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A COMPARATIVE STUDY ON COMPUTER AIDED LIQUEFACTION ANALYSIS METHODS

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ABSTRACT

Soil liquefaction is the phenomenon of temporary loss of shear of saturated cohesionless soil under the influence of vibrations caused by earthquakes. The extensive loss of lives and civil infrastructure system like buildings, bridges, highways etc. caused by liquefaction emphasize the need for strong and reliable methods for evaluating the liquefaction potential of sites. Simplified techniques based on in situ testing methods are commonly used to assess seismic liquefaction potential. Many of these simplified methods are based on finding the liquefaction boundary. Because of this importance, engineers developed various software programs to evaluate and model liquefaction potentials of sites. In these programs, the methods, properties, calculation types, coefficients and etc. differs from each other. In order to address liquefaction engineering, this paper proposed to focus on comparing the advantages and disadvantages of different software programs used to evaluate and analyze liquefaction potentials of sites based on different methods. In this paper, it is shown that to choose the correct software program is one of the key points in the liquefaction evaluation procedure. The definitions and the properties of all the liquefaction analysis software programs that are used in the engineering literature are search a part of doctoral thesis and the results are given as a summary in this paper. Also, a table that shows how to determine the correct method and program is formed to serve for engineers. Finally, in the future works, an analysis will be done to compare the site liquefaction potential results by using all the software programs.

Key words: Liquefaction, computer softwares, numerical methods, and earthquake.

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Introduction

Liquefaction and related phenomena have been responsible for tremendous amounts of damage in historical earthquakes to residential structures all around the world. Liquefaction occurs in saturated soils, that soils in which the space between individual particles is completely filled with water called pore water. This water exerts as a pore water pressure on the soil particles that influence how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other. When liquefaction occurs, the strength of the soil decreases and, the ability of a soil deposit to support foundations for buildings and bridges are reduced. Liquefied soil also exerts higher pressure on retaining walls, which can cause them to tilt or slide. This movement can cause settlement of the retained soil and destruction of structures on the ground surface. Increased water pressure can also trigger landslides and cause the collapse of dams. Because of liquefaction occurs in saturated soil, its effects are most commonly observed in low-lying areas near bodies of water such as rivers, lakes, and oceans.

In general, there are basically some possibilities to reduce liquefaction hazards when designing and constructing new buildings or other structures as bridges, tunnels, and roads. The first possibility is to avoid construction on liquefaction susceptible soils. There are various criteria to determine the liquefaction susceptibility of the soil. By characterizing the soil at a particular building site according to these criteria one can decide if the site is susceptible to liquefaction and therefore unsuitable for the structure. Another option is, if it is necessary to construct on liquefaction susceptible soil because of space restrictions, favorable location, or other reasons, it may be possible to make the structure liquefaction resistant by designing the foundation elements to resist the effects of liquefaction. The third option involves mitigation of the liquefaction hazards by improving the strength, density, and drainage characteristics of the soil. This can be done using a variety of soil improvement techniques. For all these necessities, a study focusing on modeling or analyzing the soil liquefaction potential of the area must be done by using computer aided numerical methods with different softwares.

Literature Review

These programs assist engineers in evaluating liquefaction potential and earthquake induced settlement. It determines the liquefaction zone and settlement under earthquake conditions. They are windows based programs with graphical presentations for geotechnical reports. They offer multiple methods of calculations. They are designed as very flexible and comprehensive liquefaction analysis softwares which consider more than 50 different options and formulas.

These liquefaction analysis programs generally cover these field tests like Standard Penetration Test (SPT), Cone Penetration Test (CPT), Becker Penetration Test (BPT), Shear Wave Velocity (Vs) and etc. In these programs the soil resistance (CRR) for liquefaction analysis is calculated generally based on:

· Japanese Bridge Code
· Chinese Code
· Seed et al. (1983)
· Tokimatsu-Yoshimi (1983)
· Shibata (1981)
· Kokusho et al. (1983)
· Vancouver Task Force (2007)
· NCEER Workshop (1996)
· University of California at Davis (2004)
· Cetin & Seed (2004)

<u>1D liquefaction analysis</u>

The softwares which are appropriate for 1D modeling are summarized below.

