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Usage of Numerical Analysis Programs in Geotechnical Engineering Applications

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Abstract – Recently, it is inevitable to use numerical analysis methods for several geotechnical engineering problems solution due to the complexity of behavior characteristics of soil medium. In this study, numerical analysis methods that are used to obtain numerical analysis programs for modelling and designing geotechnical engineering projects are investigated and shortly explained. The factors that are effecting the numerical analysis solution are summarized and advantages, limitations and applicability conditions according to the geotechnical structures are evaluated with a holistic view.

Keywords – *Geotechnical engineering, geotechnical design, design programs, numerical analysis, numerical modeling.*

I. Introduction

Civil engineering is one of the founding engineering disciplines that have emerged to meet human's sheltering requirements. Therefore it has been an aspect of life since the beginning of human existence. The application of physical and scientific principles throughout their development history creates the basic characteristic computation techniques for civil engineering structures. As a professional engineering discipline, civil engineering deals with design, construction and maintenance of physical and natural environment, involving constructions like roads, dams, bridges, airports, pipelines, railways, support systems, buildings, canals, skyscrapers and divided into several sub-disciplines such as structural, geotechnical, hydrological and son on. These sub-disciplines are united in a single fact that can be summarized as “All civil engineering structures must be placed in the earth’s crust”.

Earth’s crust is constituted of soil and/or rock. Beside this some of the structures such as embankment, cofferdam, dam, railway, highway and airport fills are consisted of soils and also the constructions like foundations, excavations and slopes, fills and embankments, retaining structures and underground structures behavior are mainly depended on the characteristics of soil. The problems that are existed because of soil and rock materials are the main interest of geotechnical engineering discipline. Geotechnical engineering utilizes the principles of soil mechanics, rock mechanics, strength of materials and hydraulics for investigating subsurface materials and their physical and mechanical properties. The main problems of interest for geotechnical engineers can be defined that the determination of foundation soil bearing capacity, estimation of deformation behavior, evaluation of natural or man-made slopes stability, assessment of the risks by construction area conditions, prescription of earthworks and the foundation type of structures, monitoring site conditions and so on.

The knowledge about the development process of geotechnical engineering begins with the studies of Karl von Terzaghi at 1920s. Terzaghi (1924) demonstrates that soil is differentiated from other structural materials by its non-homogenous and anisotropic structure. Therefore the solution of problems related to soil have to solve with distinctive principles which is reflecting the real behavior [1].

The problems that are encountered in the solution process of soil behavior can generally classified as stability problems, stress-strain problems and ground water effects. These problems and effects are arising due to the loading or reloading conditions of subsoil which can act static or dynamic, symmetrically or eccentric, single or distributed and etc. Action and reaction effects are generated according to the forces that are transferred from superstructure to the foundation to ensure or to damage the systems structural stability. These action and reaction effects have delivered a common behavior between superstructure and substructure and this mutual effect is named soil-structure interaction. The behavior of the soil layers laying under the superstructure depending on the loads transferred from the ground surface is important to select the type and material of load bearing foundation. Shallow or deep foundation systems can be selected according to the levels of static and dynamic loads transferred from the upper system. Retaining structures are used due to the lateral resistance and stability of soil masses beside the excavation areas or slopes. The design of retaining structures can be done with the knowledge of lateral earth forces. In such cases the basic design consideration is to make the system geometry and material properties simple as it can be. After all appealing the closed form solutions or using empirical relations is applied to achieve design. But closed form solutions or empirical relations don’t consider boundary conditions, material constitution behavior and permanency all together. Because of these reasons, a requirement to use numerical analysis methods is borne for geotechnical engineering. Numerical analysis is a branch of mathematics that is used to solve the problems which have continuous variables. The increasing complexity and growing usage of geotechnical systems make it necessary to perform numerical analysis in the design of geotechnical structures. Traditional methods of analysis that are mentioned above such as closed form solutions, limit equilibrium and etc. cannot derive all the design requirements more particularly related to the effects of in-situ stress conditions, new constructions on existing structures, sudden increase of water level or water level changes due to the excavation or tunneling, effects of changeable environment, dynamic effects of earthquake or machine foundations and so on. For evaluating a successful geotechnical design, appropriate material constitutive models, boundary conditions, drainage conditions and construction program have to be applied by numerical analysis. These are the common phenomenons of civil engineering problems that are encountered in the numerical analysis process but there isn't an actual unique implementation and application method to design same problem in the same way. For a specific selected case, different answers to problems and various design conditions are evaluated with different solutions done with numerical analysis software's.

