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EFFECT OF FREQUENCY ON THE EQUIVALENT VISCOUS DAMPING RATIO OF SOILS AT SMALL CYCLIC STRAINS

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ABSTRACT

Equivalent viscous damping ratio of soil, λ, is critical parameter in seismic site response analyses, in particular λ at small cyclic shear strain amplitudes, γ_c, that dominate the response in many earthquakes. Damping ratio λ is affected by various parameters, including the frequency of cyclic straining, f. Although the effect of f on λ was studied in the past, some of its aspects still need to be clarified. To examine the effects of f on λ at small γ_c, 17 soils were tested in a cyclic simple shear device for small-strain testing in the range of γ_c between approximately 0.001% and 0.01%. Soils ranged from clean sands to clays of high plasticity, while f varied between 0.03 and 1.0 Hz. For some soils λ consistently increased with f. For some soils, below $f \approx 0.2$ Hz λ decreased with f, while beyond $f \approx 0.2$ Hz it increased. Besides the test results, the paper includes brief description of testing device and procedure.

Introduction

Many soil dynamics analyses consider cyclic behavior of soil in pure shear. An example is the behavior of soil at level horizontally layered ground due to vertically propagating seismic shear waves presented in Fig. 1. Under such conditions soil element is on top of the normal vertical and horizontal consolidation effective stresses, σ'_v and σ'_h, existing before the earthquake, subjected to shear stresses, τ, caused by the earthquake. Such a behavior can be simulated in direct simple shear (DSS) device. A version of the DSS device used in this study is presented in Fig. 2. This unique device for small-strain testing that employs two specimens in a single test, and is thus called the dual-specimen DSS device (DSDSS device), is described in Doroudian and Vucetic (1995;1998). The main feature of cyclic behavior sketched in Fig. 1 and obtained in DSDSS test are the cyclic stress-strain loops the properties of which need to be known to perform the seismic site response analysis. Typical characterization of cyclic loop is presented in Figs. 3 and 4. The loop is characterized by its cyclic shear strain amplitude, γ_c, cyclic shear stress amplitude, τ_c, secant shear modulus, G_s, maximum shear modulus, G_{max}, and the equivalent viscous damping ratio, λ, that depends on its thickness. In any given soil dynamics event these cyclic loop parameters depend on a number of parameters and factor, such as soil

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type, density and corresponding void ratio, consolidation stress, overconsolidation ratio, the shape of cyclic straining (that is typically sinusoidal but it can vary between triangular and trapezoidal), and the frequency of cyclic loading, f, and corresponding average strain rate $\dot{\gamma} = |d\gamma/dt|_{avg} = (4\gamma_c)/T = 4\gamma_c f$.

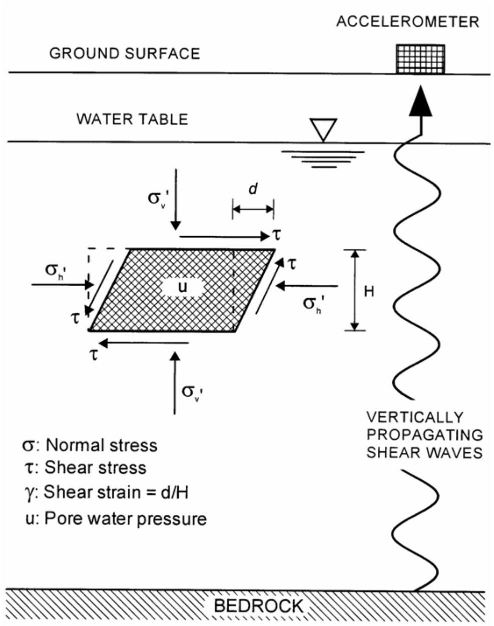


Figure 1. Idealized stress-strain conditions of soil element at horizontally layered ground due to vertically propagating seismic shear waves.