The Shake2000 is a software package that integrates ShakEdit and SHAKE. It provides a graphical user interface to SHAKE with the following features: Numerous attenuation relationships for estimating peak horizontal acceleration and velocity with distance; and, for the pseudo acceleration and pseudo velocity response spectra. Estimation of the cyclic resistance ratio (CRR) required to initiate liquefaction using: Standard Penetration Test results and the CRR vs. $N_{1,60,cs}$ chart developed by Seed et al. (1985); and Cone Penetration Test (CPT) data, as recommended by Robertson and Wride. Calculation of settlement induced by earthquake shaking using the Tokimatsu & Seed (1987), or the Ishihara and Yoshimine (1992) Method (Figure 1).

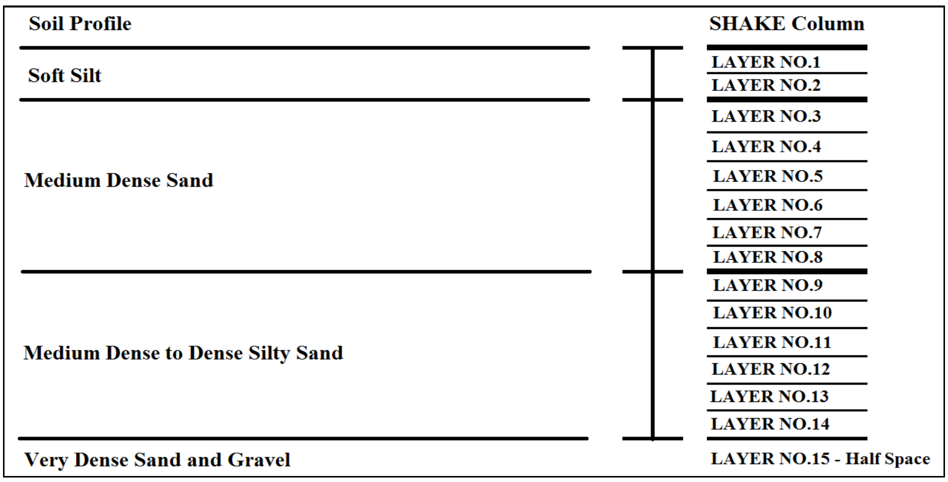

Figure 1. An Example of 1D Soil Profile from Softwares of Shake2000.

The Apollo software analyzes potential liquefaction of soil layers for one dimensional seepage. It incorporates a simplified procedure for 1D analysis of generation and dissipation of pore water pressures in sand deposit due to seismic excitation.

The LASS-II software (Liquefaction Analysis of Saturated Soil Deposits) analyzes seismic response and liquefaction of horizontally layered saturated solids. The saturated soil below the water table is modeled as a coupled two phase medium with solid granular skeleton and pore water as the constituent materials. The pore water is allowed to flow with respect to granular solid and this process is assumed to be governed by Darcy flow law with the coefficient of permeability as the material constant. Above the water table, soil is modeled as one phase solid. A nonlinear material model is used in the program which includes yielding, failure, volume change characteristics, cyclic effects and criteria for initial and final liquefaction. Two different material models are used for the behavior of soil before and after initial liquefaction. All the material parameters needed for the material model used in this program can be determined from routine laboratory tests.

The CUMLiq software is used for the evaluation of potential for liquefaction of a soil deposit using random vibration procedures. This tool estimates the potential for seismic liquefaction using known field and laboratory data of soils in combination with general statistical parameters of earthquakes. The program is designed to perform the operation according to the mathematical procedure described in "A Stochastic Approach to the Seismic Liquefaction Problem," by N.C. Donovan. A check on the applicability of the method was made by recomputing the 34 cases of liquefaction and non-liquefaction reported by Seed and Peacock in 1970.

