

On the dynamic properties of leached ore and mine waste

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Abstract

Seismic design of heap leach pads and rock mine waste dumps located at highly active seismic zones, such as Peru and Chile, requires a proper determination of the dynamic properties of the materials involved in it, such as leached ore, mine waste, soil-geomembrane interfaces and foundation soils, in order to perform seismic stability or response analysis. Shear modulus and damping ratio are two of the most important soil parameters in seismic analysis, which are nonlinear and strain-dependent. Variation of normalized shear modulus and damping ratio with shear strain curves are commonly used to show these characteristics.

This paper presents a summary of laboratory testing executed at the University of Texas at Austin using resonant column, torsional shear and cyclic-triaxial tests, for obtaining normalized shear modulus and damping ratio curves. Those tests were performed on samples of crushed and blasted leached ore and rock mine waste taken from different heap leach pads and mine waste dumps currently in operation in Peru. These curves were compared with those of the existing literature, showing a good agreement primarily for the blasted samples. However, in the case of the crushed leached ore sample, results seem to indicate that the geologic origin and mineralogy of the ore and mainly the crushing process may influence the dynamic properties.

Based on the testing program results, the authors proposed normalized shear modulus and damping ratio curves for leached ore and mine waste materials obtained by a blasting process, over a range of standard confining pressures.

Introduction

Heap leach pads (HLP) are constructed by stacking precious or base metal ore materials, blasted or blasted/crushed, in loose and relatively dry fill lifts, commonly placed at the angle-of-repose. The ore is placed on top of a geomembrane liner and foundation and irrigated with sodium cyanide (for gold and

silver) or acidic (for copper, nickel and uranium) solutions that dissolve metals into the heap. On the other hand, rock mine waste dumps (MWD) are constructed by stacking blasted rock mine waste materials in a similar fashion as heap leach pads but usually without a liner system. Failure of these massive facilities would generate heavy environmental and economic damage and therefore, both static and seismic slope stability analyses are paramount for its operation and closure.

In highly active seismic regions, seismic design of these facilities, which usually involved seismic response analysis and calculation of seismic induced permanent displacements, is crucial during design stages. Hence, it is necessary a proper determination of the dynamic properties of the materials involved in these seismic evaluations, such as leached ore (LO) and mine waste (MW). Since MW and run-of-mine (ROM) ore are essentially similar materials, the determination of the dynamic properties of MW materials not only can be used for dynamic analysis of MWD, but also for understanding the dynamic behavior of ROM ore.

Currently, several empirical curves for dynamic properties exist in the literature for different types of soils, such as: Seed and Idriss (1970) for sands, Seed et al. (1986) and Rollins et al. (1998) for gravelly materials, Vucetic and Dobry (1991) for clays, Darendeli (2001) for fine-grained soils, Menq (2003), for sandy and gravelly soils, and Senetakis et al. (2013) for quartz and volcanic sands. However, since there is currently no database available for estimating dynamic properties of LO or MW, the curves from dynamic laboratory tests must be obtained and compared with curves from existing literature to guide seismic design of HLP or MWD.

Samples were taken from three different sites, from which five different material types were tested in the laboratory. Of the five samples collected, two came from HLP and three from MWD. Two of the sites were gold mining operations where both the HLP and MWD were evaluated. The third site was a polymetallic mining operation where only the MWD was evaluated. All of the sites were located in a seismically active area along the Andes Mountains in Peru. Photographs of a HLP and MWD from the same site are shown in Figure 1.

Materials

The LO and MW materials tested in this study were obtained from three different mining projects (labeled Project 1, 2 and 3) and were reconstituted in laboratory using the parallel-gradation technique. This method scaled the field particular-size distribution (PSD) curve to a parallel one considering the maximum particle size allowed by the testing device, which is usually between 10 to 15 times smaller the maximum particle size of standard LO and MW. This technique was first developed by Lowe (1964) and then extensively used by Marachi et al. (1969), Thiers and Donovan (1981) and Varadarajan et al. (2003) to perform drained monotonic triaxial tests on rockfill, crushed rock and alluvial soils, respectively. The PSD curve of the materials tested in the laboratory maintained similar coefficient of

uniformity (C_U), PSD shape and dry density as the materials in the field but limiting the fines content to a maximum of 10%. Photographs of the field materials and laboratory samples are shown in Figure 2.



