Constitutive Model Input Parameters for Numerical Analyses of Geotechnical Problems: An In-Situ Testing Case Study.

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Abstract. Numerical modeling and finite element analyses are increasingly becoming cost effective methods for assessing geotechnical problems. The use of in-situ testing methods, notably the SDMT, along with stiffness reduction approaches utilizing G-γ curves are used to obtain stiffness related input parameters for numerical modeling. This paper presents the steps used to obtain stiffness parameters based on shear wave velocity measurements taken from SCPTu and DMT data and presents a case study of a monitored embankment.

Keywords. constitutive model, modeling, numerical analysis, in-situ, CPT, DMT, stiffness, stiffness degradation

1. Introduction

Numerical-method based analyses encountered in common geotechnical software utilize various constitutive soil models and stiffness related inputs to characterize site conditions and predict soil response. Customarily, rigorous laboratory testing is needed to determine site specific stiffness related inputs for these models. Often, reference tables are used to provide stiffness estimates based on soil type. In-situ testing can provide a site specific and cost effective method to determine stiffness related characteristics of geomaterials that may include sands, silts and clays.

Stress related deformation calculations involve linear elastic, nonlinear elastic and elasto-plastic models (with and without strain hardening) and their respective input parameters. The purpose of this paper is to address the determination of site-specific soil characterization and stiffness parameters for use in numeric and/or finite element analyses utilizing in-situ testing methods, in particular seismic flat dilatometer testing (SDMT). A case study of an instrumented embankment utilizing linear elastic constitutive relations in Newport News, Virginia is also presented.

2. Stiffness and Stiffness Degradation

Stiffness related inputs for numerical analyses primarily include variants of Young's (elastic) modulus, E along with poisson's ratio, ν. Elastic modulus variants of secant modulus in drained triaxial test at 50% strength (E_{50}), tangent modulus for primary oedometer loading (E_{oed}), as well as unloading/reloading modulus (E_{ur}) are commonly needed values.

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Poisson's ratio values determined through laboratory triaxial testing and/or geophysical testing should generally be used as shown in Table 1.

Table 1. General values for Poisson's Ratio based on soil type.

Soil Type	Poisson's Ratio (ν)
Granular Material	0.3
Drained Cohesive Material	0.3 – 0.4
Undrained Cohesive Material	0.5

Small strain stiffness and nonlinear soil behavior rely on shear modulus value determination. The fundamental shear modulus, G_0, is first determined for a soil profile using seismic shear wave velocity testing via SDMT, seismic piezocone testing (SCPTu), spectral analysis of surface waves (SASW) or other methods. Dilatometer testing of the subsurface then provides the basis to produce a G-γ modulus reduction curve for each representative soil type. Next, the G-γ modulus reduction curve is translated to an E-γ modulus reduction curve using elastic theory. The site specific E-γ modulus reduction curve along with data obtained from SDMT testing can then be used to determine modulus inputs for use in numerical simulations.

2.1. Stiffness Degradation from Dilatometer Testing

Hyperbolic G-γ modulus reduction curves follow the typical behavior indicated by Fig. 1 (Hardin & Drnevich, 1972). The Hardin-Drnevich degradation curve is defined as:

$$\frac{G}{G_o} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_{ref}}\right)} \tag{1}$$

where γ_{ref} = reference strain

The general Hardin-Drnevich relation has been further modified to include scaling factors in order to achieve a best fit hyperbolic model of modulus reduction for various soil types based on laboratory testing. The scaling factors are seen in the inclusion of a power exponent (α) as shown in Eq. 2 (Vardenega & Bolton 2011), or alternatively, a multiplicative factor (a) as shown in Eq. 3 (Santos & Correia, 2000).

The modified Hardin-Drnevich G-γ expression curves are the basis for modulus reduction curves used in several numerical modeling suites. The use of a = 0.385 in Eq. 3 after Santos and Correia (2000) is common to many hardening soil models (Benz, 2007).

The use of Eq. 3 after Santos & Correia is most common to numerical analysis suites in determining parameters for the hardening soil model. The degradation curves as shown in Fig. 2 based on Eq. 2 and 3 reduce in distinctly different curves.