The CPTInt software is a menu driven program for CPT and CPTU interpretation. More than 35 different correlation parameters including interpretation for soil classification type by friction and pore pressure ratios, relative density and internal friction by 3 methods, SPT-N and N_1, cyclic stress ratio to cause liquefaction and that applied by earthquake, dynamic shear modulus, constrained modulus and Young's modulus over various depth intervals with a choice of units can be calculated in the parameter menu.

The Liquiter software determines by the Seed and Idriss (1982) method for the safety factor against liquefaction of saturated noncohesive layers subjected to earthquake loading. For the program, the input data are the soil unit weight, SPT relative density and the median particle diameter together with the seismic parameters necessary to simulate the earthquake. For each SPT test a correction factor is calculated that is a function of the depth where the test is performed and the relative density. It is possible to consider the presence of a surface load or the overlying layers. The analysis is based on the resistance factor to liquefaction calculated as the ratio between the limit shear stress that induces liquefaction and the maximum shear stress induced by the earthquake, taking into account the pore pressures and deformations developed during the earthquake.

The CLiq software analyses liquefaction potential from CPT data. It provides users with a graphical environment specifically tailored for CPT and CPTU data. The software addresses advanced issues such as cyclic softening in clay like soils and thin layer transition zone detection. It provides results and plots for each calculation step, starting with the basic CPT data interpretation through to final plots of factor of safety, liquefaction potential index and post earthquake displacements, in both vertical settlement and lateral displacements.

The LiqIT software carries out the analysis of liquefaction of loose saturated cohesionless soils under the effect of strong ground motion. It is based on commonly used field data. It utilizes the most recent and well-known deterministic and probabilistic methods. The data are taken from field data input from SPT, CPT and Vs measurements. Overall liquefaction potential evaluation is according to Iwasaki formula.

The Peysanj software is a suite of geotechnical program to carry out analysis of bearing capacity, liquefaction, plate load test, pressuremeter test, lateral earth pressure and retaining wall calculations.

The SoilGeophysical software is an spreadsheet for geophysical and geotechnical analysis of bearing capacity for both static and seismic analysis, settlement analysis, simple slope stability, seismic hazard analysis, strong motion attenuation relationships, acceleration, displacement, velocity spectra, simple soil amplification analysis, soil liquefaction analysis.

The SPTLiq software analyzes liquefaction potential and earthquake induced ground settlements using standard penetration test (SPT) data based on the simplified Seed and Idriss procedures.

The CPTLiq software analyzes liquefaction potential and earthquake induced ground settlements using cone penetration test (CPT) data based on the simplified Seed and Idriss formula.

The LatSpread software estimates the magnitude of anticipated liquefaction induced lateral spreading based on the empirical methods developed by Youd, Hansen, and Bartlett (1999) and Bardet, Mace, and Tobita (1999) for a user specified design earthquake.

The LiquefyPro software assists engineers in evaluating liquefaction potential and earthquake induced settlement. It is based on the most recent publications and conference proceedings to find commonly accepted and state of the art calculation procedures. It offers multiple methods of calculation. Users can use a default method of calculation; or more advanced users can select an approach more suited to their local conditions. The plot option of CRR, CSR, factor of safety, and settlement can be done. Also, the plot of soil profile is possible. Choice of SPT, CPT and BPT input data can be used.

The Geostress software predicts in-situ ground deformation response to both stress and thermal induced activities, and can model consolidation, seismic loading, and creep of frozen soil. It allows the user to prescribe initial temperatures, pressures, loads, displacements, and strains, and will permit construction sequence simulations for excavations, earth fills and structural loadings. The model features a coupled solution of pore pressure response, giving it the ability to model transient changes in effective stress, consolidation and seepage for complex engineering applications. The program also includes the use of post peak strain softening models that permit analysis of statically and dynamically induced liquefaction failures, and of slope instability caused by progressive failure.

The CyberQuake software is used for determining seismic soil responses. It includes an extensible accelerogram database, tools for pre and post processing of seismic signals, graphics. Nonlinear elastoplastic or equivalent linear computations may be carried out on multi layered, dry or saturated soil profiles (Figure 2). The dynamic soil response is computed with the elastoplastic assumption for soil deposits. The main features of the soil behavior, such as shear modulus and damping ratio variation are reproduced by the cyclic constitutive model in a large strain range.

