# Overview of Development of P-CARES: Probabilistic Computer Analysis for Rapid Evaluation of Structures

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## ABSTRACT

Brookhaven National Laboratory (BNL) undertook an effort to revise the CARES (Computer Analysis for Rapid Evaluation of Structures) program under the auspices of the US Nuclear Regulatory Commission (NRC). The CARES program provided the NRC staff a capability to quickly check the validity and/or accuracy of the soil-structure interaction (SSI) models and associated data received from various applicants. The aim of the current revision was to implement various probabilistic simulation algorithms in CARES (referred hereinafter as P-CARES [1]) for performing the probabilistic site response and soil-structure interaction (SSI) analyses. This paper provides an overview of the development process of P-CARES, including the various probabilistic simulation techniques used to incorporate the effect of site soil uncertainties into the seismic site response and SSI analyses and an improved graphical user interface (GUI).

## INTRODUCTION

In the process of review and evaluation of nuclear power plant (NPP) structure designs, it is essential to understand the behavior of seismic loading, soil condition, foundation, and structural properties and their impact on the overall structural response. During the late 1980's, BNL developed the CARES program [2] for the NRC. The program provided the NRC staff with a coherent approach to effectively perform evaluations of the seismic response of relatively simplified soil and structural models. Such an approach provided the NRC staff with a capability to quickly check the validity and/or accuracy of the soil-structure interaction (SSI) models and associated data received from various applicants. By performing simplified model studies, the sensitivity of computed responses to variations in a host of controlling parameters can often be evaluated and thereby assist the staff in gaining confidence in the results obtained from the more detailed analyses.

The initial version (Version 1.0, [2]) of the CARES program was developed by combining two available computer programs which treat the free-field response calculation (the SLAVE Code, [3]) and the soil-structure interaction analysis of simplified stick models (the SIM Code, [4]) to perform simplified deterministic site response and SSI analyses. CARES was later revised to improve various analysis capabilities [5-7]. However, CARES was developed for deterministic site response and SSI analysis, and lacked the capability to perform probabilistic analysis.

Large uncertainty exists in seismic response analyses of structures. The uncertainty arises mainly from the limited understanding of the seismic sources, attenuation relations, local site soil effect, and structural properties. The current procedure for quantifying the uncertainty in seismic response analyses is to use deterministic bounding approaches such as those outlined in the Standard Review Plan (SRP) 3.7 [8] and ASCE 4-98 [9], which are widely viewed as being conservative. Recent advances in the stochastic seismic analysis have shown that a more accurate prediction of the seismic response considering uncertainty can be obtained by utilizing the probabilistic procedure. Recently published ASCE 43-05 [10] has opted for the probabilistic approach for determining the design factor for soil site, given a rock input motion. ANS "External Event PRA Methodology Standard" (ANSI/ANS-58.21 [11]) went a step further to require a probabilistic SSI response analysis for a complete-scope seismic probabilistic risk assessment (SPRA). One of the objectives of the P-CARES development is to provide a useful tool for performing the probabilistic site response and SSI analyses.

Important tasks in the probabilistic simulation are to manage the simulation process and to organize a large amount of samples and output data. P-CARES integrates various probabilistic features and ground motion analysis functions in one coherent package through a GUI, which provides a convenient on-screen model building capability for soil and structural models, automatic analysis management, and intuitive feedback of figures. The GUI can therefore greatly improve the usability and productivity of P-CARES.

This paper provides an overview of the development process of P-CARES. The quantification and treatment of uncertainties and the probabilistic simulation techniques in P-CARES will be first introduced, followed by a summary of the major features of the P-CARES program.

