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FIELD MEASUREMENTS OF LINEAR AND NONLINEAR SHEAR MODULI OF CEMENTED ALLUVIUM

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ABSTRACT

A field method has been developed at the University of Texas at Austin to evaluate the linear and nonlinear shear moduli of soil. The method utilizes a dynamically-loaded shallow footing as the seismic source and 3-D geophones embedded in vertical arrays beneath the footing as sensors. The field method was applied to cemented alluvium at the Yucca Mountain site in Nevada to evaluate the effects of stress state and strain amplitude on shear modulus. Experimental results show that small-strain shear moduli were obtained at total vertical stresses from about 10 to 250 kPa and shear moduli were evaluated at shearing strains ranging from about 10^{-4} to 10^{-2}%. Comparisons of field measurements with laboratory-determined shear modulus reduction curves evaluated with reconstituted gravelly specimens support the validity of the field method and show the need for these in-situ measurements, especially in hard-to-test soils like cemented alluvium.

Introduction

Evaluations of nonlinear soil moduli for use in geotechnical earthquake engineering studiesof critical facilities generally concentrate on shear moduli and generally involve a process that combines field and laboratory tests. The first step in the process involves field seismic tests. Thesetests are used to measure shear and compression wave velocities in the small-strain range from which small-strain shear and constrained moduli (G_{max} and M_{max}, respectively) are calculated. Field seismic tests are conducted at the existing field state. Therefore, parameters such as stress state and strain amplitude are not evaluated. The second step involves evaluating the effects of these and other parameters in the laboratory with intact and/or reconstituted soil specimens. The third step involves combining the parametric effects evaluated in the laboratory with the small-strain field measurements to develop models of the nonlinear soil moduli during

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earthquake shaking. The final step in the process involves introducing judgment and experience of geotechnical engineers, engineering geologists and engineering seismologists involved in the effort to incorporate factors such as biases, uncertainties and spatial variabilities in the models.

To evaluate directly the nonlinear moduli of soil in situ and to understand better the strengths and limitations of the four-step process described above, field methods are being developed to load and evaluate soil in the nonlinear range. The methods involve applying static and dynamic loads near the surface of the soil deposit and measuring the soil response beneath or around the loaded area using embedded instrumentation. In this paper, one field approach is presented that is used to measure linear and nonlinear shear moduli. This approach utilizes a surface footing that is dynamically loaded horizontally. The testing arrangement, stage loading sequence, and resulting measurements in strain ranges where the soil responds linearly and nonlinearly are discussed. The dynamic loads in each testing stage are applied with a Vibroseis which can be used to apply sinusoidal dynamic loads over a wide range, from loads that create only small strains in the soil (strains less than $5\times10^{-4}\%$) to loads that create significant nonlinear soil responses (strains above 0.03% depending on confinement state and material type). The Vibroseis is part of the nees@UTexas Equipment Site (http://nees.utexas.edu) that is funded by the U.S. National Science Foundation as part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The wide range in dynamic loads permits measurements of linear and nonlinear shear wave propagation from which shear moduli and associated shearing strains are evaluated. Nonlinearity in the soil occurs in the vicinity of the base of the footing where the embedded instrumentation has been placed. To illustrate the method, a set of linear and nonlinear measurements in cemented alluvium at Yucca Mountain, Nevada are presented. Cemented alluvium is a hard-to-sample soil for which no information exists in the literature on the nonlinear shear moduli. Comparisons of field measurements with laboratory-determined shear modulus reduction curves determined with gravelly specimens support the validity of the field method and show the need for the in-situ measurements.

