Integrated procedure for dynamic analysis of fault-soil-structure systems

Procédure complète pour l'analyse dynamique des systèmes faille-sol-structure

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SYNOPSIS: An analysis procedure for fault–soil–structure systems based on the Monte Carlo simulation method is presented. Both ground motion (near field and far field) and spatial distribution of soil properties are first generated using various spectral representation–based procedures. Next, dynamic nonlinear finite element simulations with stochastic input are performed. The procedure is used for assessment of soil liquefaction potential and for predicting the seismic response of large scale structures.

1 INTRODUCTION

Input ground motion and mechanical properties are the two main categories of data required for dynamic structural analysis and, as shown hereafter, are both probabilistic entities.

The characteristics of seismic ground motion at a specific location (e.g. frequency content, amplitude) are mainly governed by (1) distance from the seismic source, (2) local soil conditions, and (3) magnitude of the event. As a consequence of wave propagation and loss of coherence, there is a certain spatial variation of seismic ground motion from one location to another. To this end, the earthquake ground motion over the domain of interest can be described by a non–stationary stochastic vector process with evolutionary power, each component of the vector process representing the motion at a certain spatial location (e.g. Deodatis, 1996).

Many physical systems in general and soil materials in particular exhibit relatively large variability in their properties, even within so called homogeneous zones. Deterministic descriptions of this spatial variability are not feasible due to prohibitive cost of sampling and to uncertainties induced by measurement errors. A more rational approach to geotechnical design is made possible by use of stochastic field based techniques of data analysis, which rely more on analytical methods when dealing with various uncertainties related to soil properties. The relevant material properties over the analysis domain can be modeled as a multi–variate, multi–dimensional (mV-nD), non–Gaussian stochastic field (e.g. Popescu, 1995).

The integrated procedure for fault–soil–structure system analysis presented in the following (Fig. 1) is intended for case studies related to the analysis of ground motion, assessment of soil liquefaction, and prediction of seismic response of buildings, bridges and underground structures. The statistics of the structural response are obtained by performing Monte Carlo simulations consisting of digital generation of ground motion and sample vector fields of soil material parameters, combined with nonlinear dynamic finite element analyses.

2 SEISMIC GROUND MOTION

Three options for constructing seismic excitations are available (Fig. 1a).

2.1 Recorded Time Histories

A data base containing acceleration records of relevant seismic events has been developed. A series of procedures for transforming (e.g. scaling, filtering) the records, and displaying the characteristics of various time histories (e.g. frequency content, response spectra) help the user in selecting the appropriate input motion as ground acceleration or displacement.

2.2 Response Spectrum Compatible Acceleration

Design codes provide response spectra to be used in structural seismic analyses. Different response spectra are prescribed for various locations, corresponding to the local soil conditions. An example is provided in Fig. 2a, where the first three types of response spectra correspond to the Uniform Building Code (International, 1994), with type 1 for rock and stiff soils, type 2 for deep cohesionless or stiff clay soils, and type 3 for soft to medium clays and sands. The foutrh response spectrum, with a range of maximum spectral values corresponding to frequencies that are lower than for types 1,2 and 3, is characteristic for locations close to the epicenter.

A methodology proposed by Deodatis (1996) is used to generate seismic ground motion time histories at several locations on the ground surface that are compatible with prescribed response spectra, are correlated according to a given coherence function, include the wave propagation effect, and have a specified duration of strong ground motion. The duration of the strong motion is controlled by modulating functions selected according to the model suggested by Jennings et al (1968). The effectiveness of the algorithm is illustrated in Figure 2b, where the prescribed type 4 response spectrum (continuous line) is compared to the response spectrum (dotted line) computed from the corresponding simulated acceleration time history. Two generated sample functions, compatible with type 2