## DESCRIPTION of UNCERTAINTIES

As introduced in the previous section, the uncertainties in the seismic response analysis of the soil-structure systems include contributions from a number of sources. However, the level of uncertainties to be addressed in P-CARES is limited

to local site soil effects at this development stage. The uncertainties in structural properties, e.g., the lumped masses and the Young's moduli, are relatively small compared to other sources of uncertainties, and could be neglected without loss of much accuracy in SSI analyses. Uncertainty in ground motions is probably the largest among all sources. The implementation of a probabilistic procedure to capture the uncertainty in ground motions requires the development of a ground motion database binned in terms of magnitude and distance in a manner that allows for extending the probabilistic simulation to the ground motion database. Since the development of a comprehensive ground motion database could require sizeable effort, it was, therefore, not included in the current version of P-CARES. However, it could be considered as a future improvement to the program.

Local site soil is modeled as 1D horizontal layered soil columns in P-CARES. For each layer, the soil density, the low-strain soil shear modulus, and the layer thickness are considered random and assigned as random variables in P-CARES. Since the material damping ratios for all soil layers are obtained using the soil degradation curves and are strain-compatible with the user-specified seismic motion input, these damping ratios are treated as deterministic variables. Suppose there are $N$ layers in a soil column model, then the total number of random variables is $n = 3 \times N$ (the soil density, the shear modulus, and the layer thickness for each layer). The number of samples used in the simulation is designated as $m$ hereafter.

Lognormal distribution has been chosen to describe the marginal probability distribution for all random variables. It is reasonable when considering that (1) the soil properties are all positive, (2) the difference between a lognormal distribution and a normal distribution is small for small variations [12, 13], and (3) it is sufficient to model the layer thickness by selecting a small coefficient of variation (COV). Assuming all random variables of lognormal distribution also provides a great convenience for describing the layer-to-layer correlations, and therefore allows for a very efficient implementation suitable for the intended applications of P-CARES.

An arbitrary feasible correlation between properties for different layers can be specified in P-CARES. P-CARES can rapidly initiate the correlations between soil densities and between soil shear moduli by a simple exponential rule similar to the one in Fenton and VanMarcke [14]. For two locations $z_1$ and $z_2$ in the soil column, the correlation coefficient is determined by,

$$\rho(z_1, z_2) = \rho_c \min(\exp(1 - |z_1 - z_2| / L_c), 1),$$  (1)

in which $L_c$ is a user-specified characteristic length to control the influence range, and $\rho_c$ is a characteristic correlation coefficient corresponding to $|z_1 - z_2| = L_c$. The correlation coefficient defined by Eq. 1 has an upper bound $\rho_c$. P-CARES calculates an initial characteristic length by averaging the layer thicknesses, and the user can adjust it based on this initial value. The vertical location $z_i$ is selected as the middle point of each layer in P-CARES.

## PROBABILISTIC SIMULATION

The CARES program implemented a set of deterministic algorithms to analyze the free-field responses, soil-structure interaction, and the structural responses. These algorithms provide the essential building blocks for the probabilistic site response and SSI analyses in P-CARES because each sample in the probabilistic simulation can be viewed as a soil-structural system and hence can be analyzed in a purely deterministic sense. This section describes the approach in P-CARES to adding probabilistic simulation on top of the deterministic algorithms to achieve the probabilistic analyses.

P-CARES includes four sampling schemes for the user to utilize and can be extended straightforwardly if other schemes are in need. The basic layout of the simulation scheme is illustrated in Figure 1, in which the P-CARES core on the right side represents the collection of the deterministic analysis modules that were upgraded from the CARES code and all other components on the left side are newly implemented for probabilistic simulation. All components in the shaded box contribute to yielding a sample (a realization of the random vector). The simulation controller performs a user-specified number of simulation iterations, each of which involves fetching a sample from the shaded box, invoking the P-CARES core to conduct the free-field and/or SSI analysis, and storing the results in database files. The database files are used in post processing and in transferring free-field responses to the structural analysis module.

FORTRAN and Python programming languages were used in the P-CARES development. This mixed programming approach allows for implementing a significant set of functionalities within a short period of time, with Python serving as a powerful glue language while FORTRAN is used for heavy number crunching duties. The existing CARES Version 1.3 was first upgraded and compiled into Python modules, which work as the computational core in the probabilistic simulation. Building around this computational core, probabilistic simulation, the GUI, and other relevant components were developed to form the integrated software package. The software architecture of P-CARES follows the object-oriented approach, the current state-of-the-art programming technique, which enables it to be flexible and extensible for future upgrades.