Figure 1: (a) Heap leach pad and (b) mine waste dump in the Andes region

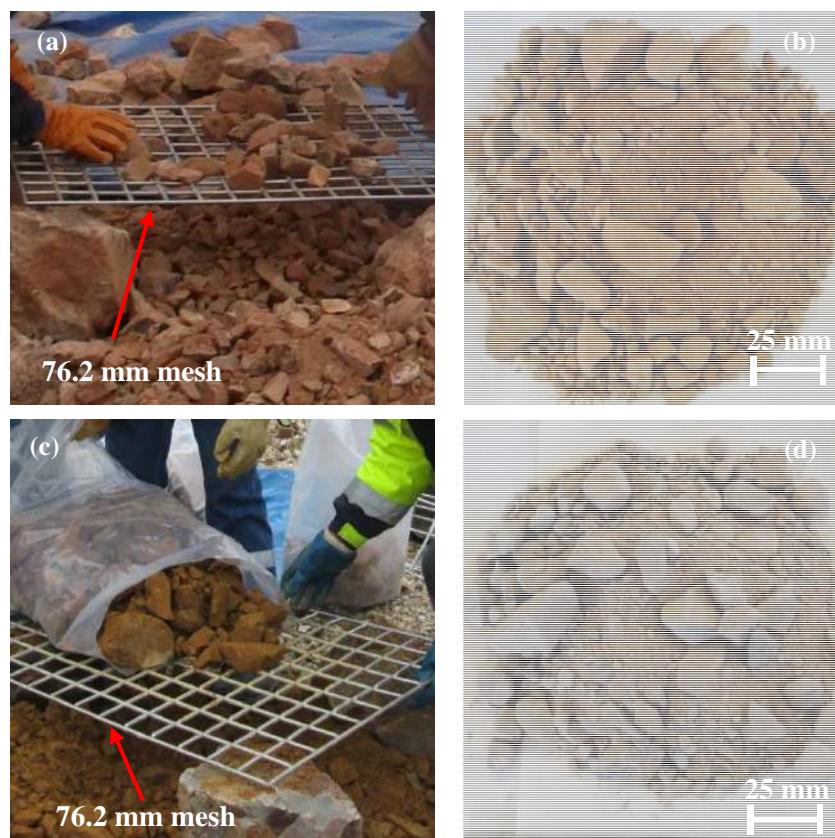


Figure 2: Photographs of leached ore tested in the field (a) and laboratory (b) and mine waste tested in the field (c) and laboratory (d)

The PSD curves of all the tested materials as placed in the field and reconstituted in the laboratory are shown in Figure 3. The field material matrix classified as well-graded gravel, poorly graded clayey gravels and well-graded silty gravels (GW, GP-GC, GW-GM) as the Unified Soil Classification System (USCS). The materials reconstituted for laboratory testing classify as well-graded sands, well-graded silty sands and poorly-graded silty sands (SW, SW-SM, SP-SM). In Project 1, two samples of LO (LO-02 and LO-03) were tested for verification purposes by using essentially the same material and reconstitution in the laboratory. A similar approach was taken for Project 2 for both LO (LO-09 and LO-11) and MW (MW-06 and MW-07). In all the other cases, only one sample set was used in the laboratory tests. The basic index properties of the specimens tested are shown in Table 1.