In this study, the numerical analyses methods that are used to design geotechnical engineering projects are described briefly. Advantages, limitations and applicability conditions according to the geotechnical structures are evaluated with a holistic view. It is thought that this study will enlighten researchers about numerical analysis usage for geotechnical problems.

II. NUMERICAL ANALYSIS METHODS

The most preferred numerical analysis methods that are used to design geotechnical projects can be classified as limit equilibrium method, finite element method, finite difference method, discrete-distinct element method. Information about aforementioned numerical methods are given below and their applications due to the geotechnical problems are told with a short information. After the significant design requirements are discussed.

A. Limit Equilibrium Method (LEM)

Limit equilibrium method is most widely used method to derive stability of geotechnical structures for decades. In the limit equilibrium method an arbitrary failure mechanism that is consisting of various arrangement of slip planes are used without exceeding the appropriate failure criterion. Each of the arbitrary selected component and all the complete mechanism have to be in statically equilibrium. Ultimate collapse load is evaluated by the examination of other arbitrarily selected different mechanisms. Collapse load determined by these different mechanisms are compared and the limit value of these loads is selected as the ultimate capacity. This condition makes the evaluated load value an upper bound for the mechanism [2]. As discussed with the lower bound method of plasticity it can be said that limit equilibrium does not consider a real collapse mechanism solution and prescind initial internal stresses in the soil. The actual solution of collapse loads have to be between the upper bound and lower bound of loads [3]. But limit equilibrium solutions are equal to upper bound values that means if the soil reaches these load value, failure will occur. The determinations are done by using the usual equations of statics that consists resolving forces due to the horizontal and vertical directions and taking moments of forces acting on the boundaries of selected system components and for the whole mechanism. By the way in the limit equilibrium method, the system and components are all in equilibrium but the equilibrium does not include internal stresses in the soil. In addition to these, in some cases it is possible to make simplifications and assumptions to provide statically determination.

The first studies about limit equilibrium method usage is done by Coulomb (1776). The subject is retaining structures and equilibrium equations are written to determine earth pressures. By the means of this approach friction rule and the failure behavior of granular materials are discovered by Coulomb failure criteria. This state constitutes a reformer perspective for physics and assumed to be the first analytical model for geotechnical engineering discipline. After, Rankine (1857) reveals a new theory about earth pressures and make it easy to calculate lateral earth pressures acting on retaining structures [1]. Coulomb and Rankine theories are important and significant tools of determining earth pressures. Thereafter the studies of earth pressure evaluation become varied by experimental research, model tests or theoretical approaches. These experiences and applications show that limit equilibrium method generally lead to good estimations for the failure loads of geotechnical structures [2].

The method of limit equilibrium is applied for foundations, walls, slopes and any combination of these structures. Also the limit equilibrium method can easily adapt to cases that foundation soil stratified or inclined. In stratified foundation profiles, all layers have different geotechnical characteristics. In inclined ground formations the boundaries are irregularly shaped. For these cases the calculations to determine the forces acting on slices and finding the critical mechanism involves lots of steps to solve. Hence it is needed to solve the problems by machine computation techniques. There exist a number of geotechnical computational numerical analysis software such as Limitstate: GEO, GEOSLOPE, Rocscience: SLİDE, Soilvision: SVSlope, GSlope, Stable WV, user defined lots of commercial software's and etc. These programs make it easy to solve complicated equilibrium equations and not time consuming like hand computation.

Besides all these, although sudden loading conditions can be defined by limit state method, the strength increase due to the loading magnitude and time cannot taken into consideration for clayey soils. Construction sequence cannot been modelled because of sudden loading modeling concept of method. Because of these constraints it is a current trend to use limit equilibrium theory with the combination of stress-strain based design procedures.