Field Test Site at Yucca Mountain, Nevada

Proposed High-Level Radioactive Waste Repository

In the United States (U.S.), high-level radioactive waste has been generated over the several decades by governmental defense programs, nuclear power plants, and research activities. These wastes are temporarily stored at more than 120 locations in 39 states over the U.S. (DOE 2008). As a long-term solution to manage the currently produced waste, a deep geologic repository has been proposed for construction by the U.S. Department of Energy (DOE). The site selected by DOE is Yucca Mountain in Nevada. Yucca Mountain is located about 160 km from Las Vegas, Nevada in a remote, desert area inside the Nevada Test Site on federal land. The proposed geologic repository is at a depth of about 300 m below the crest of the mountain and about 300 m above the ground water table.

Test Site and Alluvial Material

During May through August 2007, field linear and nonlinear dynamic tests of cemented alluvium were conducted at a location in the general area proposed for the surface, wastehandling facilities at Yucca Mountain. The test site is located about 790 m from the north portal of an existing tunnel that was constructed to investigate volcanic tuffs at the proposed repository location within Yucca Mountain. The surface material in the north portal area consists of naturally cemented alluvium. Three test pits were excavated in the cemented alluvium to investigate its characteristics in the near surface as part of the geotechnical site characterization study (Schuhen et al. 2008). Each test pit was approximately 5.8 m deep. From visual inspections of the exposed alluvium and laboratory testing of disturbed samples, the alluvium consists mainly of coarse grained particles, ranging from poorly graded sand to gravel with varying amounts of cobbles and boulders. The cementation in the alluvium is quite variable spatially. Based on 17 sieve analyses of the alluvial materials, the median grain size (D_{50}) varies from 0.4 to 24.8 mm and the uniformity coefficient (C_u) ranges from 16 to 86. The moisture content of the alluvium is on the order of a few percent. The large grain sizes and cemented nature of the alluvium puts this material in the category of geotechnical materials that are hard to sample and rarely tested dynamically in the laboratory. Therefore, nonlinear dynamic properties of intact, naturally-cemented alluvium do not exist in the literature.

Field Tests at Yucca Mountain

Field Test Set-Up

The field test set-up employing a shallow footing and embedded instrumentation is illustrated in Fig. 1. The basic ideas and procedures for the field set-up are discussed in detail in Stokoe et al. (2006) and Park (2010). To prepare the test site, shallow surficial soil was excavated to remove all vegetation and expose the intact alluvium. Next, a concrete footing was constructed. PVC-cased holes were cast in the footing and were used as guides to drill 7.6-cm diameter boreholes in which 3-D geophones were installed. Each 3-D geophone was composed of three small geophones with natural frequencies of 28 Hz and damping ratios of 50%. The 3-D geophones were constructed by epoxying the individual geophones arranged in a triaxial configuration in 3.7-cm cubical cases. A square tab was attached to the top of each case so that an aluminum rod placed over the tab could be used to lower and orient the case. After a 3-D geophone was lowered to the desired depth, the geophone was grouted in place. Once the grout was cured, the positioning aluminum rod was pulled from the geophone and the borehole was filled with sand to the next shallower geophone location. This procedure was repeated for all geophone installations, including the upper-most 3-D geophones in the base of the footing. Finally, the PVC casings inside the footing were filled with grout. Detailed information about the field set-up at Yucca Mountain can be found in Schuhen et al. (2009) and Park (2010).

Small-Strain Downhole Tests

Traditional downhole seismic tests were performed to evaluate the small-strain moduli of the alluvium by measuring velocities of: (1) vertically propagating constrained compression (P) waves with vertical particle motion, and (2) vertically propagating (S) waves with horizontal particle motion. The downhole testing arrangement is illustrated in Fig. 1a. The circular concrete footing was utilized as the seismic source as follows. At given static loads on the footing, transient impacts were applied by striking the footing using small, hand-held hammers. The impact locations were: (1) on top of the footing at both locations directly above the vertical