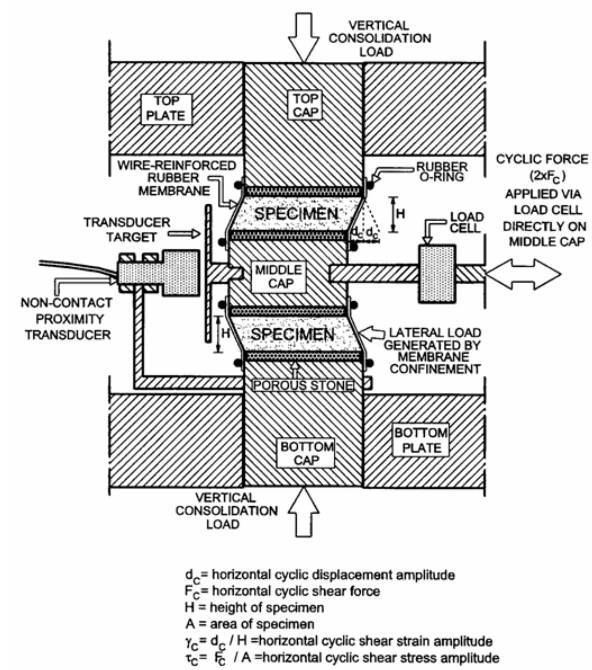


Figure 2. NGI type of dual-specimen direct simple shear (NGI DSDSS) apparatus for small-strain testing (Doroudian and Vucetic, 1995; 1998).

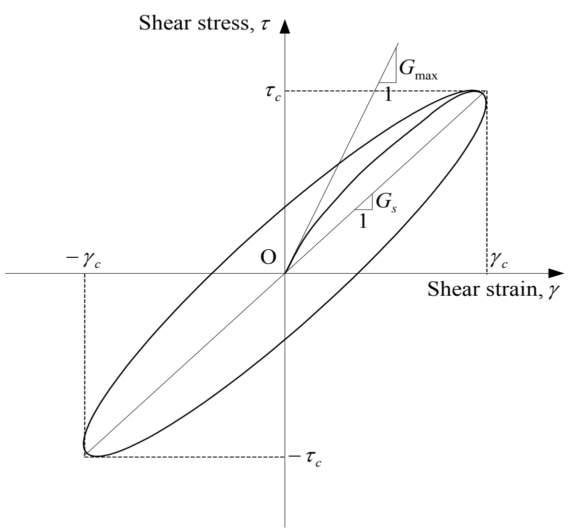


Figure 3. Idealized fully closed initial cyclic stress-strain loop with definition of parameters.

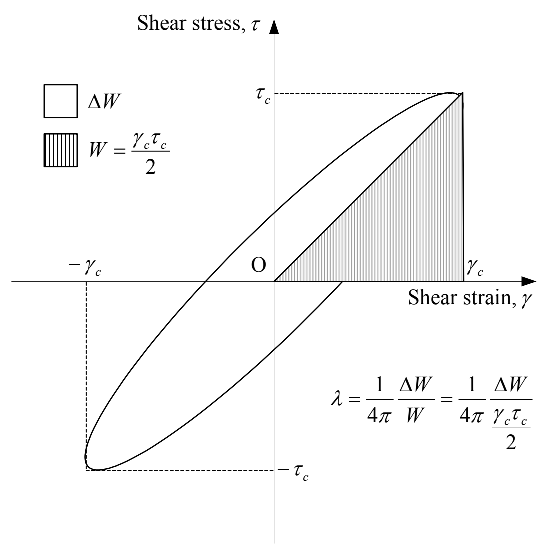


Figure 4. Definition of the equivalent viscous damping ratio, λ.

The effects of the frequency, f, and associated average strain rate, $\dot{\gamma}$, on the equivalent viscous damping ratio, λ, have been studied by many researchers (e.g., Shibuya et al., 1997; d'Onofrio, 1996; Cavallaro, 1997; Lanzo and Vucetic, 1998; Lanzo et al., 1999; Hsu and Vucetic, 2002; Stokoe et al., 1995, 1999). In spite of these numerous studies, the effects of f and $\dot{\gamma}$ on λ are not entirely clear. In general, the studies show that in most cases λ increases with f, such as shown in Fig. 5. However, it has been also observed that in the range of f approximately below 0.1 Hz λ in some soils decreases as f increases, and then above 0.1 Hz it increases with f. This interesting trend is shown in Fig. 6.

