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Reliability Assessment of Dynamic Soil Properties

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ABSTRACT

Dynamic soil properties are very important topic in geotechnical earthquake engineering due to associated with dynamic loading. Probabilistic analysis of dynamic soil properties is as effective tools to evaluate uncertainty of soil parameters. In this paper, Monte Carlo Simulation (MCS) is used for reliability assessment of dynamic soil properties. For this purpose, a famous model is selected for predicting normalized shear modulus reduction and damping ratio curves. The selected stochastic parameters are internal friction angle, dry and saturated unit weight of soil which is modeled using normal probability distribution functions. To assess the reliability of dynamic soil parameters a computer model is developed for generating input parameter uncertainties. The results show that the shear modulus and damping ratio have more uncertainty for middle range of shear strain. The sensitivity analysis's results show that saturated unit weight is the most effective parameter in shear modulus and damping ratio.

Keywords:

Damping ratio, Shear modulus, Monte Carlo Simulation, Reliability assessment.

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1. Introduction

The response of soils to cyclic loading is controlled mostly by the dynamical properties of the soil. [1] There are several types of geotechnical earthquake engineering problems associated with dynamic loading, some examples include: wave propagation, machine vibrations, seismic loading, liquefaction and cyclic transient loading, etc. The dynamical properties associated with dynamic loading are shear wave velocity (Vs), shear modulus (G), damping ratio (D), and Poisson's ratio (n) that shear modulus and damping ratio are the most effective properties. [2] The analysis of the geotechnical earthquake engineering problems in civil engineering requires characterization of dynamic soil properties using different equations that one of this equations is the Ishibashi & Zhang (1993).[3] However, the inherent uncertainties of the characteristics which affect shear modulus and damping ratio dictate that this problem is of a probabilistic nature rather than being deterministic.

Reliability assessment provides a means of evaluating the combined effects of uncertainties. Thus, as an alternative or a supplement to the deterministic assessment, a reliability assessment of dynamic soil properties would be useful in providing better engineering decisions. In general, the uncertainty in dynamic soil properties is divided into three categories: uncertainty in equations, uncertainty in parameters and human uncertainty. Equation uncertainty is due to the limitation of the theories and equations used in performance prediction [4]. Parameter uncertainty is the uncertainty in the input parameters for analysis [5], while human uncertainty is due to human errors and mistakes [6]. In this research parameter uncertainty is assessed.

2. Deterministic Analysis of Dynamic Soil Properties

In the present study, a two layered soil with a dry and saturated layer is considered. Figure 1 shows this type of soil and its parameters.

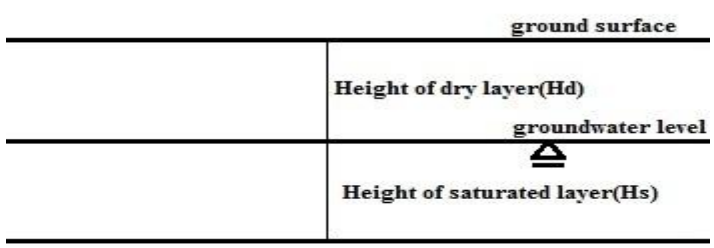

Figure 1. Soil layers with a dry and saturated layer.

Dynamic soil properties are defined by shear modulus ratio ($\frac{G}{G_{max}}$) and damping ratio (D). These parameters has been proposed by Ishibashi and Zhang [3] as:

$$\frac{G}{G_{\max}} = k(\gamma, PI)\sigma_m'^{\,(m(\gamma, PI)-m_0)} \tag{1}$$

Where

$$\sigma_m' = \frac{2\sigma_v' + k_0\sigma_v'}{3} \tag{2}$$

That it is the mean of normal effective stresses in kN/m^2.

$$k_0 = 1 - \sin\phi \tag{3}$$

Where ϕ measured in degrees. $k(\gamma, PI)$ and m (γ, PI) related to Plasticity Index (PI) and can be obtained from following equations:

$$k(\gamma, PI) = 0.5[1 + \tanh\{\ln(\frac{0.000102 + n(PI)}{\gamma})^{0.492}\}] \tag{4}$$

That $n(PI)$ is taken from the Table1:

Table1. Values of n (PI).