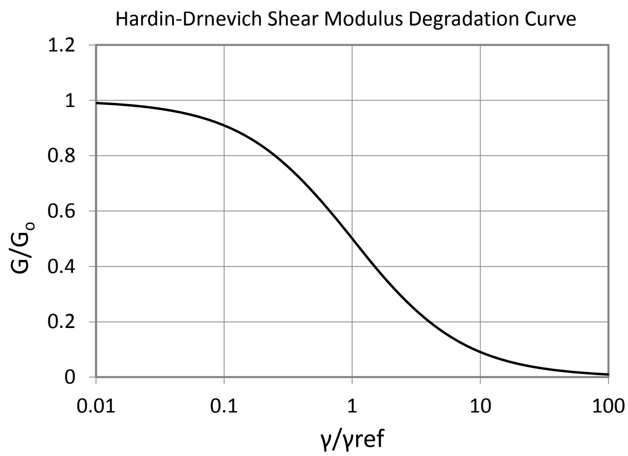

Figure 1. Shear modulus reduction curve
(after Hardin and Drnevich 1972)

$$\frac{G}{G_o} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_{ref}}\right)^{\alpha}} \tag{2}$$

$$\frac{G}{G_o} = \frac{1}{1 + a\left(\frac{\gamma}{\gamma_{ref}}\right)} \tag{3}$$

To construct the site specific G-γ modulus degradation curve, the working shear strain γ_{DMT} corresponding with G_{DMT} must be determined (Cox & Mayne, 2015).

Once the G-γ modulus degradation curve is determined using in-situ testing, a corresponding E-γ modulus degradation curve can be constructed using Hooke's law and elastic theory as shown in Figure 3.

Then, the secant modulus in triaxial testing at 50 percent strength E_{50} can also be determined using values obtained from SDMT testing. Where according to Vermeer (2001),

$$E_{50} \cong M_{DMT} \tag{4}$$

The unloading/reloading modulus in the drained/undrained triaxial test, $E_{ur,}$ cannot readily be determined using data obtained from DMT testing and must be calculated using accepted relationships if not using laboratory testing such as that given by Vermeer (2001),

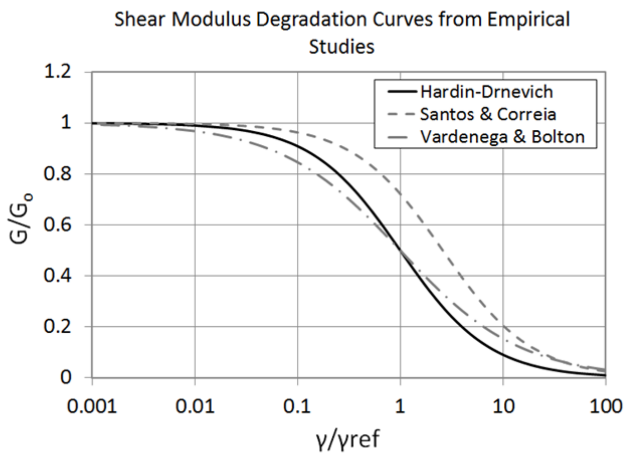

Figure 2. Reduction curves from fitted experimental data studies

$$E_{ur} \cong 4E_{50} \tag{5}$$

One will note that when viewing the stiffness degradation curve, E_{50} is the smallest of the modulus values discussed. Most numerical programs maintain an elastic stiffness cutoff at E_{ur} (corresponding to G_{ur}), where hardening plasticity accounts for further stiffness reductions.

Advanced hardening models include the values of G_o and $\gamma_{0.7}$ as inputs to define the nonlinearity and small strain stiffness relationships for various geomaterials. Once G_o is determined from seismic shear wave velocity testing, the stiffness degradation curve as shown in Figure 2 can be used to define $\gamma_{0.7}$.