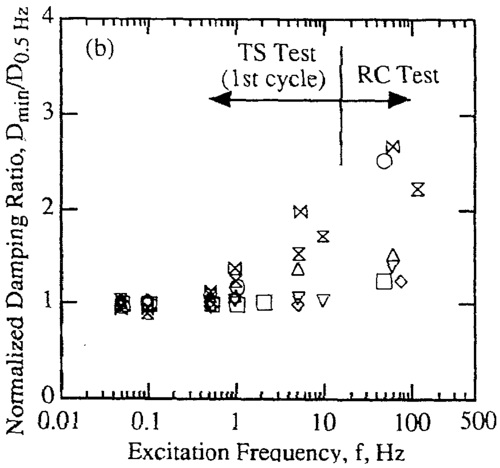


Figure 5. Variation of damping ratio at very small cyclic strain, D_{min}, with frequency, f, for undisturbed clays obtained in the combination of resonant column (RC) and torsional shear (TS) device (Stokoe et al., 1995).

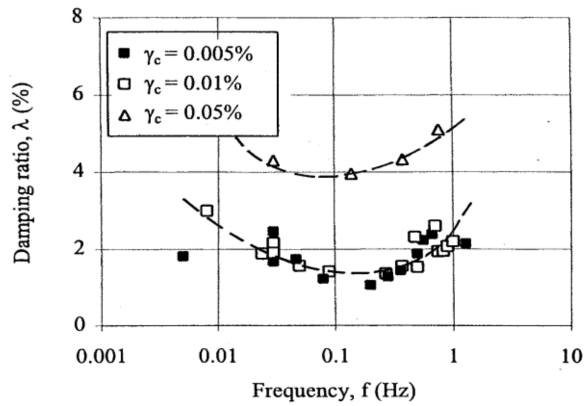


Figure 6. Variation of λ with f between $f \approx 0.01$-1.0 Hz for a high-plasticity clay having PI=44 (Lanzo, et al., 1999).

Program of testing and analysis

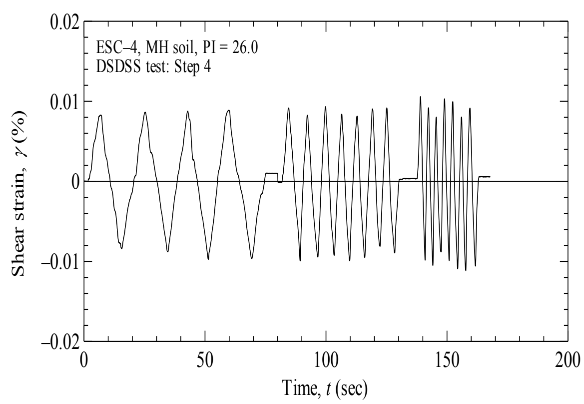
To throw more light on the effects of f and $\dot{\gamma}$ on λ the authors tested 17 soils (Tabata and Vucetic, 2004) and analyzed results on 6 soils tested by others (Matesic and Vucetic, 2003). On these soils, listed in Tables 1 and 2, 37 cyclic tests were conducted. These include 9 tests on Kaolinite clay conducted by the authors but not listed in the tables. All tests were conducted in the cyclic strain-controlled mode, which means that the series of consecutive cycles with constant cyclic shear strain amplitude, γ_c, were applied. Each test included up to six consecutive cyclic strain-controlled loading steps of constant γ_c of approximately 0.0003 %, 0.001 %, 0.003 %, 0.01 % and 0.03 %. Considering that the cyclic threshold hear strain for sands to clays with PI≈60 ranges between approximately 0.01 and 0.1% (Dobry et al., 1982; Vucetic, 1994), the cyclic shearing in all but the last step was certainly nondestructive, which justifies the testing in consecutive steps. In each step after every 4 to 7 uniform cycles the frequency was changed. Selected results from two steps of a test on high plasticity silt (PI=20, LL=65) consolidated to σ'_v=126 kPa are presented in Fig. 7. The results show several stress-strain loops from two steps and how *f* varied in one step.

Table 1. Summary of testing program carried out by the authors.

Test no.	Test name	Symbol	Plasticity index PI	Liquid limit LL (%)	Vertical consolidation stress σ_{vc} (kPa)	Void ratio e	Degree of saturation S_r (%)
1	Arleta-1	○	NP	NP	136	0.62	85
2	Obregon-2	●	18	40	123	N/A	N/A
3	Obregon-3	■	22	45	282	0.64	89
4	Obregon-4	◆	31	56	374	0.55	94
5	ESC-4	▲	26	65	126	0.89	98
6	ESC-8	▼	21	54	316	0.62	94
7	Dayton-2	▼	34	59	149	0.79	100
8	Dayton-3	▲	27	54	286	0.59	91
9	SIV-1	*	37	66	167	0.76	100
10	SIV-2	△	NP	NP	298	0.78	76
11	SIV-4	▽	NP	NP	652	0.65	92
12	Meloland-2	□	4	27	55	0.62	100
13	Meloland-3	◎	30	61	101	0.78	91
14	Meloland-5	◇	16	30	187	0.67	97
15	LBM-1	△	8	26	94	0.51	94
16	LBM-3	△	18	48	289	0.70	100

Table 2. Summary of testing program conducted by Matesic and Vucetic (2003).