PI	0.0	0-15	15-70	>70
n(PI)	0.0	$3.37 \times 10^{-6} \times PI^{1.4}$	$7 \times 10^{-7} \times PI^{1.97}$	$2.7 \times 10^{-5} \times PI^{1.115}$

$$m(\gamma.PI) - m_0 = 0.272[1 - \tanh\{\ln(0.000556/\gamma)^{0.4}\}]\exp(-0.0145 PI^{1.3}) \tag{5}$$

Also D could be obtained from the equation:

$$D = \frac{0.333(1 + \exp(-0.0145\,\mathrm{PI}^{1.3}))}{2} \times [0.586(\frac{G}{G_{\max}})^2 - 1.547(\frac{G}{G_{\max}}) + 1] \tag{6}$$

Where PI is the plasticity index and measured in percent of water content.

3. Available Methods for Probabilistic Analysis of Dynamic Soil Properties

Many investigators have employed statistical and probabilistic methods for assessing dynamic soil parameters. There are many potential sources of uncertainty in this problems and probabilistic approaches have been developed to deal with them. Uncertainties in cyclic loading can be evaluated using the standard probabilistic seismic hazard analyses [7]. Uncertainties in dynamic soil parameters can be treated in three categories: analytical methods, approximate methods, and Monte Carlo simulation.

1. In analytical methods, the probability density functions of input variables are expressed mathematically. They are then integrated analytically into the dynamic soil properties relationship to derive a mathematical expression for the density function of the dynamic soil properties. Limited attempts have been made to apply analytical methods. The jointly distributed random variables method lies in this category.

2. Most of approximate methods are modified versions of two methods namely, First Order Second Moment Reliability Method (FOM) [8] and Point Estimate Method [9]. Both approaches require knowledge of the mean and variance of all input variables as well as the performance function that defines dynamic soil properties [10].

3. Monte Carlo simulation uses randomly generated points to cover the range of the values that enter into a calculation [11]. As many as 10,000 to 100,000 generations points may be required to adequately represent a deterministic solution. The computation of probabilities by Monte Carlo simulation is a procedure commonly adopted to solve problems that are not readily solved by analytical methods.

In this research, the Monte Carlo simulation method is used to assess the reliability of dynamic soil properties with considering the uncertainties in parameters. This method is described in the following sections.

4. Monte Carlo Simulation

The Monte Carlo simulation method is used to solve problems by generating suitable random numbers and assessing the dependent variable for a large number of possibilities. The procedure involves the definition of the variables that generate uncertainty and the Probabilistic Distribution Function (PDF); determination of the value of the function using variable values randomly obtained considering the pdf; and repeating this procedure until a sufficient number of outputs is obtained to build the pdf of the function. The number of required Monte Carlo trials is dependent on the desired level of confidence in the solution as well as the number of variables being considered and can be estimated from[12]:

$$N=\left[\frac{d^2}{4(1-\varepsilon)^2}\right]^n \tag{7}$$

Where N is the number of Monte Carlo trials; d is the standard normal deviate corresponding to the level of confidence;   is the desired level of confidence (0 to 100%) expressed in decimal form; n is the Number of variables. If the problem has n variables, the number of trials increases geometrically, according to power n.

During a Monte Carlo simulation, values are sampled at random from the input probability distributions. Each set of samples and the resulting outcome from that sample are recorded. This method provides a probability distribution of possible outcomes and, hence, gives a much more comprehensive view of what may happen.

5. Stochastic Parameters

To account for the uncertainties in dynamic soil properties, 3 input parameters have been considered as stochastic variables. The selected parameters are internal friction angle (ϕ), dry unit weight of soil (γ) for dry layer and saturated unit weight of soil (γ_{sat}) for saturated layer. The distribution functions of the above mentioned stochastic parameters are as follows:

$$F(\phi)=\phi_{\mathrm{mean}}+\sigma_{\phi}\mathrm{randn}\,(N, 1) \tag{8}$$
$$\phi_{\mathrm{min}} \leq \phi \leq \phi_{\mathrm{max}}$$
$$F(\gamma)=\gamma_{mean}+\sigma_{\gamma}\mathrm{randn}\,(N, 1) \tag{9}$$
$$\gamma_{min} \leq \gamma \leq \gamma_{max}$$
$$F(\gamma_{sat})=\gamma_{sat_{mean}}+\sigma_{\gamma_{sat}}\mathrm{randn}\,(N, 1) \tag{10}$$
$$\gamma_{sat_{min}} \leq \gamma_{sat} \leq \gamma_{sat_{max}}$$

Where:

$$\begin{cases} \phi_{min} = \phi_{mean} - 4\sigma_{\phi} \\ \phi_{max} = \phi_{mean} + 4\sigma_{\phi} \\ \gamma_{min} = \gamma_{mean} - 4\sigma_{\gamma} \\ \gamma_{max} = \gamma_{mean} + 4\sigma_{\gamma} \\ \gamma_{sat_{min}} = \gamma_{sat_{mean}} - 4\sigma_{\gamma_{sat}} \\ \gamma_{sat_{max}} = \gamma_{sat_{mean}} + 4\sigma_{\gamma_{sat}} \end{cases}$$

6. Case Study

To demonstrate the efficiency and accuracy of the proposed method in determining the shear modulus ratio and damping, an example problem with arbitrary parameters is selected. The stochastic parameters are shown in Table 2 and the deterministic parameters are given in Table3 100000 Generation points are used for Monte Carlo simulation.

