Effective Stress-Based Large Strain Modulus Degradation Response of Fully Saturated Clean Sands

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ABSTRACT Current state of practice to assess ground response under seismic loading is mostly based on well-known and widely-used total stress-based equivalent linear assessment methodology, as part of which, mostly, strain compatible shear modulus and damping relationships need to be used. As implied by its name, "total stress", accumulation of excess pore water pressure which is a significant component of cyclic response, is not considered. Neglection of this component will produce unconservatively biased deformation and intensity estimations for soil sites at which cyclic-induced strains exceed small to medium strain range. Inspired from this gap, aim of this study is defined as development of probabilistic-based models for assessment of large strain modulus degradation response of fully saturated clean sands. For this purpose, an intensive literature survey was performed, and available resonant column, simple shear and cyclic triaxial test results were compiled. This data was assessed by probabilistic methods to develop a framework which takes into account not only the cyclic shear strain amplitudes but also the generation of excess pore water pressure.

1 INTRODUCTION

Current state of practice to assess ground response under seismic loading is mostly based on well-known and widely-used total stress-based equivalent linear assessment methodology, as part of which, mostly, strain compatible shear modulus and damping relationships need to be used. Despite its common use, as implied by “total stress”, one of the major limitations of total stress-based equivalent linear analysis is that the accumulation of induced pore pressure, as well as residual soil straining are not considered. However, for assessing soil sites, where expected shear strain levels exceed the small to medium strain range of $10^{-6} \leq \gamma \leq 10^{-2}$, the use of total stress based equivalent linear assessment methodology may produce unconservatively biased deformation and intensity estimations. More specifically, within the confines of this manuscript, it is intended to present probability-based strain and induced pore pressure compatible shear modulus degradation relationships, use of which enable effective stress-based seismic ground response assessment of soil sites composed of fully saturated or dry soil layers subjected to relatively larger cyclic shear strain levels.

In the literature, there exist a number of studies aiming to identify important factors affecting highly nonlinear modulus degradation responses of sandy soils. Although the pioneering studies were performed in mid-60’s, the findings of Hardin and Drnevich (1972a, 1972b) are judged to be the cornerstone of the progress, as many successors (e.g. Seed and Idriss 1970, Seed et al. 1984, Darendeli 2001, etc.) benefited from and build up on their proposed approach. Commonly adopted research methodology involves performing laboratory tests, in the form of resonant column, cyclic triaxial, simple shear or torsional shear, on the basis of which, an analytical framework is then founded. Thus, a similar, laboratory based testing approach is adopted for this study. For this purpose, an intensive literature survey was performed, and available resonant column, simple shear and cyclic triaxial test results were compiled. Additionally, on Kizilirmak and Monterey sands, cyclic simple shear and triaxial tests were performed. As opposed to conventionally preferred drained cyclic testing approach, an undrained testing procedure is adopted on saturated sand samples, during which, straining induced cyclic pore pressure response is also monitored. This choice is one of the distinguishing features of this study, and enables to assess modulus degradation response as functions of not only cyclic shear strain amplitudes but also induced pore pressure.

2 DATABASE COMPILATION EFFORTS

Efforts aiming to develop a semi-empirical or empirical model or validate and calibrate existing models naturally require the compilation of a high quality database. For this purpose, existing literature was carefully studied. Due to lack of complete documentation of both pore pressure and shear strain responses at every cycle of loading, among all, only Wu et al. (2003) and Bilge (2005) databases were possible to be used. These two studies were mostly focused on large strain response of clean saturated sands, and hence small strain response is judged to be under-sampled or under-represented. To eliminate this discrepancy, well-documented resonant column test data of VELACS project (Arulmoli et al. 1992) was incorporated into the database. For simple shear (from Wu et al. 2003 database) and cyclic triaxial (from Bilge 2005 database), shear moduli values (G) were calculated according to the relation between applied cyclic stresses and resulting strains; whereas, reported G were directly used for resonant column tests. The resulting database is presented in Figure 1 as a function of maximum shear strain amplitude.