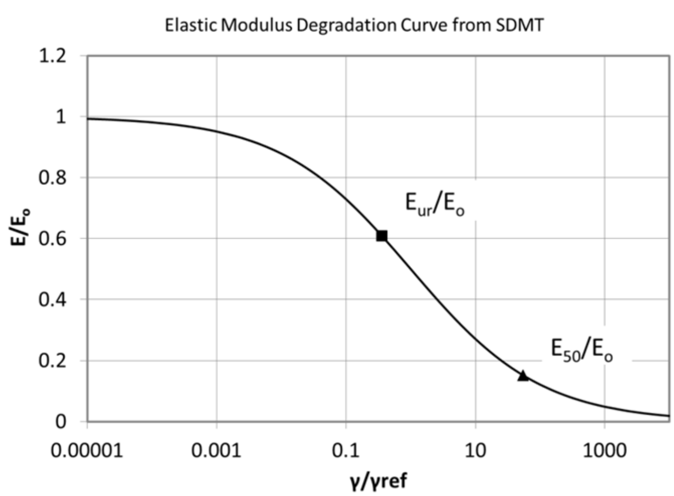

Figure 3. Elastic Modulus reduction curve using SDMT

3. Case Study Of A Monitored Embankment: Newport News, VA

A linear elastic constitutive model used in commercially available settlement software was used to assess the applicability of utilizing stiffness parameters determined from in-situ testing methods. The embankment studied was part of a protection system for an electron beam accelerator constructed in Newport News, Virginia in 1986 with initial analysis presented by Mayne & Frost. The embankment was constructed on site soils consisting of interlayered sands, silts and clays of the *Norfolk Formation* to an approximate depth of 7 m underlain by preconsolidated low plasticity clays and silts along with silty sands of the *Yorktown Formation*.

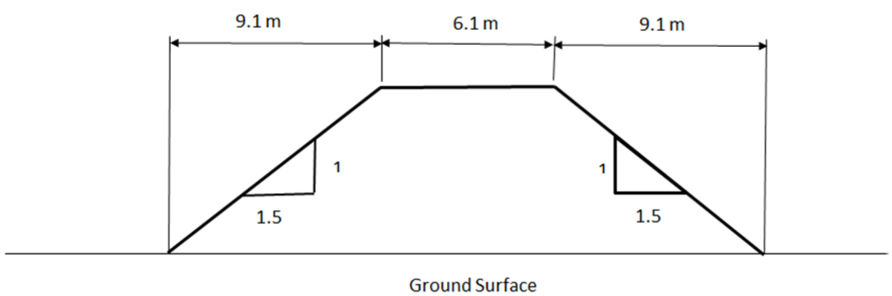

Figure 4. Cross Section of Test Embankment in Newport News, Virginia, (after Mayne & Frost)

Instrumentation used to monitor deformations of a test embankment included horizontal inclinometer pipe, settlement plates, borros points, pneumatic piezometers and open standpipes. A cross section of the embankment is shown in Fig. 4. Settlement estimates were calculated using various methods that included estimates based on oedometer testing (OED 86), estimates based on DMT testing (DMT 86) and a FEM model (FEM 86) based on work by Duncan (Mayne & Frost, 1988).

In the current case study, inputs to the settlement software program were based on DMT and SCPTu data available at the site. A multi-layer theory stress anlaysis was conducted based on Hankel transforms utilizing numerical methods presented by Yue (Rocscience, 2009). The requested input for elastic settlement calculations for each soil layer was E_s, defined as the one-dimensional Young's modulus. The input for consolidation settlement for each soil layer using a linear elastic soil model was m_v, the coefficient of volume compressibility. The operative constrained modulus from DMT testing M_{DMT} was used as the in-situ input for E_s following Eq. 4. The reciprocal of the operative constrained modulus M_{DMT} ($1/ M_{DMT}$) was used as the in-situ input for m_v. Table 2 includes the layer definitions and inputs used in the settlement analysis.

The results of the in-situ generated input parameter analysis are shown in Fig. 5 and a comparison of the estimated settlements from multiple calculation methods shown in Fig. 6.