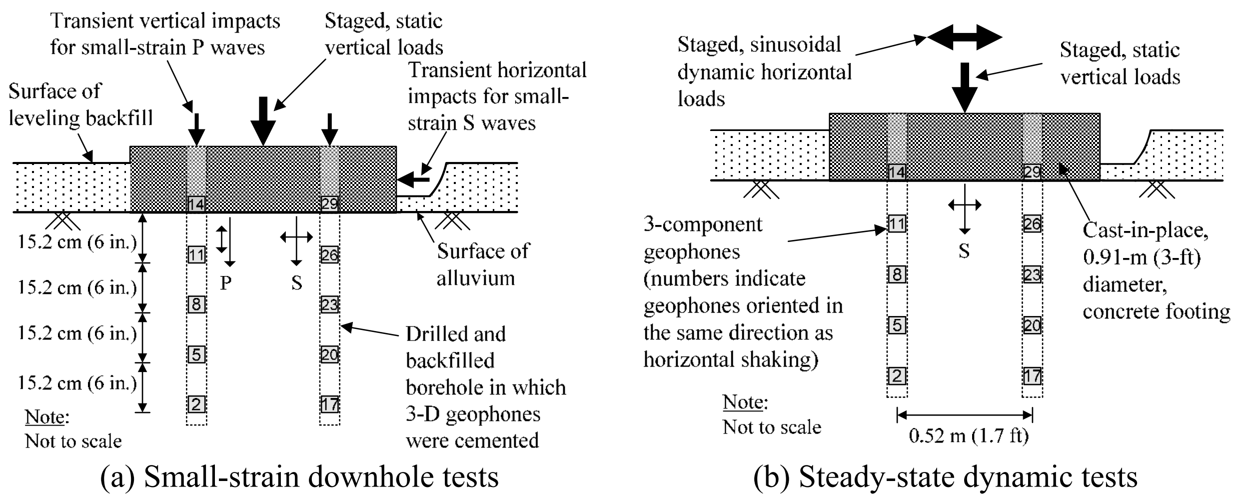


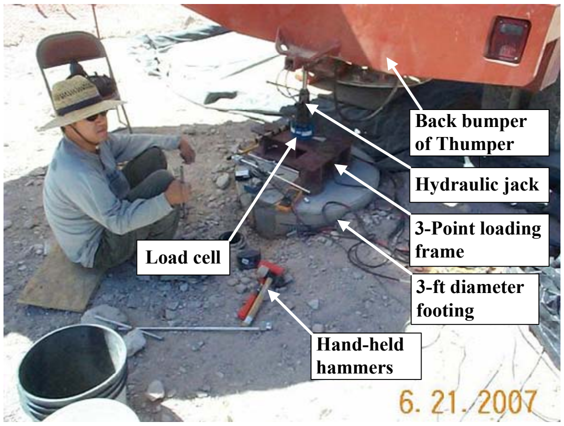
Figure 1. Schematic illustration of the field set-up for: (a) small-strain downhole seismic tests and (b) steady-state linear and nonlinear dynamic tests

sensor arrays for P-wave measurements, and (2) at the mid-height on the side of the footing in the horizontal direction for S-wave measurements. The propagation of P and S waves from the transient impacts through the soil mass was monitored with the embedded geophones. The small-strain downhole tests were conducted at various static-load levels; hence at different confining stresses. In this manner, variations of small-strain shear and constrained moduli (G_{max} and M_{max}, respectively) with confining pressure were evaluated from the log V_S-log σ_v and log V_P-log σ_v relationships, respectively. The topic of this paper is shear wave measurements; hence, only the shear moduli results are discussed. A photograph of small-strain downhole testing is shown in Fig. 2a. In this photograph, a static load is being applied to the 0.91-m diameter footing using Thumper (a small-capacity Vibroseis) as a reaction mass.