The architecture of P-CARES relies on a fundamental procedure that is shared by all simulation schemes in order to streamline the simulation process and to facilitate future addition of other simulation schemes. This procedure will be introduced first in the following paragraph and the individual simulation schemes will be described subsequently.
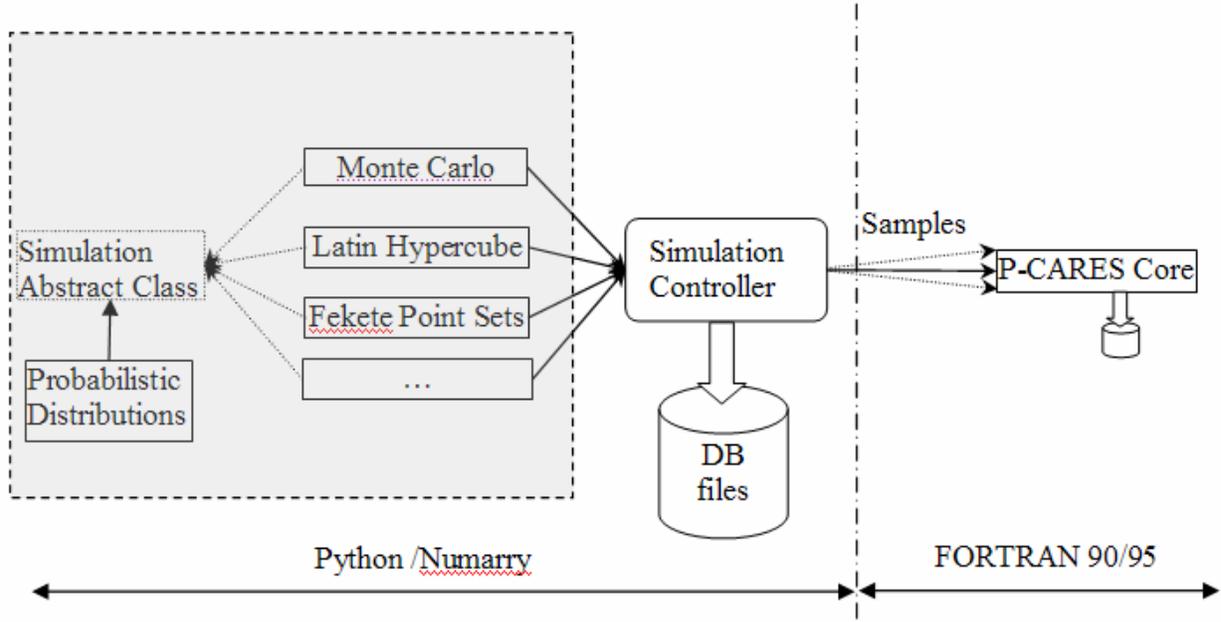
**Figure 1 Layout of the Simulation**

**The Fundamental Simulation Procedure**

The basic probabilistic modeling strategy is to unify different simulation schemes such that the majority of the task can be done in the fundamental procedure. This procedure assumes that an independent standard normal random vector is available. If an independent uniformly distributed vector is supplied, it can be first transformed to an independent normal vector by the inversion method. The independent normal vector is then transformed to a correlated normal random vector, which is converted to a lognormal-distributed random vector by taking the exponential of the normal random vector. Individual simulation schemes differ only in how the samples are generated before the correlation is incorporated. The fundamental simulation procedure can therefore be outlined in a method-neutral manner as follows.

