided LEM, the critical slip surface and the corresponding factor of safety are obtained by iteration, in which the geometry of slope is discretized into elements. In each step, a slip surface is selected, and in the next step, another slip surface is chosen; therefore, the geometry of problem is changed. Finally, the slip surface with a minimal factor of safety is introduced as the critical slip surface. However, only an approximate factor of safety can be determined by the FEM aided LEM [10]. In order to achieve a precise factor of safety by FEM, highly refined mesh is needed [10] resulting in a more costly analysis [11], or a nonlinear elastoplastic analysis is required to obtain good results, which is time consuming as well. The high variability in soil properties may also lead to unreliable responses in the FEM analysis [13]. In FEM aided LEMs, re-meshing at any stage of the calculation is a simple step in FEM [10]. However, it may require more computational time or may cause mesh distortion. These limitations of the FEM with predefined elements motivate engineers to use mesh-free techniques. Over the past decades, mesh-free methods (MFMs) have been developed within the engineering sciences, and these methods are used to solve various problems with complex geometries

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[14–18]. Mesh-free methods have two distinct differences to FEM: (1) shape function definition is based on nodes position, and (2) the nodal connectivity evaluation depends on the number of nodes [19].

MFM was first introduced by Gingold [20] in astrophysical simulations. Lucy [21] applied and enhanced the smooth particle hydrodynamics (SPH), which was used for fluid flow modeling. Although the SPH is able to deal with larger local distortion in comparison with grid-based methods like FEM, there are some difficulties concerning the use of SPH that can be listed as follows: (1) the imposition of essential boundary condition (Dirichlet boundaries) due to the shape functions properties; (2) instabilities observed in the solid due to states tensile stress; (3) excess deformation can be made by parasitic pattern; and (4) low consistency [22]. Since the original version of SPH suffered from instabilities and inconsistencies, many improvements were inserted into the SPH [23]. The reproducing kernel particle method (RKPM) was introduced in 1995 [24]. The RKPM overcomes a certain number of difficulties present in the SPH method; however, the imposition of the essential boundary conditions remains a challenging issue. The consistency achieved in the RKPM allows the use of RKPM approximations within the weak form framework to discretize the partial differential equations [23]. The element-free Galerkin (EFG) method was introduced in 1994 and was one of the first mesh-free methods based on the weak form framework. The EFG is consistent and stable, although the EFG substantially is more expensive than the SPH method [24]. The moving least square (MLS) method was developed in the late 1960s for general surface problems. MLS methods are the same with kernel methods. The weight function of MLS approximation is obtained based on kernel approximation which is consistent. Some of the major advantages of MLS method are partition of unity, the imposition of essential boundary conditions, coupling with finite element method, and the speed of computation [23]. Beside these advantages, MLS is not without disadvantage. The MLS shape functions do not satisfy the Kronecker delta property (see Fig. 2) [24].

Libersky and Petscheck [25] used MFM in solid mechanics such as impact, crack growth, fracture and fragmentation. After that, MFMs were used to solve various problems, especially in which discontinuities may happen [26,27]. Some of the MFMs, such as the natural element method (NEM), have special abilities. NEM focuses on principles completely different from the previous MFMs such as SPH and RKPM. NEM properties are between MFMs and FEM [22]. In other words, the NEM shape functions satisfy the Kronecker delta property, while simultaneously using the higher-order and the smoothness of mesh-free shape functions. NEM is direct and proceeds as an FEM in imposition of a boundary condition for convex domains. Thus, it can be carried out by relocation in a system of linear equations. NEM shape function also changes flexibility around nodes as shown in Fig. 2. NEM proposes the Voronoi diagram and its natural neighbors to define shape functions [22]. The Voronoi diagram is a method for dividing a domain into a number of regions based on the position of each point (node). Here, each node will have corresponding region comprising of all nodes closer to that node [28]. The Voronoi diagram leads in the partition of unity [29]. Sukumar [28] introduced NEM and used it in solid mechanics. Then, NEM is utilized to solve many problems as Shahrokhabadi and Toufigh [29] exploited it to solve unconfined seepage problems.

The main purpose of this study is to introduce NEM for interface modeling in reinforced slope analysis. NEM is used in an adaptive mesh procedure, in which the mesh distortion is not a serious issue. NEM is also used for stress analysis in reinforcements and soil in reinforced slopes. In each iteration, a new slip surface is chosen, and the geometry of the problem and position of nodes are updated in each step. In applying conventional methods for stress-strain analysis such as FEM and mesh creation in each phase of solution, mesh distortion may occur. NEM and its adaptive mesh in each step of solution and its favorable properties, including local compact besides δ–Kronecker satisfaction, make it simple to be used [28].

2. Natural element method

The Natural Element Method (NEM) is a Lagrangian Approximation mesh-free method, which is permitted to carry out calculations without mesh distortion. The main property of NEM in contrast to the FEM is its independency upon the mesh arrangement, in which mesh quality has significant influence on the results [30]. The eye-catching properties of NEM, such as the partition of unity and lack of sensitivity to mesh distortion, have led to the usage of this method in various engineering problems [31,32]. Another merit of NEM is the imposition of essential boundary conditions by substitution in a system of linear equations [33]. NEM interpolants are linear between nodes on the convex boundary whose essential boundary conditions can be applied easily.

NEM is based on the natural neighbors interpolation plan [34,35]. Moreover, local distribution and density of nodes are two key factors for the computation of correlation among nodes [36]. These interpolants are calculated based on the Voronoi cells of nodes set, which are created both in the problem domain and along boundaries. The discrete model of the domain (Ω) comprises of diagrams covering the whole domain named Voronoi diagrams. In the case of our problem, the soil is tessellated.

Sukumar [37] demonstrated the remarkable properties of NEM in elastostatic problems, and the fact that the spectacular feature of NEM is "acceptable preciseness" in data interpolation.

2.1. Natural neighbors

The concept of natural neighbors is introduced by Sibson [34] for interpolation scattered data. The Voronoi diagram and Delaunay tessellation are the two important concepts to calculate natural neighbors. Voronoi cells are obtained by dividing a given domain (Ω) to special subdomains (Ω_i) [36]. The Voronoi tessellation is one of the most fundamental and beneficial geometric structures, which can be applied on an irregular set of nodes.

A given set of nodes $N = \{n_1, n_2, n_3, \ldots, n_m\}$ is supposed in R^2 space in which the Voronoi cell is a division of plane into T_I, which is relevant to node n_I. T_I determines an area where the interval between each node and n_I is less than the other nodes in set N. A Voronoi diagram for n_I is defined as:

$$T_I = \{X \in R^2 : d(X,X_I) < d(X,X_J) \quad \forall J \neq I\} \tag{1}$$

where $d(x,x_I)$ is the Euclidean interval between x, and x_I.

It is obvious that each Voronoi diagram 1st is the junction of open half-spaces, each of which are confined by a perpendicular bisector. Therefore, each Voronoi cell is closed and convex (see Fig. 1a).

The Delaunay triangle derivation from the Voronoi diagram is built by the nodes whose Voronoi cells have joint boundaries (see Fig. 1b). The duality between the two nodes implies that a Delaunay border between the two nodes in the surface should exist; their Voronoi cells have the common border.

Delaunay triangles have some features. One of their main features is the Empty circumcircle criterion. If $DT(n_J, n_k, n_I)$ is assumed to be a Delaunay triangle of the set N, the circle of DT does not comprise other nodes of N. n_j, n_k, n_I are three triangle vertices and the center of the circle is on the intersection of Voronoi cell boundaries, which built the Delaunay triangle [37]. Based on