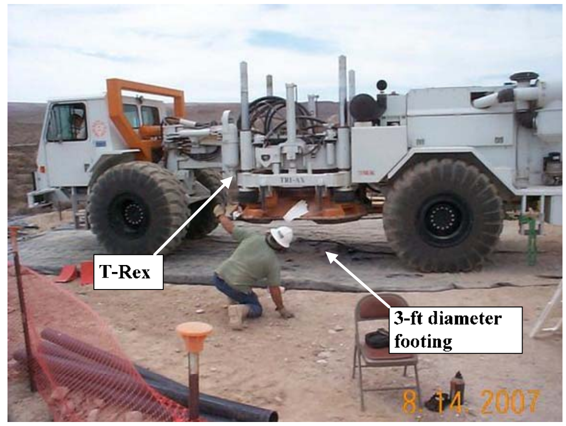
Nonlinear Dynamic Testing

Field testing to evaluate the nonlinear shear moduli of the alluvium involved staged testing. Each stage consisted of: (1) applying a constant static vertical load to the alluvium using the surface footing, (2) then applying horizontal sinusoidal loading with a constant amplitude for afixed number of cycles at a fixed frequency to generate shear waves within the alluvium, (3) repeating Step No. 2 over a range in load levels that created a range in strains in the soil, and (4) measuring the response of the alluvium beneath the loaded area during each dynamic load level using the embedded instrumentation. The schematic illustration of the field set-up at each stage of linear and nonlinear dynamic testing is shown in Fig. 1b. This testing is referred to as steady-state dynamic testing herein. The mobile vibroseises of nees@UTexas, Thumper (small-capacity Vibroseis) and T-Rex (large-capacity vibroseis), were used to apply both the static and dynamic loads employed in the steady-state dynamic tests. Fig. 2b shows T-Rex (large-capacity vibroseis)being positioned over the 0.91-m diameter footing in preparation for steady-state dynamic testing.

The static load applied to the footing was held constant during each testing stage. Then, a series of steady-state dynamic loads, consisting of 10 to 15 cycles of sinusoidal loading at each



(a) Conducting downhole tests



(b) Preparing for steady-state dynamic tests

Figure 2. Photographs of field testing being performed at alluvial site

load level, were applied. The range in load levels was used to create shearing strains in the alluvium that ranged from small strains in the linear range ($<4\times10^{-4}$%) to large strains that created significant nonlinearity (at 5×10^{-3}% where G/G_{max} ~ 0.6). As an example, nonlinear testing at a static load level of about 36 kN was performed using a series of 10 different dynamic loads, ranging from +/-2 to +/-27 kN. The shear waves that were generated at each dynamic load level were monitored to obtain the wave propagation velocities. The set of dynamic loads was repeated at other static load levels. Therefore, the effects of strain amplitude and confining state on the G-log γ and G/G_{max}-log γ relationships were evaluated in the field.

Staged Loading Sequence

As noted above, field testing was performed in a staged sequence. Several constant static loads were used in an increasing sequence. At each static load, the dynamic loads were applied in an increasing sequence, with small-strain tests conducted at the start and end of each stage as shown in Fig. 3. Static load levels of about 18, 36, 71 and 142 kN were used in Stages 2, 3, 4 and 6, respectively. As part of the staged loading sequence, two static load-settlement tests were performed to investigate the soil more completely. The static load-settlement tests are illustrated in Stages 5 and 7 in Fig. 3. However, these tests are not discussed in this paper.

Data Analysis Procedure

Small-Strain Downhole Tests

S-wave velocities were calculated from wave travel times determined between geophone pairs located at predetermined distances apart (see Fig. 1). In these tests, the distances were determined within about 2.5 mm because the travel distances were short (in the range of 15.2 to 61.0 cm). Wave travel times evaluated over such short distances require high signal-to-noise ratios so the time of the arrivals are readily identified, often within a few micro-seconds in stiff soil. Typical waveforms and the analysis procedure used to evaluate the S-wave velocity of the cemented alluvium are shown in Fig. 4. In this figure, the initial S-wave arrival at each geophone is identified by the solid dot above the waveform.