Suppose **X** is the lognormal random vector representing the various random properties with mean vector $\boldsymbol{\mu}_X$ and covariance matrix $\boldsymbol{\Sigma}_X$, and **Y** is a normal random vector with mean vector $\boldsymbol{\mu}_Y$ and covariance matrix $\boldsymbol{\Sigma}_Y$. The covariance between random variables $X_i$ and $X_j$, i.e., the $(i, j)$th entry $\sigma_{X_i X_j}$ in the covariance matrix $\boldsymbol{\Sigma}_X$, can be determined using their correlation coefficient $\rho_{ij}$ by the following equation:

$$\sigma_{X_i X_j} = \rho_{ij} \sigma_{X_i} \sigma_{X_j}, \tag{2}$$

where $\sigma_{X_i}$ and $\sigma_{X_j}$ are the standard deviations of $X_i$ and $X_j$. The lognormal random vector **X** and the normal random vector **Y** are related by:

$$\mathbf{X} = (e^{Y_1}, e^{Y_2}, \cdots, e^{Y_n}), \tag{3}$$

where $Y_i$ is the $i^{th}$ components in **Y**. Equation 3 also establishes the relation between the distribution parameters, which can be expressed analytically as in Law and Kelton [15]. The parameter matrices for the normal vector **Y**, $\boldsymbol{\mu}_Y$ and $\boldsymbol{\Sigma}_Y$, can be calculated in terms of those for the lognormal vector **X**, $\boldsymbol{\mu}_X$ and $\boldsymbol{\Sigma}_X$:

3

$$\mu_{Y_i} = \ln\left(\frac{\mu_{X_i}^2}{\sqrt{\mu_{X_i}^2 + \sigma_{X_i}^2}}\right)$$

$$\sigma_{Y_i}^2 = \ln\left(1 + \frac{\sigma_{X_i}^2}{\mu_{X_i}^2}\right) \qquad , \tag{4}$$

$$\sigma_{Y_iY_j} = \ln\left(1 + \frac{\sigma_{X_iX_j}}{\left|\mu_{X_i}\mu_{X_j}\right|}\right)$$

where $\mu$ means a component from a corresponding mean vector $\mathbf{\mu}$, $\sigma$ means a component from a corresponding covariance matrix $\mathbf{\Sigma}$, a subscript of $X_i$ indicates a component from the lognormal property matrix, and a subscript of $Y_i$ indicates a component from the normal property matrix. Given a correlated normal random vector, one can generate the corresponding lognormal vector using Equation 3.

   With the mean and covariance matrices $\mathbf{\mu}_Y$ and $\mathbf{\Sigma}_Y$ calculated from Equation 4, the correlated normal vector $\mathbf{Y}$ can be converted from an independent standard normal random vector, denoted as $\mathbf{Z}$ herein, i.e. $\mathbf{Z} \sim N(0,\mathbf{1})$. Since $\mathbf{\Sigma}_Y$ is a symmetric positive-definite matrix, its Cholesky decomposition $\mathbf{C}$ exists such that $\mathbf{C}^T\mathbf{C} = \mathbf{\Sigma}_Y$. Then, the dependent normal random vector $\mathbf{Y}$ can be generated using the following equation,

$$\mathbf{Y} = \mathbf{C}^T\mathbf{Z} + \mathbf{\mu}_Y. \tag{5}$$

The independent standard normal random vector can be generated by using a normal generator or by combining a uniform generator and the inversion transformation method. The later approach is more flexible because it allows methods such as Fekete Point Sets method [16] to be used.

   The inverse of the above derivation establishes the fundamental simulation procedure. All simulation schemes introduced in the next section share this procedure after the independent normal or uniform random vectors are generated.

**Simulation Schemes**

   Four different simulation methods have been implemented in the P-CARES program, including the traditional Monte Carlo simulation, the Latin Hypercube sampling method (LHC), the Engineering LHC, and the Fekete Point Sets method. Except for the Monte Carlo simulation that directly generates independent normal vectors, all other schemes generate independent uniform vectors and then use an inversion method to generate the independent normal vector. It should be noted here that the Monte Carlo method can also generate the independent normal vectors by inverting the independent uniform vectors, which however is less efficient than the one implemented.

