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学 位 論 文 要 旨 Dissertation Summary

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Elasto-Plastic Continuum Modeling for Slope Stability Evaluation: Numerical Methods and Applications

Slope instability is one of the major problems in the field of Geotechnical engineering. A majority of slope instability problems are associated with natural slopes in which vegetation plays a crucial role in the stability. Due to the complexity of problem domain with the vegetation, however, its contribution to slope stability is not sufficiently investigated, especially through analytical and numerical methods. Usually, the root network in the soil domain can be very random in terms of direction, depth, and density. Such a situation is simplified in this study by considering an average domain based on the parameters of both soil and root. With the consideration of a increasing trend of bioengineering approach in soil slope stabilization, its analytical justification pertinent to the stability factor is essential for an effective design and its implementation. Numerical simulation considering progressive failure and soil-root matrix interaction certainly provides a reliable way for the analytical evaluation. However, both progressive failure and soil-root matrix interaction cannot be easily treated both analytically and numerically. Hence, a new numerical scheme in finite element method is essential to simulate the progressive failure in a simple and effective manner. At the same time, homogenization of the soil-root matrix can be implemented for an easy treatment of networked continuum. It is expected that such a new scheme should be simple in mathematical formalism and elegant in geometrical compatibility for an efficient computation. This research work explores efficient modeling techniques for the stability of natural slopes from small- to large-scale mountain slope failures. To explore an

efficient modeling method, the numerical and computational aspects of each method need to be examined minutely. Moreover, it emphasizes the need to explore the most reliable numerical and computational method for slope stability analysis. This research considers such numerical and computational schemes that manifest very interesting aspects of the slope stability analysis with limit equilibrium method (LEM), finite element method (FEM), mesh free method (MFM), and spectral element method (SEM).

In LEM, the rate of mobilization of strength at every point on the failure surface is not considered, and the deformation of the slope cannot be estimated. The location of the unique failure surface and the determination of corresponding critical factor of safety (FOS) of the soil slope requires a large number of trial and search. With this large number of trial and search results, we need to evaluate the field of FOS, which represents the critical FOS at a point within the domain of all possible failure surfaces. In LEM, evaluation of FOS-field for different slope geometries and instability conditions shows that more unstable the slope becomes more difficult will the pinpoint location of the critical failure surface with a unique least FOS be. The region of the least critical-FOS of more stable slopes can be precisely defined over a fixed domain. Locating the region of the least critical FOS-field becomes difficult when the slope becomes more unstable. So, this method can be more suitable for a preliminary evaluation (Tiwari *et al.*, 2013a).

Likewise, FEM is based on stress-strain of an individual element in a slope. The variable rate of mobilization of shear strength at every point on the failure surface can be implemented. FEM approach can predict the probable failure surface zone. It can also give the information on deformation of the slope. Both homogeneity or heterogeneity in material properties can be well implemented. However, the computation of failure path is naturally difficult as FEM uses continuous displacement and singular functions, which need a transition discontinuous function during the evolution of fracture. This method implements transition discontinuous function, which not only describes the traction free boundaries within the fracture but also reliably explains progressive nature of the fracture (Tiwari *et al.*, 2013b). However, the numerical procedure is highly dependent on the mesh, and is very often affected by lack of convergence. FEM employs different integration point and interpolation point, which leads to a huge computational burden and consequently to solution convergence problem. This technique generally requires a highly sophisticated computing facility (i.e., super-computing or parallel-computing) for large and complex problems.

MFM, however, drastically reduces the storage memory and accelerates the computation process. In this method, the conjugate gradient iteration checks in conjugate direction and follows the gradient so that it reaches the required point in a few iterations. This technique can be useful for simplified modeling domains of relatively large size (Tiwari *et al.*, 2011).

Mathematically, the governing equations of large-scale problems comprise of higher degree polynomials to represent geometrical non-linearity. The analytical solution of a large-scale problem is very tough, and the boundary conditions and the domain of

interest are very complex. The progressive failure phenomenon needs infinite iterative process, which may lead to solution convergence as well as memory problem in computation process. The progressive failure demands an increased number of iterations, which is practically not possible for simulating a large-scale slope in ordinary computations. A high computational cost in ordinary computations and use of a super-computer and parallel processors may not be convenient for most users.

The flexibility of unstructured meshing and the adaptability of using an arbitrary order of integration via Gaussian quadrature make FEM a versatile procedure. However, the Gaussian quadrature interpolation nodes and integration points are differently cited, which leads to a huge mass matrix. To overcome this situation, a high-order FEM or spectral FEM, commonly known as SEM, takes into account the interpolation nodes of an element and the numerical integration points as the same points. With the coincidence of integration and interpolation points, the interpolating function becomes orthogonal, resulting in a diagonal mass matrix, which significantly simplifies the computational procedure and reduces the computational cost. In this approach, Gauss-Legendre-Lobatto (GLL) quadrature, also known as Gauss-Lobatto or Lobatto quadrature, is used for interpolation nodes. With this implementation, the interpolation to determine nodal quantities is not necessary, which simplifies the computation. Here, the parallel preconditioned conjugate-gradient (PCG) method is used to increase the computational storage. The parallelization of the programming codes makes the programs applicable to large-scale problem domains. Most of the existing FEM programs are sensitive to meshing, and the solution convergence problem and termination of the programs are frequent. These limitations are also studied in this research for an effective implementation of SEM procedure.