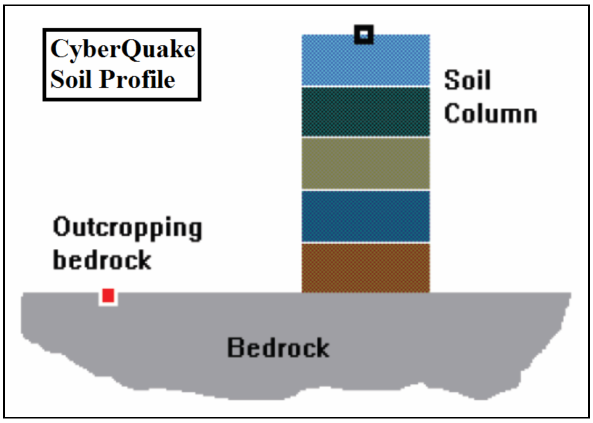

Figure 2. An Example of 1D Soil Profile from Softwares of CyberQuake.

The ZSoil software is a geotechnical, foundation and underground flow engineering program based on the finite element method that simulates most of the natural processes encountered in geotechnical and foundation engineering including stability, consolidation, creep, excavation and underground flow and liquefaction.

2D liquefaction analysis

The Versat-2D software is a computer program for dynamic 2D plane strain finite element analyses of earth structures subjected to dynamic loads from earthquakes, machine vibration, waves or ice actions (Figure 3). The dynamic analyses can be conducted using linear, or nonlinear, or nonlinear effective stress methods of analysis. The program can be used to study soil liquefaction, earthquake induced deformation and dynamic soil-structure interaction such as pile supported bridges. It has the ability of evaluating effective stress model including dynamic pore water pressure and three models for computing dynamic pore water pressure; modified stiffness parameters by dynamic pore water pressure; calculation of ground deformations caused by soil liquefaction; calculation of factor of safety against liquefaction.

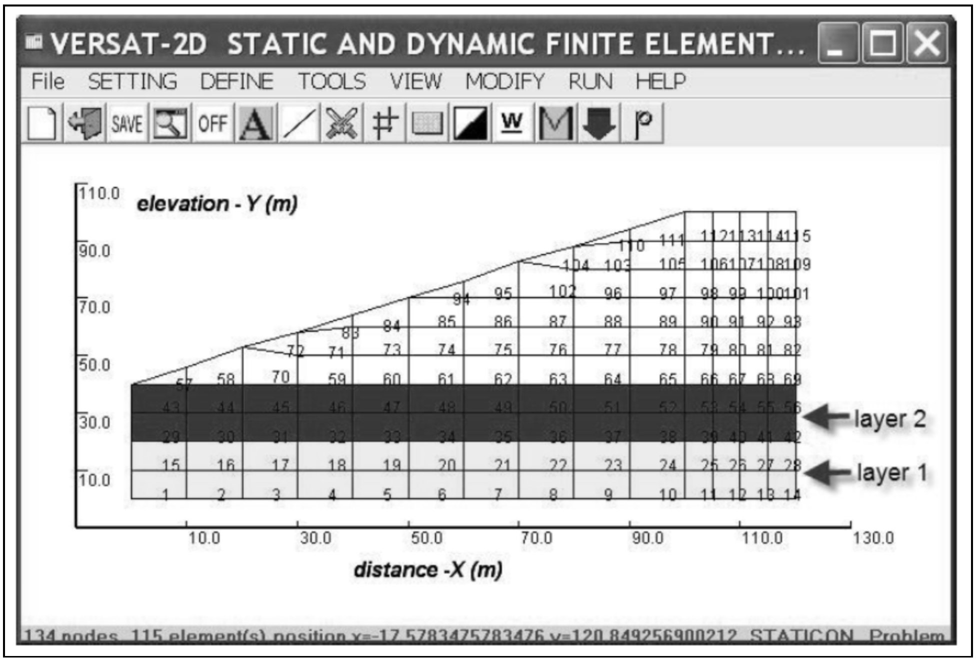

Figure 3. An Example of 2D Soil Profile from Softwares of Versat-2D.