Test no.	Test name	Plasticity index PI	Liquid limit LL (%)	Vertical consolidation stress σ_{vc} (kPa)	Over-consolidation ratio OCR	Void ratio e	Degree of saturation S_r (%)
MV1	Augusta-857	44	75	857	1.95	0.797	100
MV2	La Cienega-500-U	23	50	500	(unknown)	0.685	100
MV3	La Cienega-500-D			500	(unknown)	0.678	100
MV4	Kaolinite-300	20	53	300	1	0.945	100
MV5	Kaolinite-500			500	1	0.931	100
MV6	Riverside-35	NP	NP	35	N/A	0.6	43
MV7	Toyoura-100	NP	NP	100	N/A	0.589	0
MV8	Nevada-100	NP	NP	100	N/A	0.694	0
MV9	Nevada-300			300	N/A	0.659	0



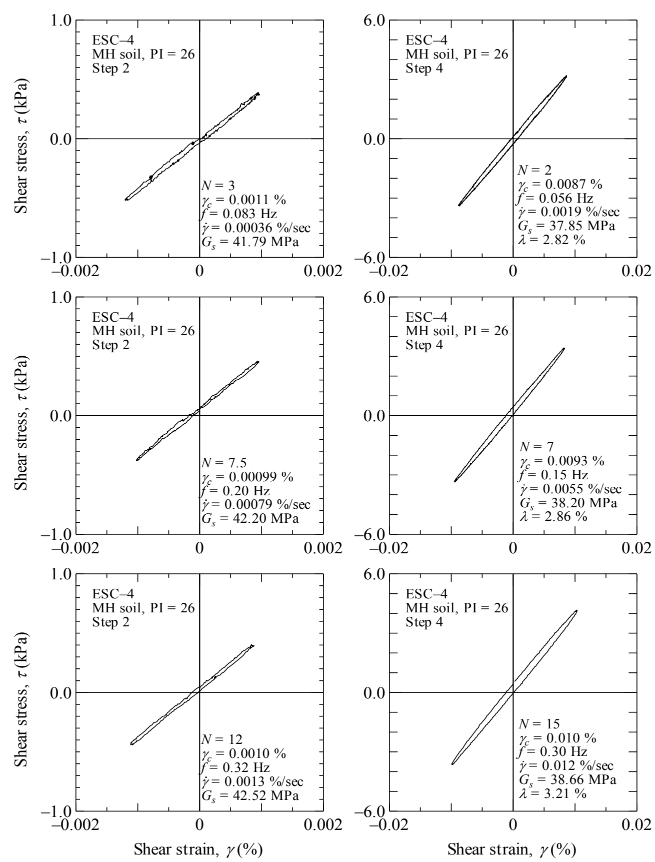


Figure 7. Example of test results from two cyclic steps (Steps 2 and 4) of DSDSS test on high plasticity silt (PI=20, LL=65) consolidated to σ'_v=126 kPa.

Selected test results

In this paper only the trend of λ with f is presented, while the trend of λ with $\dot{\gamma}$ can be found in Tabata and Vucetic (2004). Results of tests on two nonplastic soils (SW Arlita-1 and SP Nevada sands), two low plasticity clays (Meloland-5 and LBM-1 CL clays), one clay of low to high plasticity (La Cienega CL-CH clay), one silty soil of high plasticity (Kaolinite MH soil), and two clays of high plasticity (Obregon-4 and Augusta CH clays) are presented below in Figs. 8 through 11. For each soil three plots of λ versus logarithm of f are presented. First plot displays the data points only, second displays the data points along with their trend lines, while the third presents the trend lines normalized to λ at $f = 0.1$ Hz.