Table2. Stochastic parameters.

Parameters	Mean	Standard deviation
ϕ(degree)	36	1
$\gamma(\frac{kN}{m^3})$	17	0.5
$\gamma_{sat}(\frac{kN}{m^3})$	19	0.5

Table3. Deterministic parameters.

Height of dry layer (m)	Height of saturated layer (m)	Number of cyclic loading, N	Void ratio, e
3	4.5	5	0.6

The probability density functions of the stochastic parameters are shown in Figures 2–4. Moreover, in order to show the results of the presented method the final probability density function curves for the dynamic soil properties are determined. For this purpose, 100,000 trials are used for the Monte Carlo simulation. The results are shown in Figure 5 for shear modulus and in Figure 6 for damping ratio.

Figure 5. Shows that the shear modulus ratio starts from 1 in zero strain and decreased until it equals to zero at very high strain. Figure 6. Shows that damping ratio start from zero in low strain and increased with higher strain. Table 4-5 shows the amounts of the mean and standard deviation of shear modulus ratio and damping ratio for different strains.

Table 4. Values of Mean and Standard deviation for shear modulus.

Strain	0.01%	0.025%	0.1%	0.3%	0.5%	1%
Mean	0.7705	0.4790	0.1971	0.0854	0.0557	0.0302
Standard deviation	0.0079	0.0118	0.0095	0.0054	0.0038	0.0022

Table 5. Values of Mean and Standard deviation for damping ratio.

Strain	0.01%	0.025%	0.1%	0.3%	0.5%	1%
Mean	0.0519	0.1311	0.2391	0.2904	0.3049	0.3176
Standard deviation	0.0017	0.0022	0.0042	0.0026	0.0019	0.0011

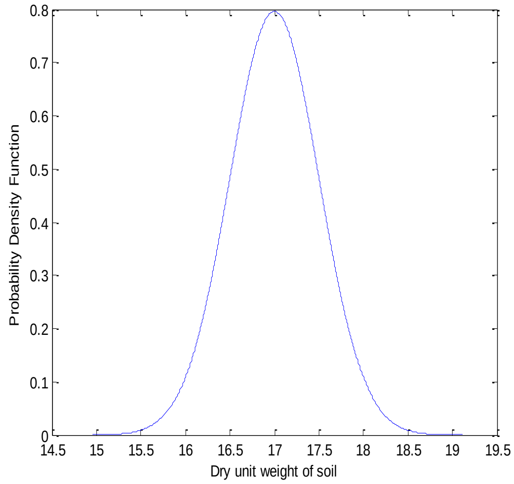

Figure 2. Probability Density Function of dry unit weight of soil.

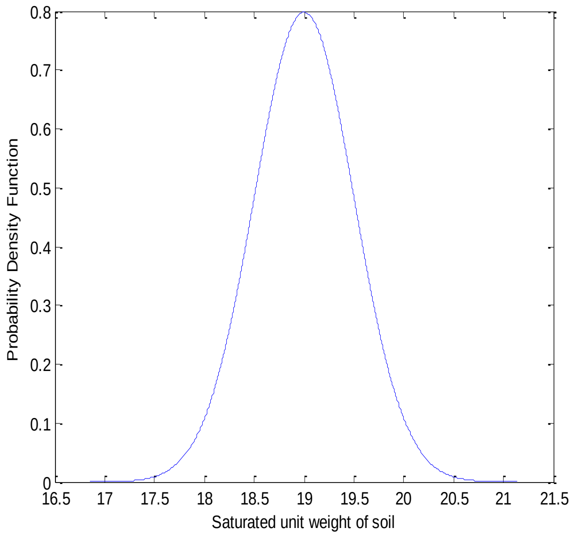

Figure 3. Probability density function of saturated unit weight of soil.