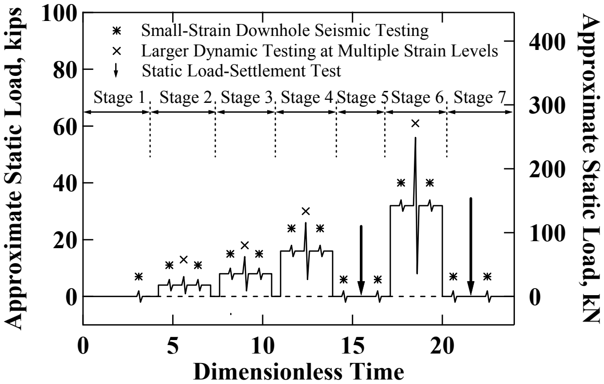


Figure 3. Staged loading sequence used in tests at Yucca Mountain, Nevada

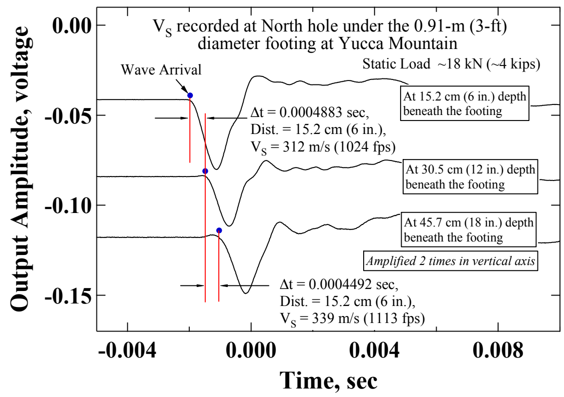


Figure 4. Typical data and data analyses of S waves in small-strain downhole tests

Estimation of In-Situ State of Stress

Total vertical stress (σ_v) must be estimated to evaluate the small-strain log V_S-log σ_v relationships. In the small-strain downhole tests, σ_v represents the combination of two vertical stresses: (1) the stress induced by the static load on the footing and the footing weight, and (2) an overburden stress due to the total weight of the soil. These two stresses were calculated separately and combined together to estimated σ_v at each static load level. To calculate the stress induced by the static load and footing weight, Boussinesq's stress distribution was utilized.

Nonlinear Dynamic Loading Tests

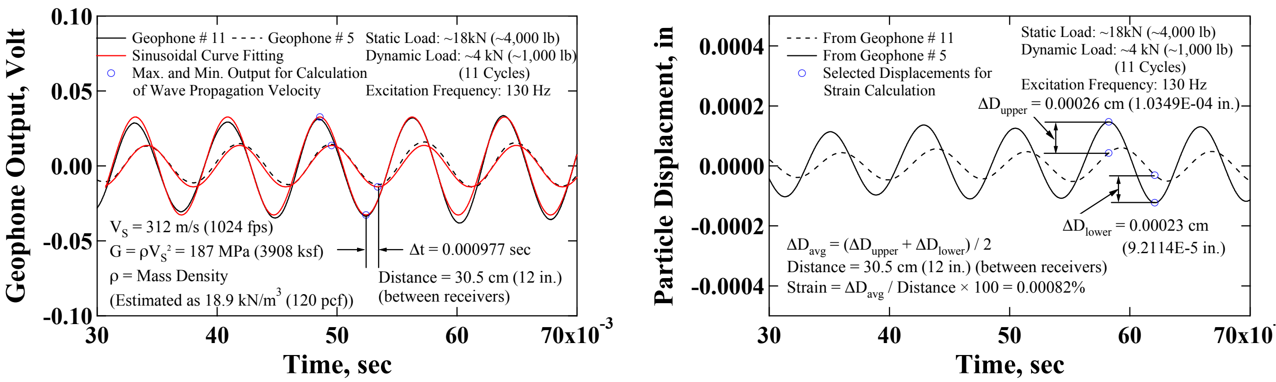
Shear moduli were determined from the relationship between shear modulus (G) and shear wave velocity (V_S) as:

$$G = \rho \times V_S^2 \tag{1}$$

where, ρ = total mass density of the soil. In the nonlinear dynamic loading tests, shear wave velocities were calculated from time delays determined between the sinusoidal signals of two geophones located vertically a known distance apart. In this study, sinusoidal waveforms with a constant amplitude and a frequency equal to the excitation frequency were fit to the steady-state portion of the geophone records using least-squares curve fitting. It was assumed that steady-statewas reached by the fifth cycle of excitation. Then, maximum and minimum points on the fitted waveforms were used to calculate interval travel times. With the spacing between geophones known, the travel times were used to calculate S-wave velocities. As an example, consider the geophone records and data analysis shown in Fig. 5a. The original geophone outputs recorded for nonlinear testing at a force level of +/-4 kN with an excitation frequency of 130 Hz under a static hold-down load of about 18 kN on the footing are shown.

Shearing strains were calculated using a two-node, displacement-based (DB) method (Rathje et al. 2004). With the DB method, the difference in horizontal displacements at a given instant in time between two geophones was divided by the distance between the two locations.

The variation of displacements between the two geophones was assumed to be linear. Displacements were computed using trapezoidal numerical integration of the monitored particle velocities. An example of this calculation is shown in Fig. 5b using the displacement-time histories at geophones # 11 and #5. In this figure, each velocity-time record was obtained by applying the geophone calibration factor to the recorded time history.



(a) V_S calculation (b) Shearing strain calculation

Figure 5. Typical geophone outputs and data analyses for nonlinear dynamic testing

Results of Field Measurements

Small-Strain Downhole Tests

The log V_S-log σ_v relationship determined in the small-strain downhole tests is shown in Fig. 6. A trend line was fit to the data using the least-squares method. The trend line was added to facilitate analysis and discussion of the data. The effect of cementation in the alluvium is seen by comparing the log V_S-log σ_v relationship predicted for uncemented gravel (Menq 2003) with the trend line. Cementation affects the log V_S-log σ_v relationship is two ways. The first way is by decreasing the "slope" of the log V_S-log σ_v curve. The second way is by increasing the value of V_S at a low vertical stress (Camacho-Padrón 2006). To evaluate qualitatively the effects of cementation on the alluvium in the field, the log V_S-log σ_v relationship for uncemented gravel is compared with the trend line in Fig. 6. For the uncemented gravel, the following material characteristics were used: C_u = 50 and D_{50} = 6 mm (the average values of C_u and D_{50} for the cemented alluvium from the tests pits). Also a void ratio of 0.27 was assumed for the uncemented gravel to represent a medium dense condition with a relative density (D_r) approximately equal to 80%. In Fig. 6, the variation of V_S with increasing σ_v can be expressed by:

$$V_S = A \times \left(\frac{\sigma_v}{P_a} \right)^{n_s} \tag{2}$$

where A = V_S at σ_v = 1 atm, σ_v = total vertical stress, P_a = one atmosphere (100 kPa), and n_S is a dimensionless exponent.