   Given a realization $u$ of a uniform random variable $U \sim U(0,1)$, a normal sample $z$ of a corresponding normal random variable $Z \sim Z(0,1)$ can be generated by,

$$z = \Phi^{-1}(u), \tag{6}$$

where $\Phi^{-1}$ is the inverse of the normal cumulative distribution function (CDF). The Inverse of $\Phi$ cannot be accomplished analytically, and its numerical solution usually involves iteration and numerical integration and therefore can be very demanding in computation. The P-CARES program uses an efficient method recently developed by Acklam [17] to obtain this inverse. This method utilizes rational approximation and therefore avoids the costly iteration. The relative error of this method is reported to be less than $1.15 \times 10^{-9}$ for $z$ in the range [-38, 8.20954]; beyond this range, the uniform sample $u$ is either too small to be represented accurately or simply unity using the current IEEE double precision real number. Therefore, this method bears no practical limitation, and the level of accuracy is adequate in the particular application of this report because the simulation occurs in the central region of the random variable space. The particular version used is a Python implementation published on the author's website [17].

<u>Monte Carlo Simulation</u>

   The Monte Carlo simulation implemented in P-CARES uses the native standard normal generator contained in the Python Numarray module, which is an algorithm in "Ranlib" developed by Ahrens and Dieter [18]. Ranlib is a selection of C routines to generate random numbers from various distributions. Since this algorithm generates independent normal numbers, the task left in the Monte Carlo simulation is simply to generate $n$ samples that serve as $\mathbf{Z}$ in Equation 5.

<u>Latin Hypercube Sampling</u>

   Monte Carlo simulation usually requires a large number of samples to yield a reasonably converged estimate, i.e., with a reasonably low variation. Among various variation reduction techniques, LHC technique has been widely used in many different domains that involve simulation [e.g., 19, 20, 21]. Following the fundamental simulation procedure, the

purpose of Latin Hypercube sampling in P-CARES is to generate $m$ sample vectors in the $n$ dimensional hypercube. It starts with dividing the range [0,1] of each uniform random variable $U_i$ into $m$ nonoverlapping intervals (with equal probability). One value $u_{ij}$ is then randomly selected from each interval, where $j$ indicates the value from the $j^{th}$ interval. The $m$ values of all random variables are combined randomly to form $m$ LHC samples, each containing $n$ values as a realization of the random vector of size $n$. It should be noted that any of the $m$ values of any random variables is used only once in forming the $m$ LHC samples. The quality of one particular set of $m$ LHC samples depends on how evenly these samples are distributed in the $n$-D hypercube.

The generated LHC samples in the hypercube are transformed to samples in standard normal space by Equation 6. Finally, the fundamental simulation procedure is applied to get the lognormal sample vectors.

Engineering Latin Hypercube Sampling

Rather than selecting a value randomly in each interval, as described above in the conventional Latin Hypercube sampling technique, a common practice in engineering application of LHC is to select the median point in each interval. This revised version, termed as engineering LHC here, removes the randomness in the marginal samples if each individual random variable is under consideration. However, the engineering LHC samples still exhibit great randomness because the marginal values of all random variables are randomly combined. The engineering LHC can avoid some extreme values that are close to the boundaries of the hypercube.

Fekete Point Set Method

Fekete Point Set method was developed as an advanced directional simulation tool in assessing structural system reliability [20]. A Fekete Point Set is a set of points on the unit hypersphere with a minimal potential energy, i.e., it minimizes the following potential energy,

$$E_t = \sum_{1 \le i < j \le m} \frac{1}{\left|\mathbf{P}_i - \mathbf{P}_j\right|^t}, \quad t > 0 \tag{7}$$

where $t$ is the order of the potential energy $E_t$, $\mathbf{P}$ represents a point on the unit hypersphere, and $m$ is the total number of point in the set. Among the three generation methods developed by Nie and Ellingwood [16], the one directly minimizing $E_2$ has been adopted in P-CARES. Detailed discussion of these generation methods is beyond the scope of this paper. In the particular applications in evaluating structural system reliability, the method was assessed in spaces of a dimension up to 20. The authors noticed that the advantage of the Fekete Point Set method over Monte Carlo simulation decreases as the dimension increases, from about several hundreds times more efficient in 3-D to about 3 times more efficient in 20-D. Spaces of a dimension higher than 20 have not been tested. Therefore, this method is included in P-CARES as an experimental approach, and the user should use it with caution.