B. Finite Element Method (FEM)

Finite element method is the most preferred method of solution in geotechnical engineering designs in actual studies and developed by application oriented engineers who are interested solving complicated problems of geotechnics [4]. Finite element method make it possible to solve complicated problems that are hard to evaluate the solution by using conventional deterministic methods or closed form solutions. In words of one syllable, it can be summarized that continuum material and/or media assumption, the use of differential equations for expressing problems and dividing the problem media into small elements constitutes the basic characteristics of the method. The elements are intersected at nodes and the differential equations are written for each of these elements firstly. Nodal equations then integrated to whole system and system equations are evaluated.

On phenomenological basis, finite element method can be defined as a method that consists of six processes (wordpress). The processes can be summarized as; i. Discretization, ii. Approximate function selection, iii. Interpolation model selection, iv. Combination of element equations for forming global equations, v. Primer and seconder quantity computation, vi. Stress-strain behavior evaluation [4].

The first step discretization contains the division of a continuum media into an equivalent system of smaller continua that is called "finite elements". These finite elements are separated by nodal lines and intersected at nodal points. The features as displacement, fluid potential forms primary unknowns of problems. The second unknown of problem include stresses from displacements, quantity of flow from fluid potentials and etc. The significant property of the method is the separation of each element and calculation of differential equations by its own function. Each finite element represents its constitutive properties and all stiffness and strength properties are formulated individually. But inductive methodology is used to obtain the equations for global matrix to generate whole structure with the use of compatibility constraints. Appropriate function selection is done on the basis of the unknown quantity with assuming an intuitional pattern. This pattern generally is selected in polynomial form with regard to nodal displacements or some generalized displacements. Problems type and degree of accuracy designates the order of polynomial. Higher degree of polynomial gives higher accuracy. Two methods are generally used to define properties of a finite element called variation and residual methods respectively. Residual method is more general and suitable to solve both linear and nonlinear problems of engineering [4].

There exist lots of geotechnical engineering design software's working with finite element method like PLAXIS, ABAQUS, MIDAS (SoilWorks), CRISP2D, DIANA (DIsplacementANAlyser), ANSYS and etc. It is able to perform analysis of complex problems including stratified or inclined foundation soil profile, dynamic or thermal load effects, multiple steps such as excavation, consolidation, loading, creep and son on. According to the ever-developing technology it becomes easy and fast to adapt different material properties with the use of different constitutive behavior models and it becomes possible to evaluate time depended stress-strain behavior. But these easily evaluated results have to be checked and interpreted with a detailed view of expertise and have to be verified with experimental tests or laboratory investigations.

Consequently finite element analysis with the combination of computer techniques presents a powerful opportunity to engineers for finding approximate solutions for the complicated real world problems and takes less time to evaluate maximum observation but it is very important to model system geometry condition, boundary situation, material constitutive behavior, linear or nonlinearity, drainage conditions, interactive behavior characteristics, material properties with respect to user addictions.

C. Finite Difference Method (FDM)

Finite difference technique is a computer based design method of differential equations which is dividing the main problem into small sub-time steps and estimates the stress-strains of the consecutive sub-time step according to the the present time step using finite difference formulation [5]. Finite difference method uses a discretization procedure that is based on the replacement of continuous derivatives in equations by finite small increments. By this way the differential equation converted to a difference equation. Accuracy of analysis with the use of finite difference method can be assessed with regard to stability and convergence. The consistency of difference equations automatically implies convergence stability. Stability and convergence are equivalent for a wide area of consistent equations.

FLAC (Fast Lagrangian Analysis of Continua) is the most known commercial program that uses finite difference logic in calculations. The program is designed to accommodate several kinds of geotechnical engineering projects that needed continuum analysis. FLAC can model the complex projects of geotechnical engineering with several phases such as non-liear material behavior, large strains, unstable systems, complex boundaries and can take into consideration the whole effects of upper structural system and all the cases that can be thought.