The Swandyne software is a dynamic interaction and nonlinear 2D program which uses the fully coupled. Dynamic equation with the assumption that the fluid acceleration relative to the solid is negligible. The program uses finite elements of both triangle and quadrilateral in shape. Since fluid velocity can be eliminated in differential equation stage so the resulting variables are skeleton displacement (u) and pore pressure (p). This is why it is called the u-p formulation. The program can be used to deal with static, consolidating, and dynamic conditions under draining or undrained conditions. The program includes a library of constitutive models which can deal with monotonic to cyclic loading of sand and clay including the modeling of liquefaction behavior.

3D liquefaction analysis

DYNAFLOW is a general purpose finite element analysis program for linear and nonlinear, two- and three-dimensional, elliptic, parabolic and hyperbolic initial boundary value problems in structural, solid and fluid mechanics. Although DYNAFLOW™ can be a very powerful analysis tool, it should be emphasized that its use requires a thorough understanding of the underlying field theories used, and of the integration techniques (both in space and time) employed.

The FEQDrain software is a finite element computer program for the analysis of the earthquake generation and dissipation of pore water pressure in layered sand with vertical drains. One method of soil stabilization for potentially liquefiable sites is the use of a system of vertical drains to dissipate the excess pore water pressure generated by earthquake loading, thus avoiding liquefaction. Performance assessments for these systems require the estimation of vertical drain spacing such that a maximum threshold level of excess pore pressure ratio is not exceeded. This program can be used to analyze 3d pore pressure generation and dissipation in layered sand deposits with geocomposite vertical drains for liquefaction mitigation. There are four different modes in which to analyze a problem. Option 1 considers the performance of a soil profile without any ground improvement. Pore pressure generated by the earthquake can only migrate in a vertical direction. Option 2 examines soil layers with perfect drain that dissipates any pore pressure that reaches it. Option 3 examines soil layers with a drain, but with constant values of vertical and horizontal hydraulic conductivity within the drain. Option 4 examines soil layers with a drain with properties guiding the nonlinear resistance that water will feel as it flows into and through the drain.

The Diana software is a well proven and tested software package with a reputation for handling difficult technical problems relating to design and assessment activities in concrete, steel, soil, rock and soil-structure interaction. Example mesh geometry of soil for dynamic analysis is given in Figure 4.

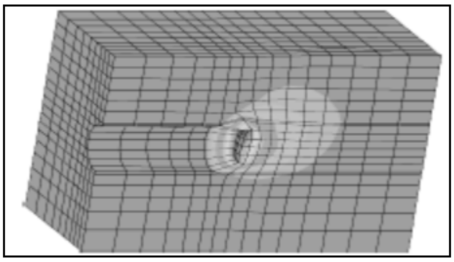

Figure 4. An Example 3D mesh geometry of soil for dynamic analysis with Diana.

The program's robust functionality includes extensive material, element and procedure libraries based on advanced database techniques, linear and non-linear capabilities, full 2D and 3D modeling features and tools for CAD interoperability. Its analysis types are linear static analysis; non-linear analysis; potential flow analysis; coupled flow-stress analysis; dynamic analysis; phased analysis; Euler stability analysis; parameter estimation; Lattice analysis. The program offers also powerful solution procedures. Main functionalities include direct and iterative solvers; automatic load and time stepping; several incremental- iterative methods (Newton-Raphson, Secant stiffness, Constant stiffness), Continuation methods and line search technique, Automatic sub structuring. The material models are elasticity, cracking models, plasticity, soil specials, viscoleasticity, interface non-linear models, temperature dependent material parameters, viscoplasticity, hyper elasticity, user supplied material models.

Geotechnical applications often provide engineers with technically demanding challenges that can be advantageously solved with the program. It offers full 3D modeling capabilities that can be used in applications as diverse as foundations, embankment, tunnels, excavations, mines and dams.