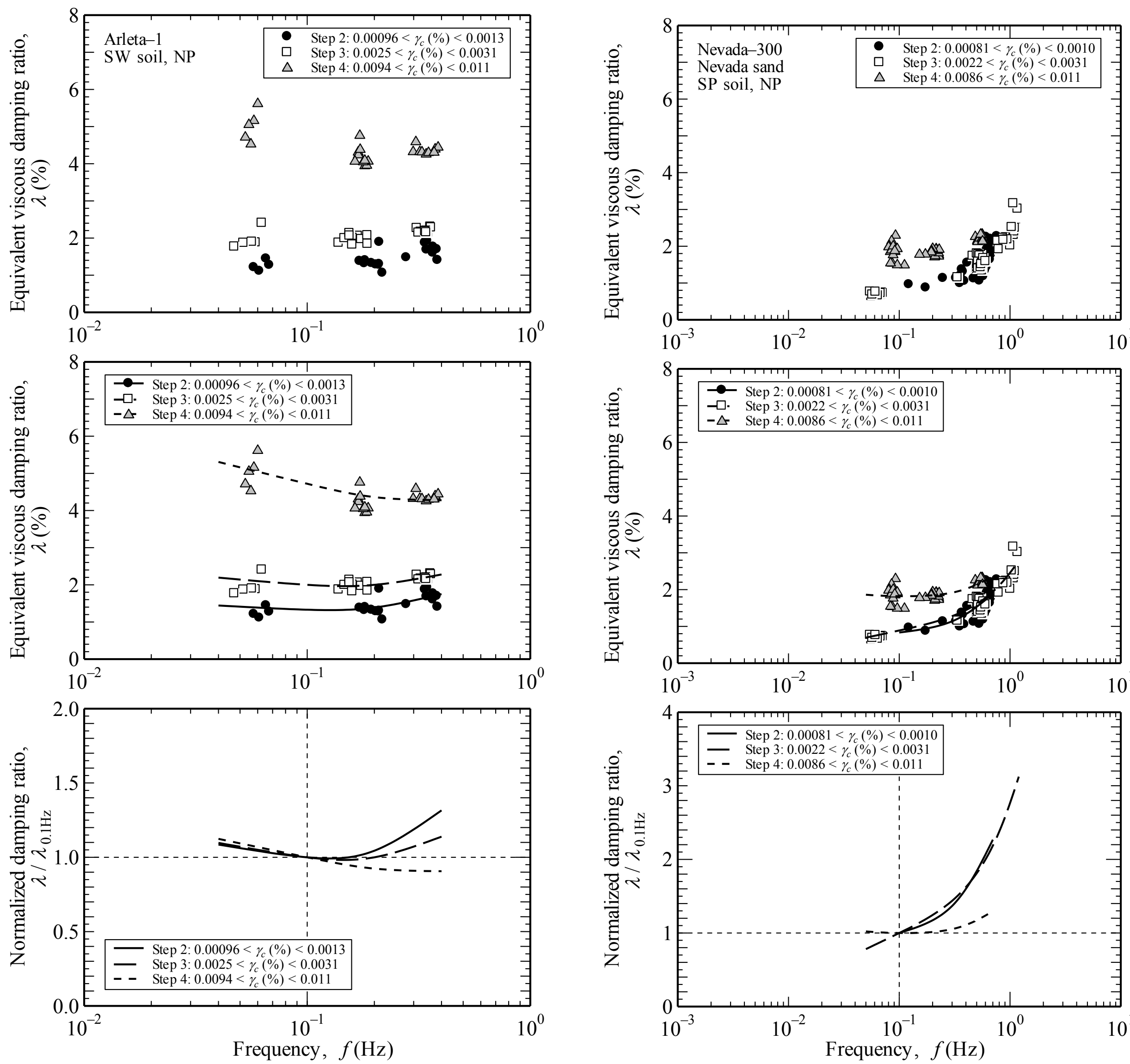


Figure 8. Results of tests on two sands, well graded Arlita-1 sand and poorly graded Nevada sand.

