Soil Dynamics and Earthquake Engineering 85 (2016) 1–10

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Challenges associated with site response analyses for soft soils subjected to high-intensity input ground motions

Shawn C. Griffiths [a], Brady R. Cox [b,*], Ellen M. Rathje [b]

[a] Department of Civil and Architectural Engineering, University of Wyoming, Department 3295, 1000 E. University Ave, Laramie, WY 82701, USA
[b] Department of Civil, Architectural and Environmental Engineering, The University of Texas, 301 E Dean Keeton Stop C1792, Austin, TX 78712, USA

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form
23 February 2016
Accepted 7 March 2016

Keywords:
Dynamic soil properties
Nonlinear site response analysis
Equivalent linear site response analysis
Soft soils
Earthquake

ABSTRACT

Nonlinear site response analyses are generally preferred over equivalent linear analyses for soft soil sites subjected to high-intensity input ground motions. However, both nonlinear (NL) and equivalent linear (EQL) analyses often result in large shear strain estimates (3–10%) at soft sites, and these large strains may generate unusual characteristics in the predicted surface ground motions, such as irregular time histories and atypical spectral shapes. One source of unusual ground motion predictions may be attributed to unrealistically low shear strengths implied by commonly used modulus reduction curves. Therefore, modulus reduction and damping curves can be modified at shear strains greater than approximately 0.1% to provide a more realistic soil model for site response. However, even after these modifications, nonlinear and equivalent linear site response analyses still may generate unusual surface acceleration time histories and Fourier amplitude spectra at soft soil sites when subjected to high-intensity input ground motions. In this study, we use equivalent linear and nonlinear 1D site response analyses for the well-known Treasure Island site to demonstrate challenges associated with accurately modeling large shear strains, and subsequent surface response, at soft soil sites.

1. Introduction

One dimensional (1D) site response analyses are typically utilized to predict the amplification and/or attenuation of seismic ground motions by modeling the propagation of shear waves as they travel from bedrock to the ground surface. These analyses help to quantify the effects of local soil conditions on shaking intensities, and ultimately yield surface time histories and response spectra necessary for structural and geotechnical design. When 1D site response analyses are conducted for soft soil sites subjected to high-intensity input ground motions, large shear strains (3–10%) are often predicted within the soil column. These large shear strains exceed the range where dynamic soil properties (i.e., shear modulus, *G*, and damping ratio, *D*) have been determined most reliably, and often approach or exceed values that are associated with shear failure of the soil. For example, the normalized shear modulus reduction (G/G_{max}) and damping relationships published by Darendeli [1] were based on limited data at shear strains greater than 0.1% and no data at shear strains greater than 0.6%, as shown in Fig. 1. Similar maximum shear strain levels exist in the databases used by others to develop dynamic soil property relationships, including Seed and Idriss [2], Hardin and Drnevich [3], and the Electric Power Research Institute (EPRI) [4]. Even the dataset for soft, fine-grained soils compiled by Vucetic and Dobry [5] only contains measurements of G/G_{max} and damping up to shear strains of approximately 1.0%. The lack of dynamic soil data at large shear strains necessitates the extrapolation of dynamic soil properties to values beyond their initial published bounds when performing site response for soft soils subjected to high-intensity input ground motions. These extrapolations may yield implied shear strengths that are either too high or too low relative to the estimated, or measured, static shear strength of the soil. To address this issue, Stewart and Kwok [6] and Yee et al. [7] proposed methods for modifying the G/G_{max} curve at large shear strains to more realistically represent soil shear strength. These modifications can be used to produce G/G_{max} curves that more realistically represent the static shear strength of the soil at shear strains greater than 1.0%. Hashash et al. [8] incorporated the G/G_{max} modifications of Stewart and Kwok [6] within a nonlinear stress–strain framework to develop G/G_{max} and damping cures appropriate for nonlinear site response analyses. Site response analyses conducted with modified G/G_{max} curves are believed to produce more reliable estimates of shear strain and ground shaking. However, even after these modifications, nonlinear and equivalent linear site response analyses may still generate unusual surface acceleration time histories and Fourier amplitude spectra.

* Corresponding author. Tel.: +1 512 471 9162.
E-mail address: brcox@utexas.edu (B.R. Cox).

http://dx.doi.org/10.1016/j.soildyn.2016.03.008
0267-7261/

This paper describes 1D site response analyses conducted for the Treasure Island site in California. The motivation for this research stems from problems encountered by practitioners and researchers when attempting to perform site response analyses for soft soil sites subjected to high intensity input design ground motions. Specifically, the analyses presented herein are used to: (1) investigate the problems encountered with modeling high intensity input ground motions at soft soil sites, (2) explore the influence of modifications to the large strain dynamic soil properties on the induced shear strains and predicted surface motions, and (3) critically evaluate the surface ground motions predicted from both nonlinear (NL) and equivalent linear (EQL) analyses before and after modifying the dynamic soil properties. Based upon previous observations and soil characteristics, the Treasure Island site is likely to exhibit liquefaction during strong earthquake events. While it is recognized that nonlinear effective stress site response analyses using a pore water pressure generation model could be used to analyze the coupled site amplification and liquefaction responses, the focus of this study was to investigate/compare the dynamic response results from EQL and NL analyses in a manner as similar as possible. Hence, the added complexities/uncertainties associated with nonlinear effective stress analyses and pore water pressure generation models have not been included for any of the analyses presented.