In addition, since soil is a multi phase material, special procedure has been implemented to deal with pore pressure modeling in the soil. Advanced analysis capabilities are also available for ground water flow, consolidation, earthquake and liquefaction process that are essential for accurate prediction of those types of coupled problems. It allows modeling of the full dynamic response of a system to be simulated either in the frequency domain or in the time domain. Time domain analyses may be undertaken assuming both material and geometrical nonlinearities. It also contains a specific library of material models for simulating the material behavior of liquefied soil: Towhata-Iai model, Nishi model and Ramberg-Osgood-Bowl model. In transient analysis you can optionally add a viscous contribution to the constitutive models for liquefaction analysis. This viscosity can be a constant value or a multi linear function of the excess pore pressure ratio.

The Flac 3D software is a numerical modeling code for advanced geotechnical analysis of soil, rock, and structural support in three dimensions. It is used in analysis, testing, and design by geotechnical, civil, and mining engineers. It is designed to accommodate any kind of geotechnical engineering project where continuum analysis is necessary. It utilizes an explicit finite difference formulation that can model complex behaviors not readily suited to FEM codes, such as: problems that consist of several stages, large displacements and strains, non-linear material behavior and unstable systems.

The dynamic analysis option permits three dimensional, fully dynamic analyses with it. The calculation is based on the explicit finite difference scheme to solve the full equations of motion, using lumped grid point masses derived from the real density of surrounding zones. This formulation can be coupled to the structural element model, thus permitting analysis of soil structure interaction brought about by ground shaking.

The dynamic feature can also be coupled to the groundwater flow model. This allows, for example, analyses involving time dependent pore pressure change associated with liquefaction. The dynamic model can likewise be coupled to the optional thermal model in order to calculate the combined effect of thermal and dynamic loading. The dynamic option extends its analysis capability to a wide range of dynamic problems in disciplines such as earthquake engineering, seismology. An example of 3D soil profile is given in Figure 5.

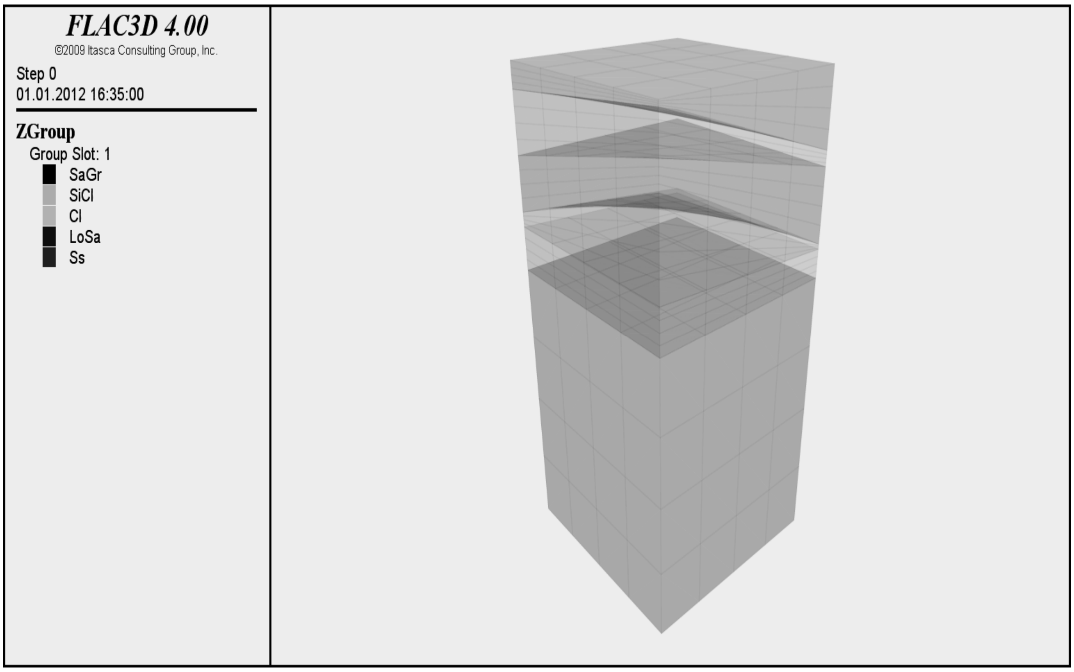

Figure 5. Example of 3D soil profile for dynamic analysis with Flac 3D.