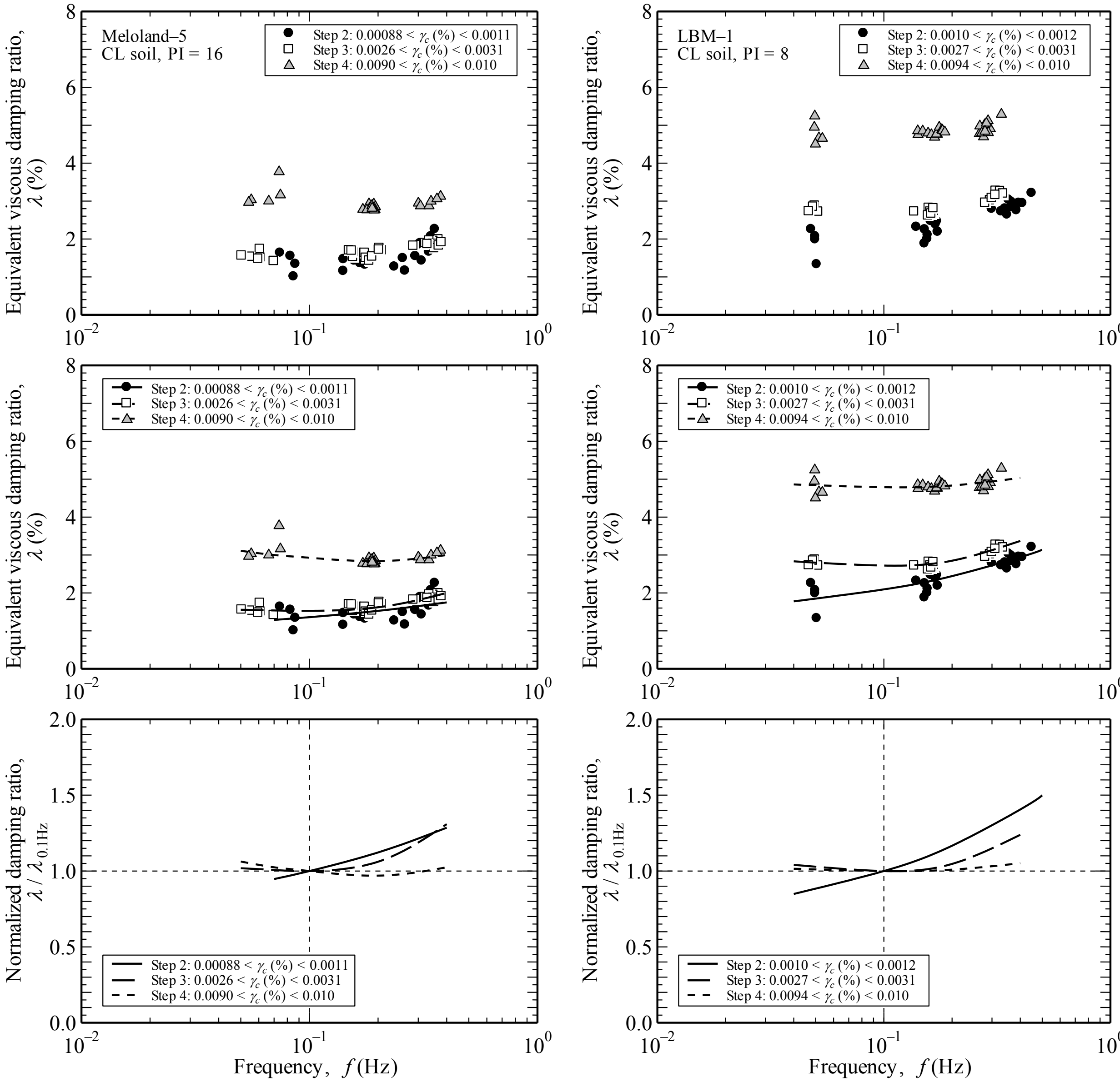


Figure 9. Results of tests on two low plasticity clays, Meloland-5 clay and LBM-1 clay.