In SEM, the nodal quadrature is originally limited to hexahedra in 3-D. Meshing is usually not automated because a careful mesh design governs the effectiveness of this procedure. A low-order FEM is not suitable for greater numerical stability and accuracy. High-order elements are well established in geotechnical FEM (e.g., 15 node triangles), but the computational burden is not addressed by any existing FEM methods. The advantage of forming a diagonalized mass matrix for a pseudo-static analysis is, in fact, not sufficient. However, this research work finds a broader scope for pseudo-static applications in natural slope instability, and predicts reliable values of safety factors through certain refinement techniques. With the application of h- (meshing) and p- (mapping) refinement techniques, SEM performs to be an efficient method over the existing FEM. The parallel processing and supercomputing may not be an urgent solution in SEM modeling to address a large-scale problem domain (Tiwari *et al.*, 2013c). The SEM procedure has three major benefits over the existing FEM procedures: 1) geometrical flexibility, 2) high computational efficiency, and 3) reliable spectral accuracy. The higher spectral degree in SEM replaces the huge computational budget of FEM.

All numerical procedures were validated by comparing the results obtained for a sample problem of Smith & Griffiths (2004). This study basically employs two open source programs in SEM (i.e., serial and parallel versions of Specfem3D-Slope and

Specfem3D-Excavation) developed by Gharti *et al.* (2012) along with the programs in LEM, FEM, and MFM developed by Tiwari *et al.* (2011, 2013a, 2013b, 2013c). The overall package of SEM utilizes the source codes for serial and parallel programming along with 3-D hexahedral meshing tool CUBIT, domain decomposing or partitioning tool SCOTCH, message passing tool among sub-domains MPI, and the plotting tool Paraview.

All computations have been carried out with the strength reduction method (SRM). The numerical and computational accuracy impact factors are identified and tested for the purpose of setting the reliable computational criteria in 3-D. Three categories of impact factors were checked for: 1) modeling domain related parameters, 2) spectral parameters, and 3) elasto-plastic parameters. This method was successfully implemented for evaluating the stability of a large-scale landslide in the Nepal Himalaya known as Laprak landslide, under seismic and saturation instability conditions.

This research is basically important to evaluate some fundamental issues related to bioengineered soil slopes, such as effect of vegetation on FOS, effect of the root depth, effect of root types, and effect of root density of a certain plants on FOS. In addition, it also explores the suitability of stochastic process on slope stability focusing at evaluation of the root-reinforcement effect. The material properties such as young's modulus, cohesion, and internal friction angle are chosen to be randomly distributed, and Monte-Carlo simulation is carried out for each random distribution with certain uncertainty. So, the effect of uncertainty is introduced in the material properties (i.e. heterogeneity) upon the uncertainty in response of soil slope resulting in reliable probabilistic estimations of the FOS, failure surface, and deformation of the slope. The probability distribution curve (PDF) suggests that with an increasing root area ratio (RAR), the mean of population data falls in a narrow range at high certainty, i.e., less material variability. RAR has a very interesting influence on the stability factor of the soil slope. Increasing RAR does not necessarily strengthen the slopes. In fact, safety factor of the soil slope first increases with RAR, but after attaining a certain value, any further increment in RAR does not impact the safety factor. Similarly, with increasing slope angle, the mean of sample data falls within a wider range of probability density curve, which increases the material heterogeneity. The material heterogeneity increases the degree of uncertainty in the prediction of factor of safety, which demands reliable information of heterogeneity for a sharper prediction.

The infinite slope equations are often used to estimate the safety factor of natural slopes. This research work also finds three major limitations of the infinite slope equation while comparing the results with the SEM: 1) limitation on slope length, 2) limitation on slope angle, and 3) limitation on root zone. The research work presents a tentative range of critical length/depth ratio (i.e., $L/H \geq 20$) that can be applied in all possible slope models for infinite slope stability analysis.

Likewise, this research work also explores the effects of vegetation on slope stability in different slope geometries and instability conditions and uses them to prepare stability charts for static and seismic slope stability. In general, stability of a slope can

be significantly improved with the use of vegetation mainly due to root-reinforcement effect on soil strength.

In addition, this research work relates to a practical problem of cut slope excavation in road opening works in theoretical domains. It also examines the effect of root-reinforcement in multi-stage cut slope excavation, and explores the limiting strength criteria for excavating slopes. The soil cohesion is chosen as the limiting criteria, and the response is carried out for a few possible friction angles keeping other parameters constant. This type of research can be useful for new road opening in complex topography and geology to minimize the construction risk and design the safe and economic road side slopes.

In conclusion, an evaluation of FOS-field is necessary to get a reliable FOS in LEM even in preliminary slope instability assessment. A new scheme in FEM can be useful to address progressive failure phenomena in any modeling domains with sophisticated computations (i.e., super-computing and parallel-computing). MFM can be useful to deal the progressive failure phenomena in large-scale problem domains with ordinary computations, but it may have a frequent solution convergence problem in complex problem domains. On the other hand, SEM-based numerical methods can effectively handle the usual computational problems in LEM-FEM- and MFM-based slope instability modeling that can encouragingly be used for large-scale slope instabilities in different stages of landslide slope enhancement measures (LSEM). This is a newly employed method in slope stability analysis so that it requires examining the elasto-plastic accuracy impact factors related to FOS. This work is necessary to set reliable computational criteria for 3-D SEM. The computational efficiency of the SEM approach can be applied to develop both seismic and static slope stability charts. This is necessary because most of the charts are prepared on the basis of LEM and modified forms of LEM and because the effects of vegetation on slope stability are not considered. This method can be applied to find out the limits of infinite slope equations applications to slope stability. This is necessary because most of the natural slopes are analyzed by infinite slope principles. This method can be applied to find out the limiting criteria for excavation and road side slope designs. Furthermore, the SEM procedure can be effectively applied to slope stability modeling for numerical stability and accuracy in small- to large-scale mountain slope failure problems.