Finite difference analysis have been generally used in the solution of piles loaded laterally and horizontally, beams on elastic foundations, analysis of consolidation behavior, wave propagation process, seepage analysis and so on.

However, for heterogeneous geotechnical engineering problems that are involving discontinuities and/or irregular surfaces, the requirement of particular formulations are arise that may not be needed in finite element solutions. That's the factor why finite element analysis gain an advantage over finite difference method.

D. Discrete and Distinct Element Method (DEM)

Distinct element method is developed by Peter Cundall (1971) to describe the mechanical behaviour of discontinuous bodies [6]. The method is firstly applied to analyse rock mechanics problems and after adapted to soil materials [7]. Limited programs are available to solve problems by distinct element method such as UDEC (Universal Distinct Element Code), 3DEC (Three-Dimensional Distinct Element Code) and PFC.

UDEC is used as a two dimensional software for simulating the the quasi-static or dynamic response to loading. The analysis are done for the media that is containing multiple, intersecting joint structures. The medium is discontinuous and represented like an assemblage of discrete blocks and the discontinuities are processed as boundary conditions between these blocks. It is expected that large displacement generation actualised throughout the discontinuities and the block can rotate. Rigid or deformable blocks can be defined by the program UDEC. Deformable blocks are constituted of a continuum mesh of finite difference zones. The relative movement of discontinuities are directed by linear or nonlinear force-displacement relations for both the normal and shear directions [8].

PFC is used to simplify the construction process, the solution and analysis of a particle simulation. The program is designed provides user to model mechanical systems that can be represented as an assembly of particles [9].

Discrete element method is an option to model continuous media by representing the material as an assemblage of independent elements like units, grains or particles. These elements are interacted with one other. Discontinuities represent the boundaries of each element and through the run of the model, the reorganization of discontinuities actualised.

Non deformable elements constitute discrete systems. Due to this point, the method is suitable for granular materials [10].

However various materials such as rocks don't behave like granular materials, discrete element method also applied to evaluate mechanical behaviour with the assumption of the material can be approximated like assemblies of discrete elements bonded each other by cohesion forces or the effects of cementation.

The discrete element method can only be applied to a computer program if it allows finite displacement and rotations of discrete bodies and new contacts should be automatically occur during the calculation process. Without allowing finite displacements and rotations, the system cannot generate mechanisms throughout the discontinuous medium. If the presence of second condition is absent, the model limits small numbers of bodies. District element method is proposed to apply to the particular discrete element idea which uses deformable contacts and an explicit [11].

III. CONCLUSION

Recently, it is inevitable to use numerical analysis methods for several geotechnical engineering problems solution due to the complexity of behaviour characteristics of soil medium. In this study, numerical analysis methods that are used to obtain numerical analysis programs for modelling and designing geotechnical engineering projects are investigated and shortly explained. The factors that are effecting the numerical analysis solution can be summarized as the type of analysis method, model geometry and boundary conditions, material constitutive model, nonlinear solution technique, drained and undrained modelling, interacted behaviour of structural systems, material properties and the user routines. Having all these in mind, numerical modelling techniques and software's supply many advantages to solve problems which are stated below. With the use of numerical analysis programs,

- It is possible to model complicated geometrical conditions,
- Material behaviour can be represented by proper constitutive models,
- Loading conditions and boundary limits can be modelled,
- Non-linear behaviour can be addressed,
- All drainage conditions can be taken into account with respect to time,
- Interacted system behaviour taken into account,
- Construction process is adaptable,
- Water effects can be modelled,
- Relative movements and penetration can be modelled,
- Ideal optimistic solution can be obtained,
- It is possible to solve different problems at the same time (integrated problems),
- Parametrical analysis can be done and optimal design can be evaluated.
- It is also possible to do back analysis to complete the lacks of design
- Fast design and maximum observation

It can be seen that appropriate use of numerical analysis for geotechnical engineering problems, programs provides users lots of conveniences [12], [13]. But also users and designers have to keep in mind that there are some limitations and uncertainties of all kinds of numerical analysis programs and the program usage is depended on user's knowledge of interpretation of data rather than running software process and obtaining excessive output.

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