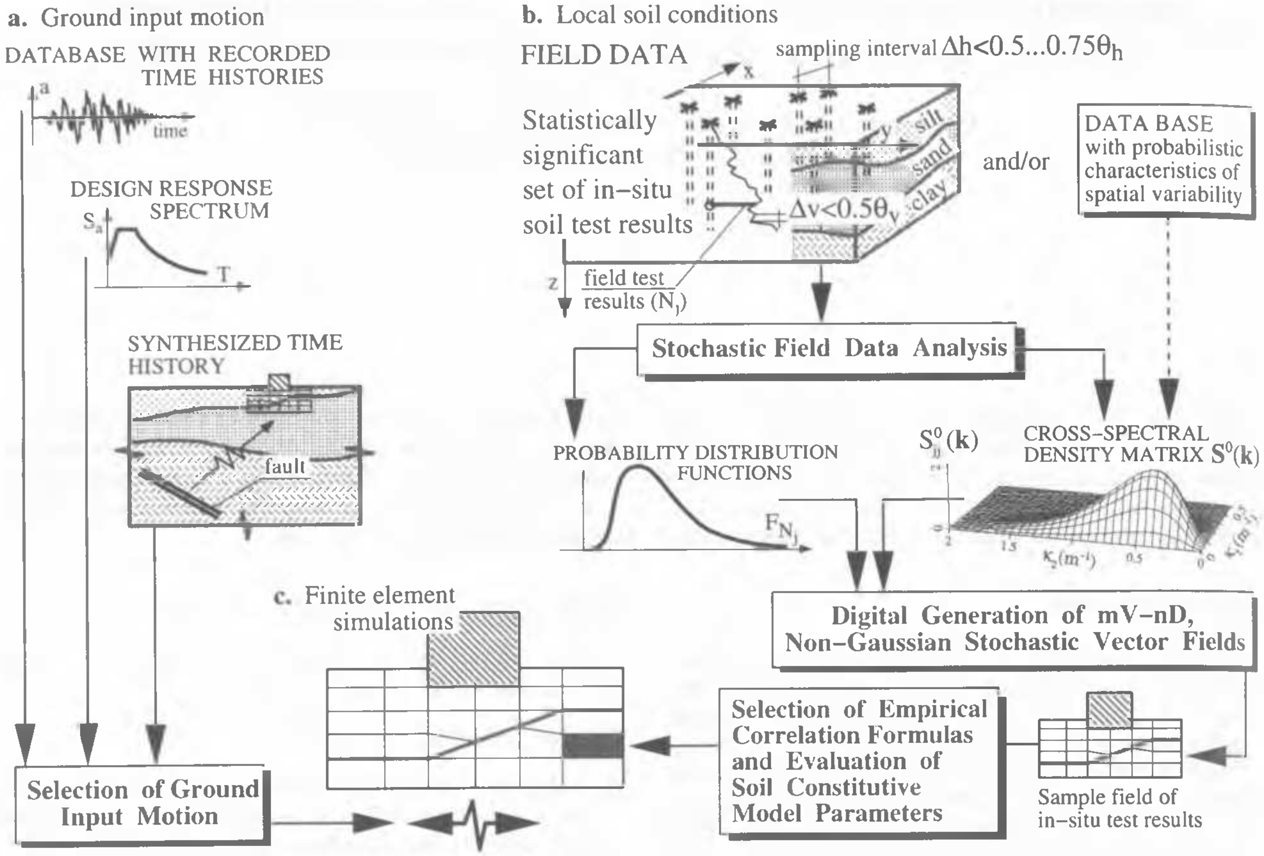

Figure 1. Flow chart of the integrated procedure for fault–soil–structure analysis.

and type 4 response spectra, respectively, are plotted in Fig. 2c.

2.3 Synthesis of Earthquake Ground Motion

Another option (Fig. 1a) is the synthesis of seismic ground motion (e.g. Zhang and Deodatis 1996). The discrete wave number technique is used to propagate waves due to the rupture of an extended seismic source through a 3-D layered half-space. With this method, it is possible to calculate the near-field and the far-field seismic ground motion at any point of a layered viscoelastic half-space, such that the spatial variability of ground motion at distances comparable to the dimensions of engineering structures can be estimated. All types of waves (body and surface) are accounted for in the formulation of the problem. Ground motion time histories with frequency content up to 3 Hz can be calculated. The extent and magnitude of permanent ground deformation can also be computed, which is very important in the earthquake response of large scale engineering structures with relatively low natural frequencies of vibration, such as long span bridges.

3 ESTIMATION OF SOIL PROPERTIES

3.1 Stochastic Analysis of Field Data

Experimental evidence shows that there is natural variability of soil properties within distinct and uniform layers. Even in case of supposedly homogeneous man–made fills, this variability is strongly manifested, as illustrated in Fig. 3a by the results of a series of piezocone tests performed for a hydraulically placed sand (Gulf, 1984): recorded cone resistance exhibits random fluctuations about some average values shown with thick lines in Fig. 3.

As expected, some degree of coherence between the fluctuations can be observed, which becomes stronger as the measuring points are closer together. This is illustrated in Fig. 3a by the presence of loose pockets (where recorded values are consistently lower than the expected average) and dense pockets in the soil mass. This spatial coherence is mathematically captured by the concept of correlation function, with its parameters expressed in terms of "correlation distances". The correlation distance can be thought as representing a length over which significant coherence is still manifested.

The probability distribution function of soil properties is another important characteristic of spatial variability. For the fluctuations of cone tip resistance shown in Fig. 3a, a skewed Beta distribution was found to fit the empirical distribution of the field test results.