3 DEVELOPMENT OF PROBABILISTIC-BASED SEMI-EMPIRICAL MODELS

The first step in developing a probabilistic model is to select a limit state expression that captures the essential parameters of the problem. The model for the limit state function has the general form g = g (**x, Θ**) where x is a set of descriptive parameters and Θ is the set of unknown model coefficients. Inspired by earlier studies and as well as the trends from test results, the key components determining the shear modulus are selected as maximum single amplitude cyclic shear strain (γ_{max}) and excess pore water pressure ratio ($r_{u,\gamma}$). After having tried a number of alternative functional forms, the following equations are adopted as the limit state function for assessing γ_{max} and $r_{u,\gamma}$ compatible G (i.e.: $G_{\gamma,ru}$) values ;

$$g_{G_N}(D_R, \sigma'_{m0}, \gamma_N, r_{u,N}, G_N, \Theta) = \ln(G_N) - \ln\left(\frac{\theta_1 \cdot D_R + \theta_2}{1 + \theta_3 \cdot \gamma_N^{\theta_4}} \cdot \left[(1 - r_{u,N} + \theta_5) \cdot 0.0479 \cdot \sigma'_{m0}\right]^{0.5 + \theta_6 \cdot \gamma_N}\right) \pm \varepsilon_{\ln(G_N)} \quad (1)$$

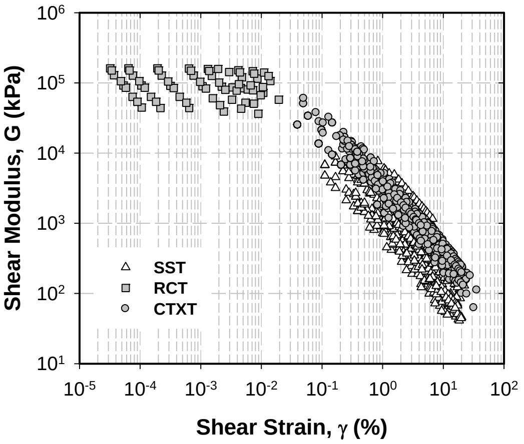

Figure 1. Summary of G vs γ database.

As part of maximum likelihood methodology, the coefficients which are estimated to maximize the likelihood functions are presented in Table 1. Note that details of the applied maximum likelihood methodology has been discussed elsewhere (e.g. Cetin et al. 2009) and will not repeated herein.

Table 1. Model coefficients.

Coefficient	Value
θ_1	528.64
θ_2	11910.89
θ_3	37.1
θ_4	1.06
θ_5	0.05
θ_6	0.01
σ_ε	1.55

Predicted and measured modulus degradation values are paired and shown in Figure 2 along with the 1:2

and 1:0.5 boundaries. Pearson's product (R^2), which is a measure of the correlation between compared values, is also calculated as 0.975. 80 % of the data pairs fall within the bounds of 1:2 and 1:0.5 and mostly accumulated along 1:1 line, suggesting unbiased and accurate model predictions.

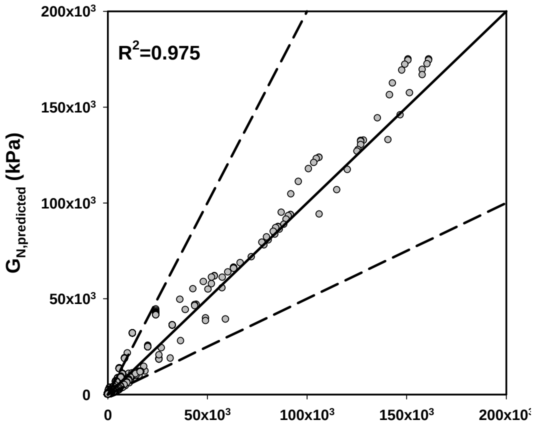

Figure 2. Comparison between measured and predicted modulus degradation values.