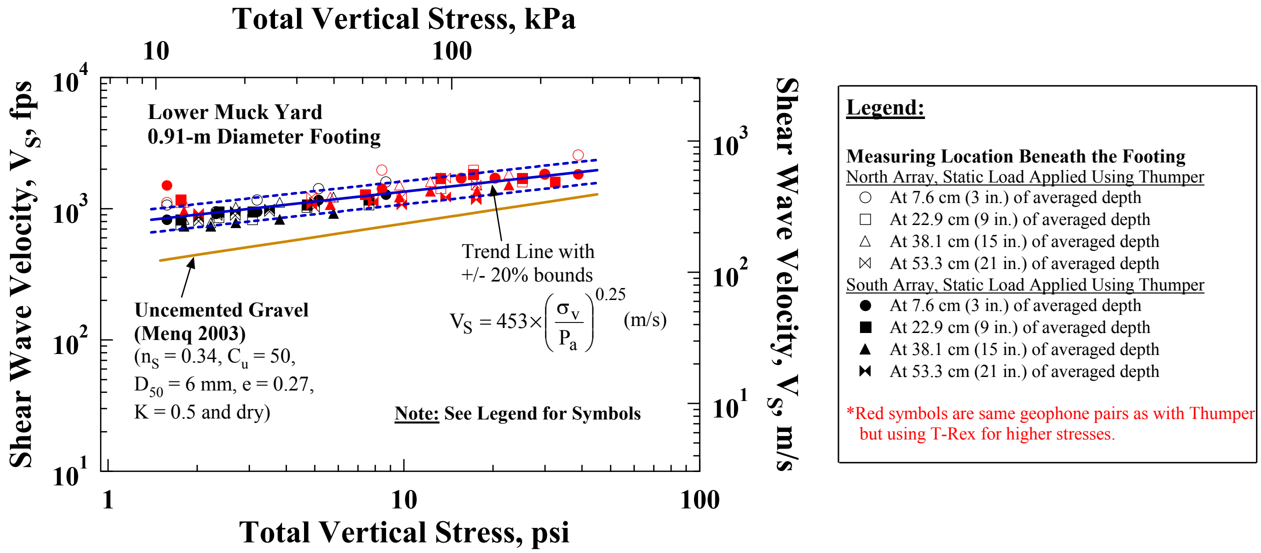


Figure 6. Comparison of log V_S-log σ_v relationships evaluated by field downhole tests and predicted for uncemented gravel (Menq 2003)

The first factor noted above that can be used to differentiate uncemented and cemented granular materials is the "slope," which is represented by n_S in Eq. 2. Note that total vertical stress (σ_v) is used instead of effective isotropic confining pressure (σ_o') in Eq. 2. The reason is that the in-situ lateral earth pressure coefficient (K) in the alluvium is unknown. However, if K is constant (which is assumed in this study), it has no impact on the "slope" (n_S). Also, σ_v is used in place of σ_o' for the following reasons: (1) the water content in the alluvium is very small (on the order of a few percent) and the effective vertical stress (σ_v') and total vertical stress (σ_v) can be considered equal and (2) σ_v is directly proportional to σ_o (or σ_o' in this case) if K does not vary in the cemented alluvium as assumed in this comparison.

As seen in Fig. 6, the estimated value of n_S for the uncemented gravel is 0.34 (Menq 2003). However, n_S from the downhole measurements equals to 0.25. Also, the V_S values at a low confining stress (at σ_v = 0.1 atm) is found to be 255 m/s. This value is more than twice the predicted value of 122 m/s for the uncemented gravel. The relative differences in n_S and V_S at 0.1 atm show that the alluvium in the field is cemented.