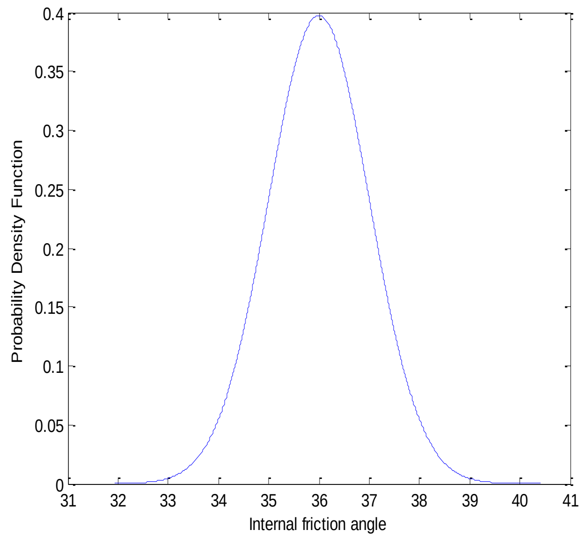

Figure 4. Probability density function of saturated unit weight of soil.

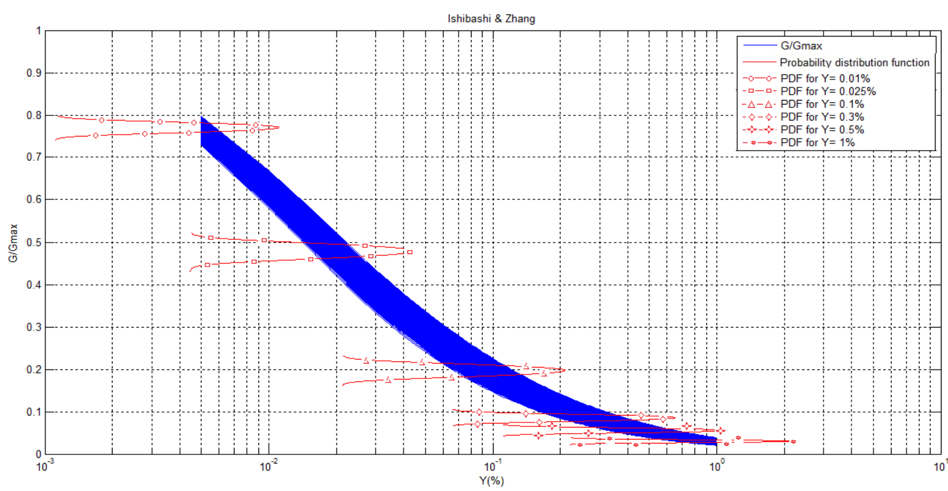

Figure 5. Probability density function of shear modulus for different strain.

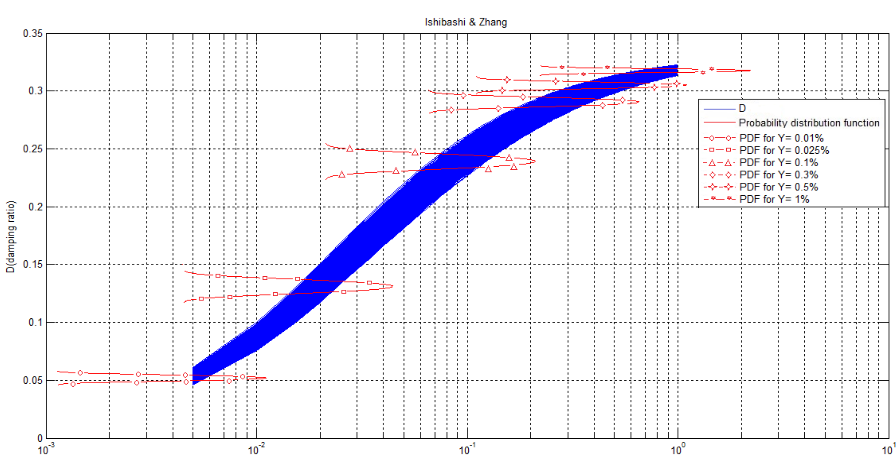

Figure 6. Probability density function of damping ratio for different strain.

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7. Sensitivity Analysis

To evaluate the model response to changes in input parameters, a sensitivity analysis was carried out. For this purpose three stochastic parameters, internal friction angle, dry and saturated unit weight were considered. To evaluate the influence of each parameter, the mean value of the parameter was increased approximately 20% while the ranges of the other stochastic input parameters were kept constant. The results are shown in Figure7-8 It is shown that as expected, with an increase in mean friction angle, the PDF of shear modulus shifts leftwards and PDF of damping ratio shift rightwards, indicating a site with a higher value of mean friction angle has a fewer shear modulus and higher damping ratio. Furthermore, Figure 7-8 shows that with increase in dry and saturated unit weight of soil the PDF of shear modulus shift rightwards and PDF of damping ratio shift leftwards implying an increase in shear modulus and decrease in damping ratio. This figures also shows that the saturated unit weight of soil is the most effective parameter in dynamic soil properties.