The next step, involves the development of modulus degradation relationship, which can be further used in effective stress-based dynamic site response analysis. Consistent with conventional assumptions, which defines G_{max} at 10^{-4} % shear strain level, G/G_{max} is then defined as a function of both γ_N and $r_{u,N}$ as follows;

$$\frac{G}{G_{\max}}=\frac{G}{G_{\gamma=10^{-4}\%}}=\frac{1+\theta_3\cdot(10^{-4})^{\theta_4}}{1+\theta_3\cdot(\gamma_N)^{\theta_4}}\cdot\frac{\left[(1-r_{u,N}+\theta_5)\cdot 0.0479\cdot\sigma'_{m0}\right]^{0.5+\theta_6\cdot\gamma_N}}{\left[(1+\theta_5)\cdot 0.0479\cdot\sigma'_{m0}\right]^{0.5+\theta_6\cdot 10^{-4}}} \qquad (2)$$

Unlike available modulus degradation relationships in the literature, note that Equation. 2 is given as a function of $r_{u,N}$ in addition to γ_N and σ'_{m0} (or σ'_{v0}). Practical use of Equation 2 requires the estimation of strain (and also drainage) compatible cyclic pore press estimations, and user is allowed to use one of the existing models for the cyclically-induced excess pore water pressure assessments (Seed et al. 1975; Dobry et al. 1985; Green et al. 2000; Cetin and Bilge 2012).

As to further address the importance of drainage conditions (or state of soil in the form of fully saturated or dry), Equation 2 is solved twice for the median values of $D_R \approx 62$ % and $\sigma'_{m0} \approx 90$ kPa of the compiled database, one for a dry specimen (i.e.: no cyclic excess pore pressure generation is permitted, drained loading) and another one for a fully saturated specimen (i.e.: strain compatible cyclic excess pore pressure generation is assessed by the cyclic-induced r_u model proposed by Cetin and Bilge 2012 (Equation 3), i.e. undrained loading). Taking the ratio of G/G_{max} values corresponding to these drained and undrained loading conditions, the individual effect of pore water pressure generation on modulus degradation is schematically presented in Figure 3.

$$r_{u,N}=1-\exp\left(-\frac{-0.590\cdot\gamma_{\max,N}}{-0.788+0.110\cdot\ln\sigma'_{v0}-(D_R/100)}\right) \qquad (3)$$

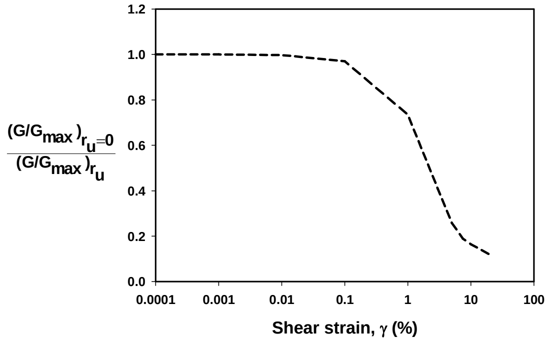

Figure 3. Effect of undrained loading conditions on G/G_{max} response as a function of γ.

With increasing shear strain levels, the effects of excess pore pressure accumulation starts to increase, and especially if γ levels exceed 1 %, corresponding degraded shear moduli of dry and fully saturated sands start to be significantly different, the extent of which may reach up to 2 to 5 times. Hence, for rigorous seismic site response assessments, fundamentally different modulus degradation behaviors of dry and fully saturated sand layers need to be properly addressed.

4 CONCLUSIONS

Within the confines of this study, the large strain modulus degradation response of fully saturated clean sands was assessed probabilistically, by cyclic triaxial, simple shear and resonant column test data. The maximum likelihood methodology was used to develop limit-state models incorporating the important descriptive variables for the modulus degradation problem.

Predicted and measured modulus degradation values are paired and shown in 2 along with the 1:2 and 1:0.5 boundaries. Pearson's product (R^2), which is a measure of the correlation between compared values, is also calculated as 0.975. 80 % of the data pairs fall within the bounds of 1:2 and 1:0.5 and mostly accumulated along 1:1 line, suggesting unbiased and accurate model predictions.

For rigorous seismic site response assessments, which involve larger strain levels, fundamentally different modulus degradation behaviors of dry and fully saturated sand layers need to be properly addressed. Proposed modulus degradation curves are believed to be a step forward to provide a robust basis to assess these differences.

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