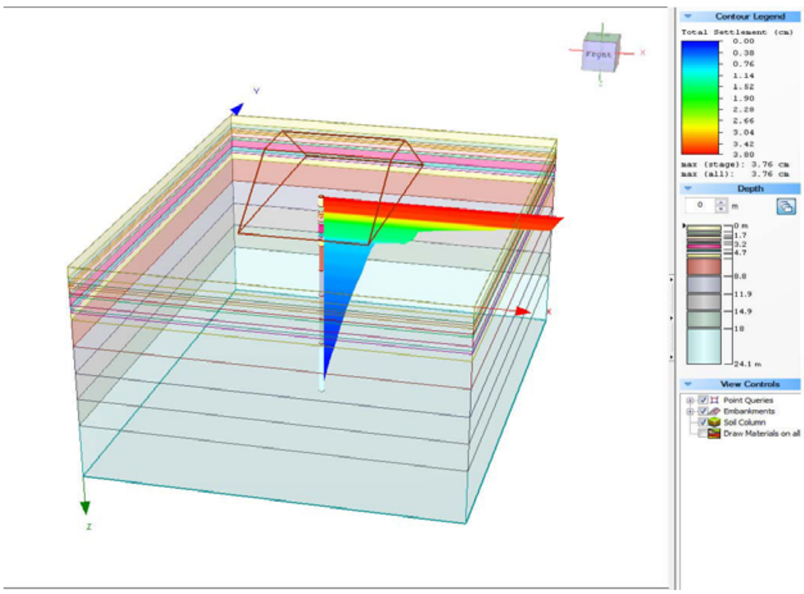

Figure 5. Settlement Results from Numerical Analysis using Input Parameters from In-Situ Testing

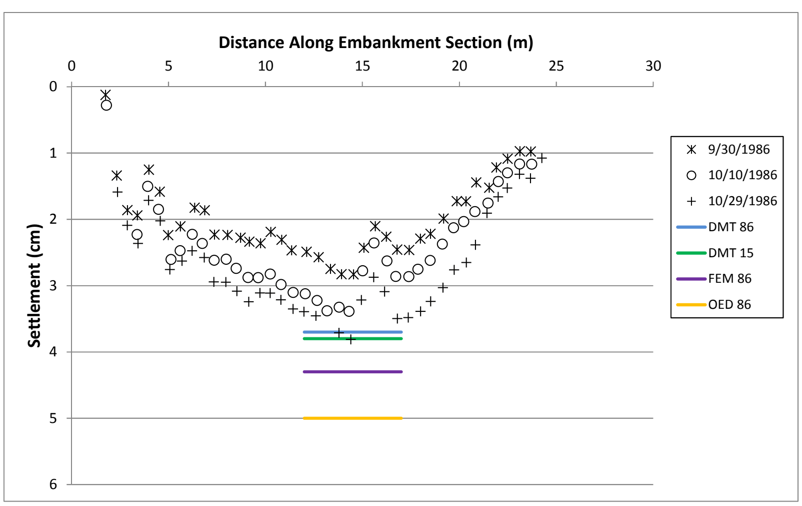

Figure 6. Comparison of Estimated Settlements for a Monitored Embankment, Newport News, VA

Table 2. Layer Properties Used in Numerical Analysis from In-Situ Testing

Layer	Depth (m)	Soil Type	Go (Mpa)	M_{DMT} (Mpa)	Es (Mpa)
1	0 - 1.1	Sandy Silt	86	100	100
2	1.1 - 1.7	Silty Sand	89	125	125
3	1.7 - 2.0	Silty Clay	71	7	7
4	2.0 - 2.3	Silty Sand	80	28	28
5	2.3 - 3.0	Silty Clay	71	3	3
6	3.0 - 3.3	Sandy Silt	75	12	12
7	3.3 - 4.5	Silty Sand	89	125	125
8	4.5 - 4.8	Silt	80	35	35
9	4.8 - 5.5	Clay	80	12	12
10	5.5 - 7.5	Silty Sand	222	105	105
11	7.5 - 10	Silty Sand	216	135	135
12	10 - 12	Silty Sand	264	90	90
13	12 - 15	Silty Sand	331	80	80
14	15 - 21	Silty Sand	282	70	70
15	21 - 25	Silty Sand	230	50	50

Results utilizing numerical methods with stiffness inputs derived from in-situ testing (DMT 15) were a very close match to calculations performed prior using DMT data (DMT 86). The estimated deformations were in agreement with measured deformations recorded from instrumentation. A FEM model of the embankment utilizing the in-situ derived parameters for non-linear elasto-plastic soil conditions is under development.

4. Conclusion

In-situ testing can provide a site specific and cost effective method to determine stiffness related characteristics of geomaterials that may include sands, silts and clays. Seismic testing to determine fundamental shear modulus G_0 values along with DMT testing can be used to produce G-γ modulus reduction curves that are then translated to an E-γ modulus reduction curve using elastic theory.

A case study of an instrumented embankment utilizing linear elastic constitutive relations in Newport News, Virginia was examined. Linear elastic input parameters of E_s and m_v were assigned to the settlement model. The model predicts the observed settlement accurately and provides a simplistic and cost effective method to determine site specific stiffness parameters for numerical analyses in all soil types.

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