Optional modules include: thermal and creep calculations, dynamic analysis capability, and user defined constitutive models written in C++ Continuous gradient or statistical distribution of any property may be specified Automatic 3D grid generator using predefined shapes to create intersecting internal regions convenient specification of boundary conditions and initial conditions water table for effective stress calculations round water flow fully coupled to mechanical calculation Structural elements (liners, piles, cables, etc.) that interact with the surrounding rock or soil built-in programming language (FISH) to add user-defined features. Graphical output in six industry standard image formats and animated output in two (AVI and DCX) external geometry import option for leading computer aided design (CAD) tools.

Comparisons

The comparison of usefulness of the liquefaction analyses programs can be done by looking at the advantages and disadvantages that are focusing on different parameters. Some of these parameters are given in Table 1 to compare them.

Table 1. Different Properties of Liquefaction Analyses Programs.

Program Name	Methods based on	Soil Layer Properties	Earthquake Motion	Used Test Types Parameters	Analysis Possible in Dimensions of			Factor of Safety	Cooperate with Other Programs
					1D	2D	3D		
Apollo	Simplified Formulas Approach	1D Seepage profiles	No Information	No Information	Yes	No	No	No	No
Shake 2000	Simplified Formulas Approach	for All Types of Soils	No Information	SPT, CPT	Yes	No	No	No	Shakedit and Shake
LASS-II	Laboratory Test Results Approach	Horizontally layered saturated soils	No Information	SPT, CPT, etc.	Yes	No	No	No	No
CUMLiq	Stochastic Approach	for All Types of Soils	General statistical parameters for Earthquake motion	No Information	Yes	No	No	Yes	No
CPTInt	CSR based Approach	No Information	Use dynamic shear modulus and other parameters	SPT, CPT	Yes	No	No	Yes	No
Liquiter	Based on Resistance factor	Saturated noncohesive soils	No Information	SPT	Yes	No	No	Yes	No
CLiq	Simplified Formulas Approach with CPT	for All Types of Soils, also focus on clay like soils	No Information	CPT	Yes	No	No	Yes	No
LiqIT	Deterministic and Probabilistic Methods Approach	Loose saturated cohesionless soils	Iwasaki formula	SPT, CPT, Vs	Yes	No	No	Yes	No
Peysanj	Simplified Formulas Approach	No Information	No Information	No Information	Yes	No	No	No	No
Soil Geophysical	Simplified Formulas Approach with Spreadsheet	for All Types of Soils	No Information	SPT, CPT	Yes	No	No	No	No
SPTLiq	Seed and Idris formulas Approach	for All Types of Soils	No Information	SPT	Yes	No	No	Yes	No
CPTLiq	Seed and Idris formulas Approach	for All Types of Soils	No Information	CPT	Yes	No	No	Yes	No