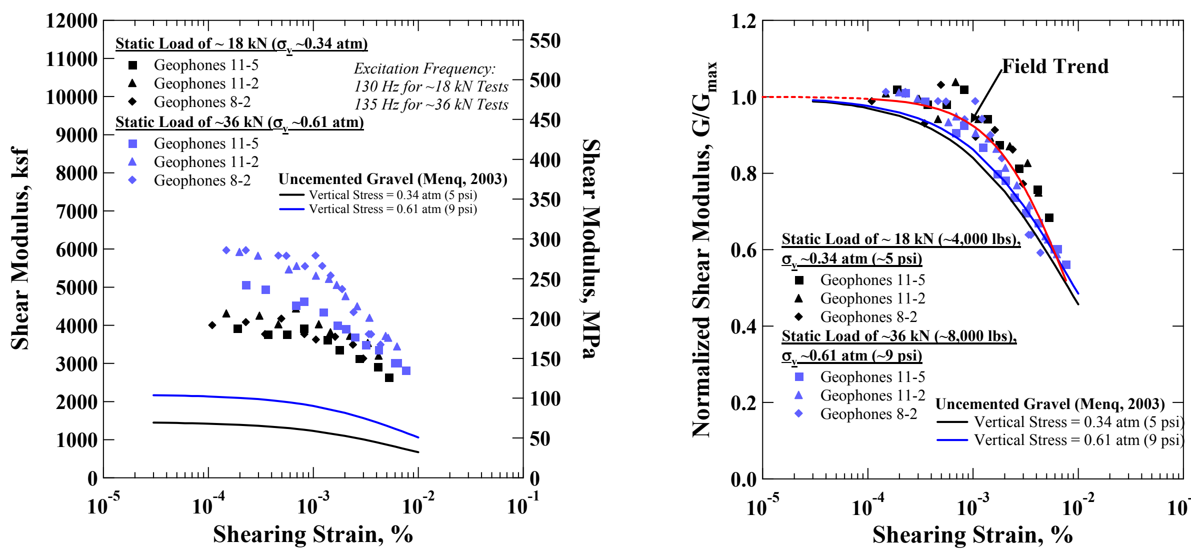
Steady-State Dynamic Loading Tests

The G-log γ and G/G_{max}-log γ relationships were evaluated using the 0.91-m diameter footing under two different static loads of ~18 and ~36 kN. Testing with an excitation frequency in the range of 130 to 135 Hz was performed. This range in frequencies resulted in the best shape of the sinusoidal waveforms monitored with the embedded geophones. Three geophone pairs were used to investigate the nonlinear shear modulus of the cemented alluvium. These pairs are between geophones # 11 and # 5, # 11 and # 2, and # 8 and # 2. The locations of the geophones are shown in Fig. 1. The G-log γ and G/G_{max}-log γ relationships from testing at both static loads are shown in Fig. 7a and 7b, respectively. The largest shearing strain measured was 8×10^{-3}% and this level occurred between the geophones # 11 and # 5.

Shear modulus reduction curves for uncemented gravel predicted by Menq (2003) at estimated equivalent confining states are also shown in Figs. 7a and 7b. Two observations can be made using these figures. First, G values from the field measurements are about 2.3 to 3 times higher than the values predicted for the uncemented gravel as shown in Fig. 7a. This observation indicates that the alluvium tested is cemented as discussed in the results from the small-strain downhole tests. The second observation is that G/G_{max}-log γ curves from the field measurements shift to the right compared to the G/G_{max}-log γ curves predicted for the uncemented gravel (Fig. 7b). In other words, the field G/G_{max}-log γ relationships show linear behavior to higher strains than uncemented gravel. However, the field G/G_{max}-log γ curves also show somewhat more nonlinearity as strain level increases above the linear strain range compared to the laboratory curves for uncemented gravel. Although these observations are qualitative, the two observations agree well with the dynamic behavior of cemented soil studied with laboratory measurements by Camacho-Padrón (2006).

Conclusions

The field testing method to evaluate the log V_S-log σ_v, G-log γ and G/G_{max}-log γ relationships was applied to cemented alluvium at Yucca Mountain, Nevada. The testing results showed that the small-strain V_S was obtained at σ_v from about 10 to 250 kPa and shear modulus reduction curves (G/G_{max}-log γ) were determined over shearing strains ranging from about 10^{-4}% to 10^{-2}%. Comparisons of field measurements with laboratory-determined relationships evaluated with reconstituted specimens of uncemented gravel indicated that the alluvium tested in the field is cemented. This comparison also supports the validity of the field method and show the need for in-situ measurements of hard-to-sample materials like cemented alluvium.



(a) G-log γ (b) G/G_{max}-log γ

Figure 7. Nonlinear shear modulus measured in the field for cemented alluvium and predicted from Menq (2003) for uncemented gravel

Acknowledgments

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