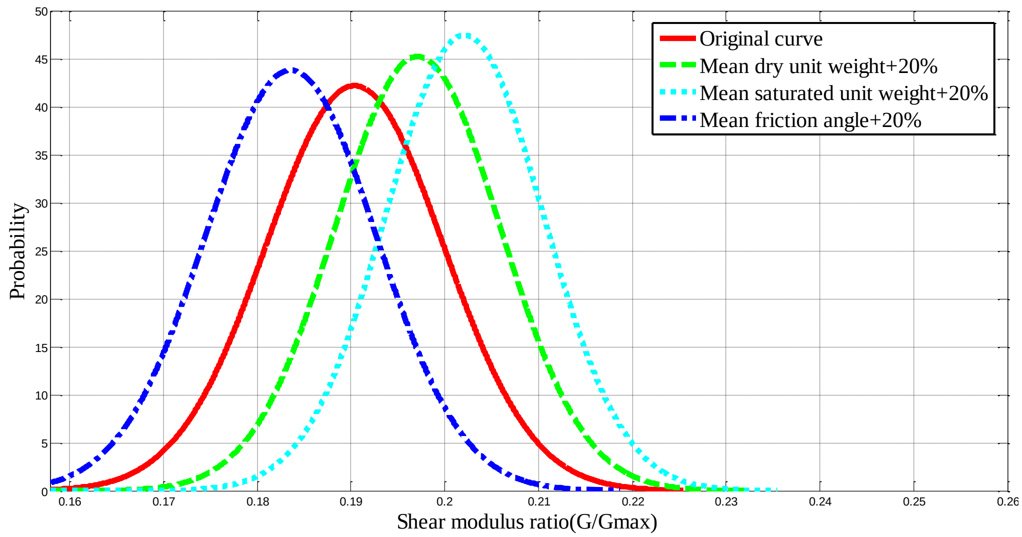

Figure 7. Sensitivity analysis for shear modulus.

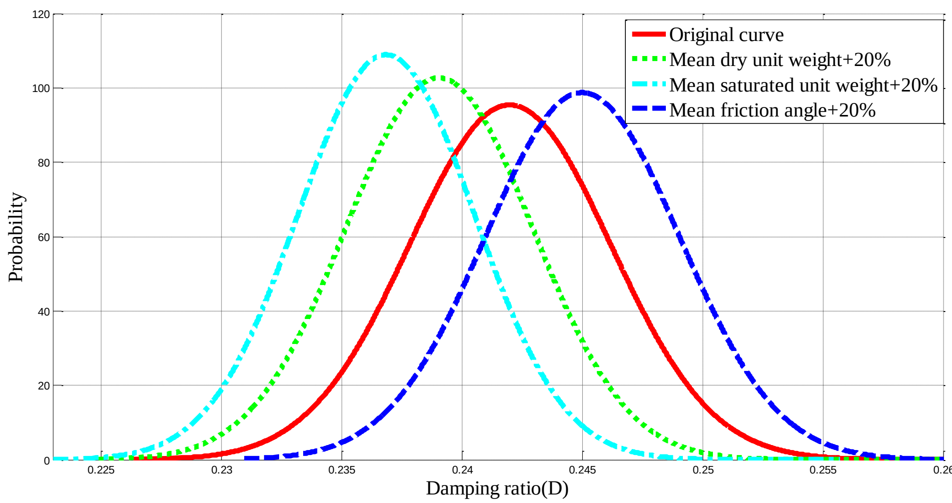

Figure 8. Sensitivity analysis for damping ratio.

8. Conclusions and Discussions

Determination of dynamic soil properties is a probabilistic problem due to the inherent uncertainties. Uncertainties in shear modulus and damping ratio can be assessed in terms of the uncertainties in geotechnical parameters model performance as well as human uncertainty. In this paper the Monte Carlo simulation method was used to assess the reliability of the proposed method for the analysis of the dynamic soil properties. The selected stochastic parameters were internal friction angle, dry and saturated unit weight of soil which was modeled using normal probability distribution function. The results showed that the standard deviation of shear modulus and damping ratio are increased with strain. And in high strain it will be decreased again, however the mean of shear modulus started from 1 and decreased with strain until it equal to zero in very high strain and the mean of damping ratio started from zero and increased with strain.

The sensitivity analysis of the selected method indicated that this method can correctly predict the patterns of influence of the stochastic parameters. The sensitivity analysis also showed that the saturated unit weight of soil is the most effective parameter in dynamic soil properties.

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