A Fekete Point Set is on the unit hypersphere, and must be transformed into the hypercube to be useful in P-CARES. Such a transformation developed by Nie [20] has been incorporated together with the generation procedure in P-CARES. When generating a Fekete Point Set in P-CARES, this transformation is automatically applied at the end of generation without user's intervention. A fact of this transformation is that an $n+1$ dimensional unit hypersphere maps to an $n$ dimensional hypercube, because the unit hypersphere has one degree of freedom constrained by its radius.

These simulation schemes implemented in P-CARES provide the capabilities to perform probabilistic site response and soil-structure interaction (SSI) analyses based on relatively simplified soil and structural models. P-CARES automatically manages data and calculations in the probabilistic simulation with any requested number of samples. The sample soil profiles and the response spectra of the simulated soil and structural responses can be aggregated statistically in terms of mean, median, and different percentiles curves. These statistical measures may provide more valuable insights and inferences than those in deterministic soil and structural analysis, in the process of review and evaluation of nuclear power plant (NPP) structure designs. The probabilistic analysis capability in P-CARES becomes especially important as the nuclear industry is gaining wider acceptance of the probabilistic approach to account for the uncertainties inherent in the natural and built environments.

**SUMMARY OF MAJOR FEATURES**

Featured with a convenient and intuitive GUI as shown by the screenshots in Figure 2, P-CARES provides three major function categories: seismic motion analysis, site response analysis, and SSI and structure analysis. These functions are organized in a command tree structure on the left side of the window. The post-processing tool in the command tree is implemented for simulation results. The right side of the window is the main display panel, which is used to enter data, manage calculation, and plot results. Data for the soil profile, the kinematic interaction, and the structural model are stored in one project file, and all input are processed through the GUI. Options for calculation are set through the GUI as well. Output