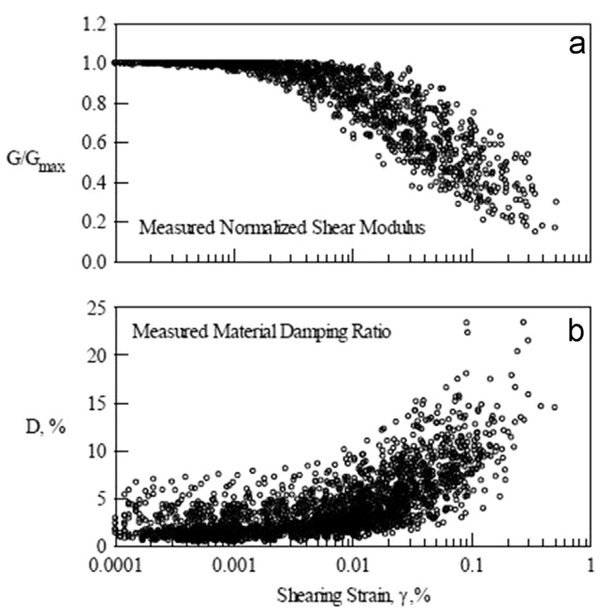

Fig. 1. Modulus reduction and damping data from Darendeli [1].

2. Modification of dynamic soil properties at large shear strains

Dynamic site response analyses at soft soil sites may require estimates of shear modulus (G) and damping ratio (D) over a shear strain range spanning four orders of magnitude (i.e., $< 10^{-3}$% to 10%). The variation of these dynamic properties with strain are defined using a G/G_{max} curve (where G_{max} is the maximum shear modulus at small strains) and a damping curve. While static soil properties such as shear strength are routinely measured at shear strains well above 1.0%, dynamic soil property curves commonly are measured up to only moderate shear strains (i.e., 0.3–1.0%). Theoretically, dynamic and static testing methodologies should be able to be combined to model the entire stress–strain behavior of the soil, but this has proven difficult in practice because static tests optimized to obtain shear strength estimates are not good at obtaining accurate shear modulus measurements at smaller strains, and vice-versa. Thus, the commonly utilized G/G_{max} curves obtained from dynamic testing have historically been extrapolated to larger shear strains without consideration for the shear strength implied by the large strain portion of the curve.

The shear stress (τ) as a function of shear strain (γ) can be obtained from a normalized G/G_{max} curve, the in-situ V_s, and the soil mass density (ρ) according to:

$$\tau = \gamma \cdot G = \gamma \cdot (G/G_{max}) \cdot V_S{}^2 \cdot \rho \tag{1}$$

When this relationship is extrapolated to large shear strains, a shear strength is implied at strains where failure is typically defined in static testing (i.e., 3–5%). This implied shear strength may or may not be realistic relative to expected soil behavior.

Examples of G/G_{max} curves that have been extrapolated to 10% shear strain are presented in Fig. 2. The following properties/parameters are assumed for this sandy soil layer: an effective friction angle of 33°, a shear wave velocity (V_s) of 150 m/s, an over consolidation ratio (OCR) of 1.0, a coefficient of uniformity (C_u) of 3.0, a vertical effective stress (σ'_{vo}) of 58.4 kPa, and a K_o value of 0.5. This information was used to develop appropriate G/G_{max} curves using four common relationships. Here, each relationship has been extrapolated beyond its approximately 0.3–1% data limits to a shear strain of 10%. The G/G_{max} curves of Seed and Idriss [2] and EPRI [4] were simply extrapolated to larger strains along a hyperbolic trend, while the Darendeli [1] and Menq [9] relationships are defined by equations that can be easily extrapolated to shear strains of 10%, even though they are not constrained by data at such large shear strains.

Fig. 2b shows the shear stress versus shear strain curves implied by each extrapolated G/G_{max} relationship according to Eq. (1). Also shown is the estimated Mohr–Coulomb shear strength (τ) of 38 kPa, which was calculated using the vertical effective stress

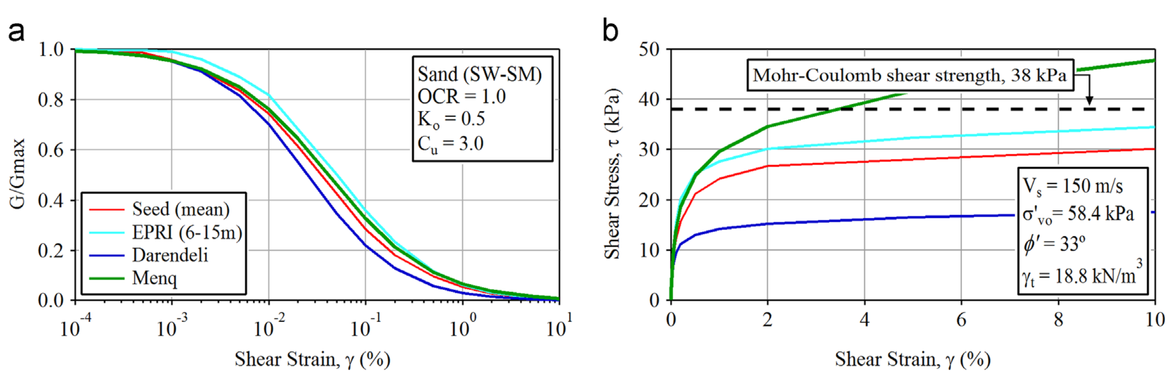

Fig. 2. (a) Modulus reduction curves for a well graded sandy soil with silt from Seed and Idriss [2], EPRI [4], Darendeli [1] and Menq [9], each of which has been extended to 10% shear strain from the published maximum shear strains of 0.3–1.0% in their databases and (b) associated shear stress implied by the modulus reduction curves in comparison with the Mohr–Coulomb shear strength.