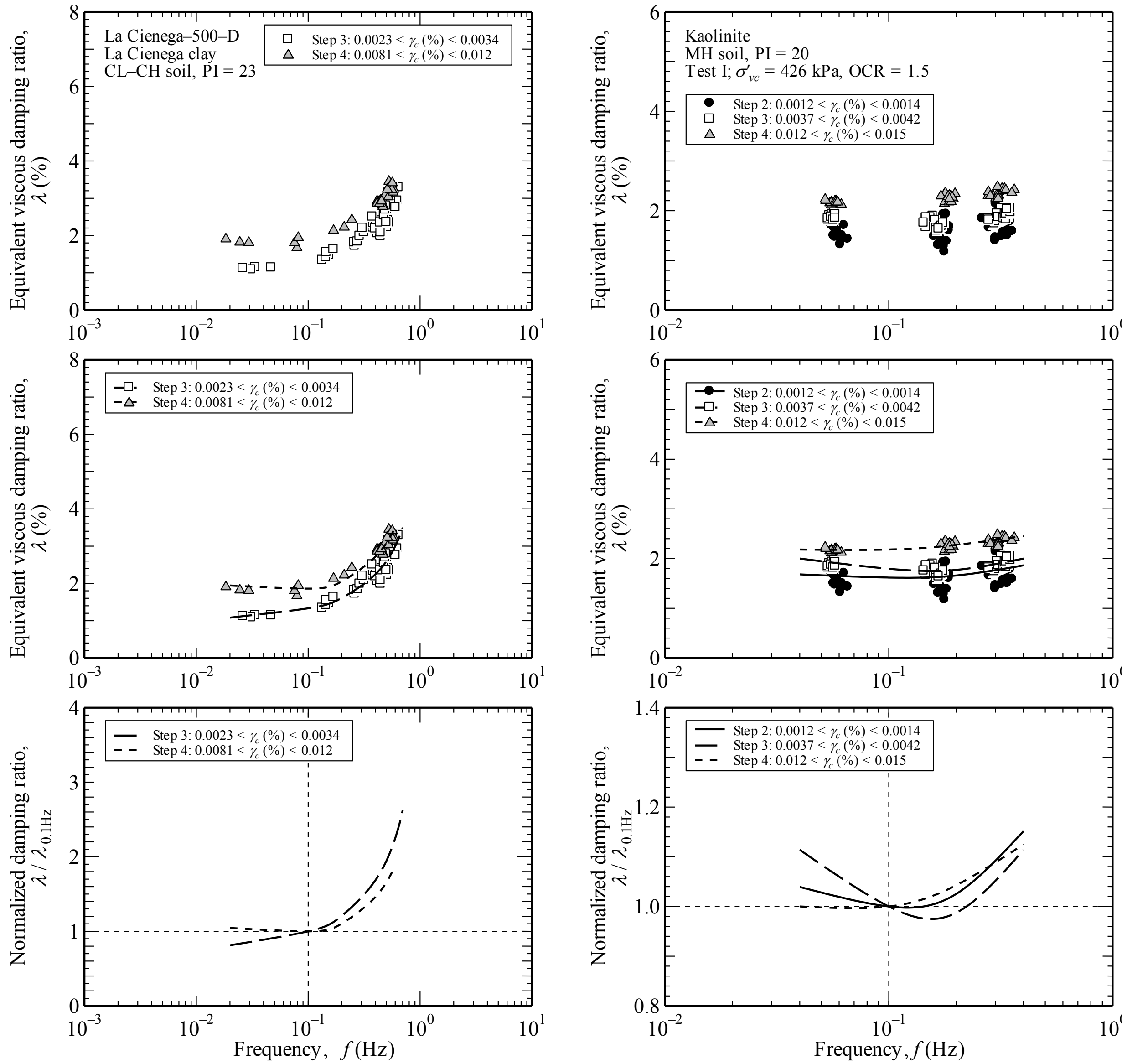


Figure 10. Results of tests on low to high plasticity La Cienega clay and silty Kaolinite soil of high plasticity.