Programe Name	Methods based on	Soil Layer Properties	Earthquake Motion	Used Test Types Parameters	1D	2D	3D	Factor of Safety	Cooperate with Other Programs
LatSpread	Empirical Method Approach	No Information	No Information	No Information	Yes	No	No	No	No
LiquefyPro	Multiple Methods Choice	for All Types of Soils	No Information	SPT, CPT, BPT	Yes	No	No	Yes	No
Geostress	Pore Pressure Calculation Approach	for All Types of Soils	No Information	SPT, CPT	Yes	No	No	Yes	No
Cyber Quake	Deterministic Approach	Multilayered, dry or saturated soils	Dynamic response is computed with elastoplastic assumptions	SPT, CPT, Vs	Yes	No	No	Yes	No
ZSoil	FEM	for All Types of Soils	No Information	SPT, CPT	Yes	No	No	Yes	No
Versat-2D	FEM with 3 models for Computing Dynamic Pore Pressure	for All Types of Soils	Dynamic analyses using linear, nonlinear or nonlinear effective stress methods	No Information	Yes	Yes	No	Yes	No
Swandyne	FEM with both triangle and quadrilateral shapes	Sand and clay	No Information	No Information	Yes	Yes	No	Yes	No
DYNAFLOW	FEM	for All Types of Soils	Eq. acc. time history generation, for eq. motions compatible with prescribed acc. response spectra	SPT, CPT, Vs	Yes	Yes	Yes	Yes	FEMGV etc.
FEQDrain	FEM with 3D pore pressure generation	Only Sand with vertical drains	Earthquake motion possible in different direntions	SPT, CPT, etc.	Yes	Yes	Yes	Yes	No
Diana	FEM with 3D pore pressure generation	for All Types of Soils	Full dynamic response of a system is possible	SPT, CPT, Vs, etc.	Yes	Yes	Yes	Yes	CAD, Excel, etc.
Flac 3D	FDM with 3D pore pressure generation	for All Types of Soils	Full dynamic response of a system is possible	SPT, CPT, Vs, etc.	Yes	Yes	Yes	Yes	CAD, FISH, C++, etc.

On the other hand, there are also other parameters that affect the success of developed models. Some of these are time of model running, time of developing the model, user defined opportunities, used coefficients because of the program needs (calibrations) and the multiplicity of example models in the literature and etc. After these comparisons are done, some recommendations are taken into account. In case of, working with pore pressures are important the most recommended programs to cope with liquefaction analysis by using pore pressure generations are given in Table 2.

Table 2. Recommended programs to cope with liquefaction analysis with pore pressure generations.

Program Name	Generation Success
Flac 3D	1
Diana	2
FEQDrain	3
Versat-2D	4
Geostress	5

If the modeling and the analyzing time is important and the engineer wants to get preliminary results for the case, using software which is not so complex to use and which gives result with a good success rate must be chosen. For this reason, the recommended programs for solving the liquefaction potentials in a short time are given in Table 3.

Table 3. Recommended programs for solving liquefaction potentials in a short time.

Program Name
Shake 2000
CPTInt
LiqIT
LiquefyPro
Cyber Quake

In this study, it is shown that to do liquefaction analysis with programs is not so easy because of the software’s complexity. But in the doctorate thesis by modeling finite difference based model, neural network based model and simplified model, it is seen that despite difficulty of working with three dimensional, FEM and FDM approaches, choosing detailed programs are giving more trustful results. Some programs that are recommended for solving liquefaction potations in detailed models are in Table 4.

As a result, a detailed search about the qualities and properties of the suitable program must be done before a detailed liquefaction analysis.

Table 4. Recommended programs to solve 3D liquefaction potential in detailed models.

Program Name
Flac3D
Diana
FEQDrain

Discussion

Come to realize the importance of earthquake induced liquefaction risk areas; given the speed and results of analysis of the structure in terms of potential importance for the region can be seen. Therefore, the liquefaction analysis programs described above in terms of general features are compared in this article.

However, in addition, by using all programs analysis must be done with liquefiable region datasets and both the results and effectiveness of the programs should be performed and compared. Matters to be considered here is; the scope of work will take longer to finish all analyses and the researcher's who will do the models must be proficient about liquefaction programs and liquefaction occurrence.

In addition, this study is a part of the doctoral thesis and comparison of the numerical methods, as part of the thesis, were taken into consideration by numerical results in the thesis related chapters.

Conclusion

In conclusion, in these programs the methods, properties, calculation types differs from each other and to address liquefaction engineering, this paper proposed to focus on comparing different software programs used to evaluate and analyze liquefaction potentials to impact homes and to recommend some programs for different conditions. It is observed that detailed modeling such an important issue is critical to get the correct results. Therefore, for future works a more detailed study will be performed by solving the same case with all the software programs, inclusive of Flac 3D, Neuroshell and Simplified formula procedures.

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