from P-CARES are interpreted in forms of various plots, which can be saved as popular images or saved to data files that are suitable for post-processing in other programs.  The 3D structure model, including beams and shear walls, can be displayed directly on screen for inspection.  The GUI layout is designed for the user's greatest convenience in conducting common analyses, such as site response analysis or structural analysis separately.  However, various components can be combined to achieve analyses that involve free-field convolution, kinematic soil-structure interaction, and the structural analysis.
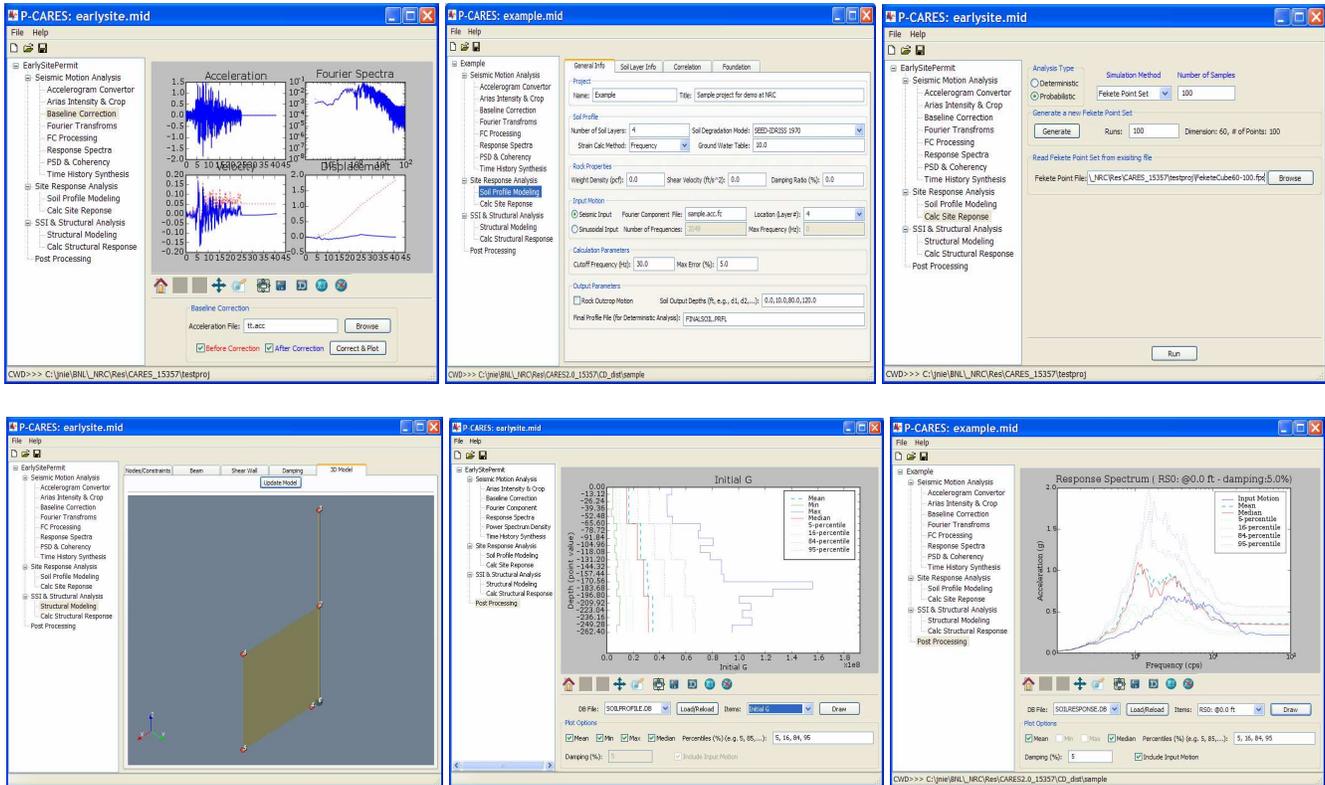


**Figure 2 A Few Screenshot of P-CARES**

**Seismic Motion Analysis**

A set of utilities are provided for the user to pre-process the input seismic motions and to perform some of the post processing tasks, especially for the deterministic site response and structure response analyses. These utilities are organized in an order convenient for typical analysis situations. The 8 included utilities are: 1) an accelerogram converter that converts a raw acceleration time history in various formats to P-CARES format, 2) a utility that displays the cumulative Arias Intensity and can save a portion of the whole time history by chopping and zero-padding, 3) a baseline correction utility to remove the residual velocity and displacement from a time history,  4) a utility that performs forward/inverse FFT and generates relevant plots, 5) a Fourier component processing utility that can filter or smooth a given Fourier component file, 6) a response spectra utility that can produce response spectra plots for multiple damping values, 7) a power spectra density and coherency utility that can plot auto-power spectra and various coherency measures, and 8) a time history synthesis utility to generate a time history that matches a given response spectrum, which can be one of the NUREG/CR-0098 spectra [22], Regulatory Guide 1.60 spectra [23], or a user specified spectrum.  The operation of these tools mostly just involves a few clicks or a very limited amount of typing, and the outputs are publication quality plots.