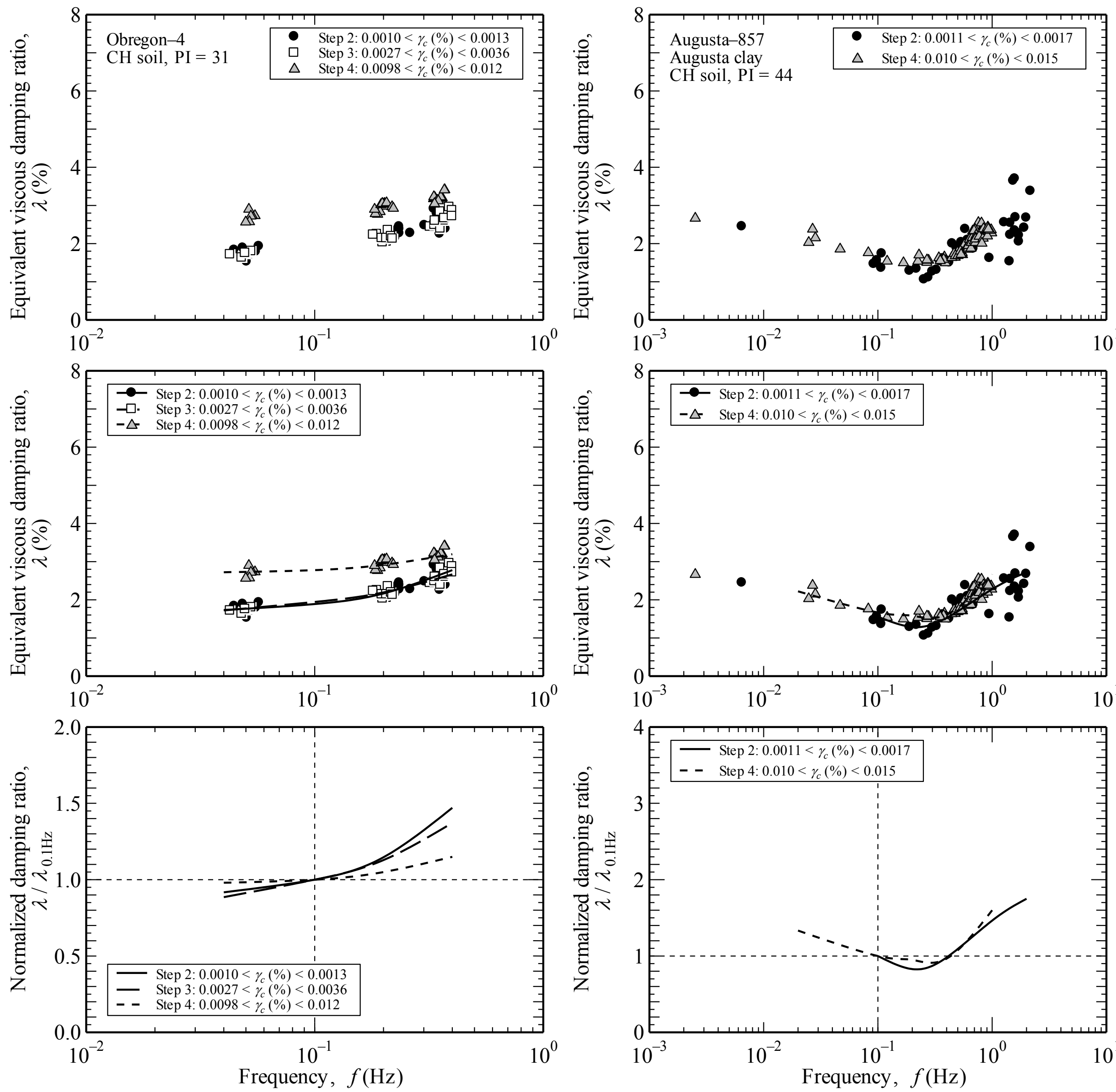


Figure 11. Results on two clays of high plasticity, Obregon-4 clay and Augusta clay.

The above results and the remaining results in the original report (Tabata and Vucetic, 2004) reveal no particular uniform behavioral pattern for similar soils. For example, as shown in Fig. 8, for SP Nevada sand λ is only increasing with *f*, while for Arlita-1 SW sand it first decreases and then beyond $f \approx 0.2$ Hz it increases with *f*. Very similarly, as shown in Fig. 11, for Obregon-4 high plasticity clay λ is only increasing with *f*, while for Augusta high plasticity clay it first decreases and then beyond $f \approx 0.2$ Hz it increases with *f*. As far as the results on low plasticity clays, low to high plasticity clay, and high plasticity silty soil presented in Figs. 9 and 10 are concerned, in some soils there is one trend and in some soils there is the other trend.

Conclusions

The experimental investigation on the effect of the frequency of cyclic loading, f, on the equivalent viscous damping ratio of soil, λ, summarized in this paper, as well as the results that can be found in the literature, reveal that for f larger than 0.2 Hz λ increases with f. In the range of f approximately below 0.2 Hz, however, λ in some soils decreases with f. In other words, in some soils λ consistently increases with f, while in some soils below $f \approx 0.2$ Hz λ decreases with f and then beyond $f \approx 0.2$ Hz it increases. More research is needed to explain these two trends and why there are two instead of just one trend. In earthquakes, however, frequencies are typically much larger than 0.2 Hz, so for the purpose of seismic site response analysis it is safe to say that the equivalent viscous damping ratio of soil, λ, increases with the frequency of cyclic loading, f.

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