Whenever simultaneous field measurements are available (e.g. piezocone tests provide cone tip resistance, sleeve friction and dynamic pore pressure) it is possible to estimate the cross–correlation between various soil properties. Consequently, the assembly of field test results over the domain of interest can be viewed as a multi-variate, multi-dimensional (mV-nD), non-Gaussian stochastic field,

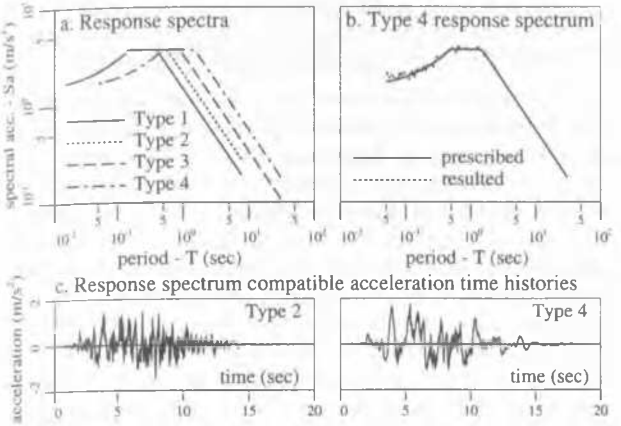

Figure 2. Response spectrum compatible acceleration time histories: a. prescribed response spectra; b. prescribed and resulted values for the type 4 response spectrum; c. simulated sample functions.

each scalar component of the vector field representing one of the relevant soil properties. The probabilistic characteristics of the stochastic field are (Fig. 1b): (1) the cross–correlation structure, represented in the wave–number domain as a cross–spectral density matrix, and (2) the probability distribution function of each component. For a detailed presentation of field data analysis procedures leading to estimation of probabilistic characteristics of spatial variability, the reader is referred to Popescu et al, 1997c.

For the case when available field data is inadequate for stochastic analysis (e.g. when the sampling distance is larger than the expected correlation distance), the user can rely on information obtained from soil deposits with similar characteristics, which is stored in a database. Conversely, the database is updated every time a new stochastic analysis is performed based on a significant set of field test results.

3.2 Digital Generation of Vector Fields

Based on the probabilistic characteristics of spatial variability inferred from in–situ soil data analysis, sample functions of a stochastic vector field are then generated. Each sample function represents a possible realization of relevant field test results over the analysis domain. Such a sample function, with values of cone tip resistance simulated at the field test locations, is presented in Fig. 3b. It can be observed that recorded and simulated values are different at each spatial location, but they have the same average values and exhibit identical probabilistic characteristics.

The simulation algorithm uses a spectral representation–based method to generate sample functions of an mV–nD, non–Gaussian stochastic vector field, which are compatible both with a prescribed cross–spectral density matrix and with prescribed non–Gaussian probability distribution functions. A Gaussian stochastic vector field is first generated, according to its target cross–spectral density matrix. It is then mapped into a non–Gaussian vector field, using a memoryless transformation in conjunction with an iterative scheme (Yamazaki and Shinozuka, 1988). For a detailed description of the proposed algorithm, and a discussion of issues concerning its rate of convergence, the reader is referred to Popescu et al. (1997a).

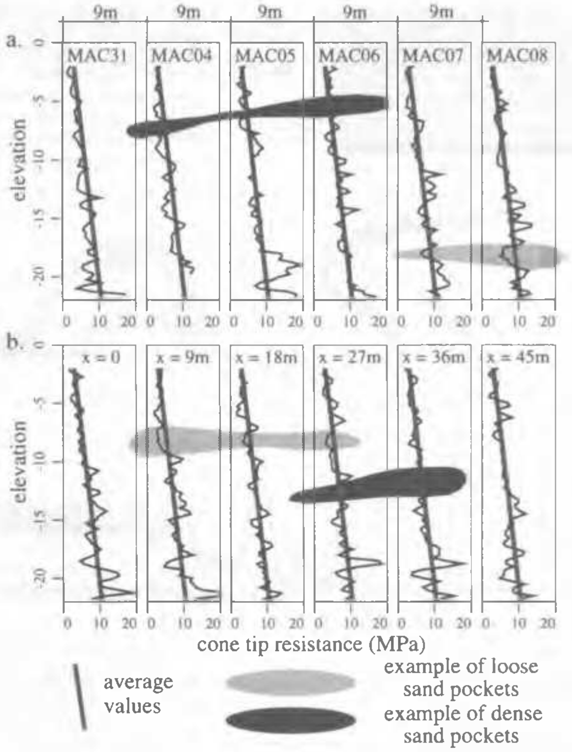

Figure 3. Comparison between in–situ recorded cone tip resistances (a.) and simulated values obtained at the same locations from one sample function (b.).