**Site Response Analysis**

Both deterministic and probabilistic analyses of site response can be performed in P-CARES with majority of the information shared. The soil column model can be built using the soil profile modeling command in the site response analysis module. The soil column is assumed to be a one dimensional layered soil system with the shear wave propagating vertically through the soil layers. The hysteretic property of the soil is modelled with specified degradation curves and the input seismic motion; the resultant soil shear modulus and damping of each layer are compatible with the maximum effective strain induced by the input seismic motion. The user can specify the number of layers, soil degradation model, soil layer properties, water table, rock properties for rock outcrop, and output locations for free-field responses.  The input seismic motion can be placed at the ground surface, at any layer interface, or in the rock outcrop. If a joint SSI analysis is to be performed, the user

should also provide the foundation type, dimension, and the embedment depths in the soil modelling stage. The inclusion of the kinematic soil-structure interaction in the site response analysis can be turned on or off by a simple click. P-CARES will automatically generate the side and base soil properties from the input soil column profile, record the output motions at locations spanning over the embedment depth, and then generate the SSI input motions.

For a deterministic analysis, the user does not need to provide the probabilistic distribution parameters for the soil layer properties, and the correlation table. In particular, the output motion files are in the format of Fourier component, and can be processed using seismic motion analysis tools. The user must choose the "Deterministic" analysis option to activate this analysis. For probabilistic site response analysis, the additional data that the user must enter include the probabilistic distributions for the soil layer properties and the correlation coefficients if the correlations between soil layers are required. The user must choose the "Probabilistic" analysis type, select a simulation scheme among the Monte Carlo simulation, LHC, engineering LHC, or the Fekete Point Set method, and provide the number of samples to be used for the simulation. The output motions and final soil profiles can be processed in the post processing module.

### SSI and Structural Analysis

The structure model in P-CARES is a lumped mass linear elastic structural system, which consists of beam elements, spring elements, shear wall elements, and the rigid link elements. A P-CARES beam element is a 3 dimensional beam with shear stiffness enabled, while a spring element is a 3 dimensional beam without shear capacity. The shear wall elements cannot resist any out-of-plane deformation and rotational deformation. The user can specify the nodal definitions and constrains, coupled degrees of freedom, rigid links, element type and connectivity, material properties, sectional properties, the damping model and parameters, SSI node, and a list of output nodes. The output motions are in the Fourier component format. The structural model can be viewed and inspected using the 3D viewer.

Four kinds of analyses can be performed in this module. The structural analysis module can be used as a standalone package for deterministic SSI analysis and Frequency Domain Shaker Analysis, which require the specification of the foundation and the SSI input motions or the forcing function. A common application of this tool is to perform the joint deterministic or probabilistic SSI and structural analysis. In these two analyses, P-CARES internally sets the SSI model to Beredugo and Novak model [24] for circular foundations or Pais and Kausel model [25] for the rectangular foundations, and automatically transfers the SSI node properties and the translational and rotational kinematic motions generated in the site response analysis to the SSI analysis. Since all structural properties are considered deterministic as described previously, the uncertainties exhibited in responses in the SSI and structural analysis are due to the random SSI node properties and the random input motions applied at the SSI node.

### Post Processing for Simulated Results

Three database files that are accepted in the post processing are the final soil profiles, soil responses at various user specified depths, and structural responses at the user specified nodes. The final soil profile database includes the soil layer thickness, soil damping, soil density, low strain shear wave velocity, final shear wave velocity, low strain shear modulus, and final shear modulus. The soil and structural response database include the input motion and responses, all in Fourier component format. Response spectra are the only output plot at this point. The statistics used in the post processing include mean, minimum, maximum, median, and an arbitrary number of percentiles that the user can specify.

### SUMMARY

The mixed programming in Python and FORTRAN in the development of the P-CARES program has shown to be a very efficient and effective approach. Building on an existing FORTRAN code that can only perform deterministic site response and SSI analysis, P-CARES provides the capabilities to perform both deterministic and probabilistic site response and soil-structure interaction (SSI) analyses based on relatively simplified soil and structural models. It also provides a range of useful seismic motion tools that can quickly produce graphical plots for accelerogram assessment or generation. The P-CARES GUI integrates all these functions into one package to improve the usability and productivity. The features of P-CARES described in this paper demonstrated the coherent integrations through GUI of various functional modules required for probabilistic site response and SSI analyses.

### DISCLAIMER NOTICE

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