3.3 Estimation of Soil Constitutive Parameters

The parameters of the soil constitutive model to be employed for numerical simulations are evaluated at each spatial location (finite element centroid) over the analysis domain, based on simulated in–situ test values (Fig. 1b). An automated procedure was implemented to estimate the parameters of a multi–yield plasticity model (Prevost, 1985) from cone penetration or standard penetration test results. The user is prompted to select from a large number of empirical correlation formulas reported in the literature those correlations which best suit the specific soil materials used in the application.

3.4 Stochastic Input Finite Element Simulations

For each simulated sample function representing field test results it corresponds one set of soil constitutive parameters, representing stochastic input for one finite element simulation (Fig. 1c). The numerical computations are performed using the code DYNAFLOW (Prevost, 1995), which is a finite element analysis program for static and transient response of linear and nonlinear two– and three–dimensional systems. The Monte Carlo simulation results are provided in terms of a range of predictions, as shown in the next section. Providing that the number of sample functions is sufficiently large, the statistics of structural response can be inferred.

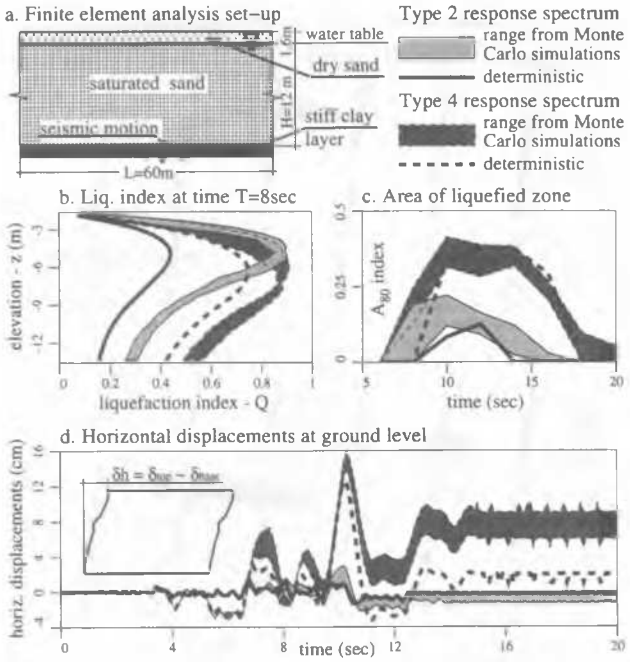

Figure 4. Liquefaction strength assessment of a soil deposit.

4 NUMERICAL EXAMPLE

Liquefaction risk assessment of a saturated soil deposit is presented next to illustrate the proposed Monte Carlo procedure. A loose to medium dense hydraulically placed sand deposit (Fig. 4a), with geomechanical properties as well as spatial variability characteristics estimated from the piezocone test results presented in Fig. 3a, is subjected to a horizontal earthquake motion. Response spectrum compatible acceleration time histories are used, considering two possible situations (Fig. 2c): type 2, for large epicentral distance, and type 4, corresponding to a site close to the epicenter.

Six sample functions of a stochastic vector field with probabilistic characteristics estimated from field data analysis are used to derive six sets of stochastic input parameters for the soil constitutive model used in the finite element program. Some of the numerical simulation results are presented in Fig. 4 in terms of:

1. Liquefaction index (Fig. 4b):

$$Q(z,t) = \frac{1}{L}\int_0^L r(x,z,t)\mathrm{d}x \qquad (1)$$

where $r(x,z,t) = \frac{u(x,z,t)}{\sigma'_{v0}(x,z)}$ is the ratio of excess pore pressure with respect to the initial effective vertical stress, and L is the dimension of the analysis domain in horizontal direction (Fig. 4a).

2. Area of liquefied zone (Fig. 4c):

$$A_{80}(t) = \frac{1}{LH}\int_0^H \int_0^L 1_{[r(x,z,t)\geq 0.8]}\mathrm{d}x\mathrm{d}z \qquad (2)$$

where H is the depth of the saturated soil layer (Fig. 4a).

3. Horizontal displacements at the ground level, relative to the displacements at the base, where the input motion is applied (Fig. 4d).

The results of Monte Carlo simulations are shown in Fig. 4 by shaded areas representing ranges of predictions obtained from six sample functions. Results of deterministic finite element analyses, obtained using the average values of soil parameters, are also presented for comparison. It can be concluded that the amount of dynamically induced pore water pressure build–up and, consequently, the seismic response of saturated soil deposits are strongly affected by spatial variability of soil properties, as well as by the frequency content of seismic motion. For more details on these effects and their implications to geotechnical design, the reader is referred to Popescu et al (1997b).

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