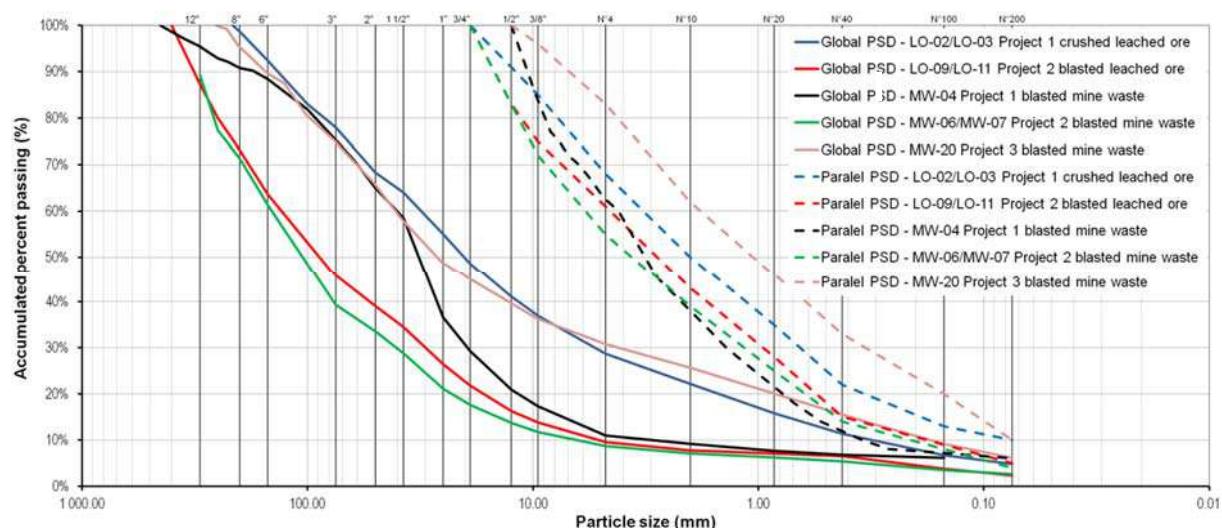


Figure 3: Gradation curves for samples used in the laboratory testing program

Table 1: Index properties of field material and specimens subjected to RCTS and CTX testing

Sample	Material	Location	Gs ¹	Cu ²	Cc ³	D ₅₀ ⁴	Fines	WC ⁵	γ _f ⁶	ε ⁷	USCS ⁸
			-	-	-	(mm)	(%)	(%)	(kN/m ³)	-	-
LO-02/ LO-03	Project 1 crushed leached ore	Field	2.25	90	2.77	20.3	4.9	2.60 - 2.80	15.3 - 16.5	0.433 - 0.480	GW
		Laboratory	2.25	36	0.79	3.5	5.0	0.70 - 3.36	15.4 - 16.5	0.406 - 0.480	SW
LO-09/ LO-11	Project 2 blasted leached ore	Field	2.61	28	1.46	90.0	2.5	2.17 - 2.23	20.0 - 21.4	0.150 - 0.214	GW
		Laboratory	2.61	28	0.80	3.1	5.0	2.94 - 2.96	20.0 - 20.3	0.299 - 0.318	SW
MW-04	Project 1 blasted mine waste	Field	2.50	12	3.00	32.6	5.8	1.00 - 12.70	-	-	GP-GC
		Laboratory	2.50	12	1.33	3.2	6.0	8.80	15.5	0.712	SW-SM
MW-06/ MW-07	Project 2 blasted mine waste	Field	2.67	21	0.18	111	2.0	0.40 - 4.50	20.8 - 23.8	0.111 - 0.265	GW
		Laboratory	2.67	26	0.92	3.0	3.0	4.24 - 4.76	20.5 - 21.7	0.265 - 0.328	SW
MW-20	Project 3 blasted mine waste	Field	3.23	220	2.5	25.4	6.0	1.90 - 2.80	20.2 - 27.9	0.166 - 0.607	GW-GM
		Laboratory	3.23	24	1.2	1.0	10.0	2.39 - 3.33	23.4 - 24.5	0.320 - 0.390	SP-SM

Notes: 1) Specific gravity, 2) Coefficient of uniformity, 3) Coefficient of curvature, 4) Average diameter by mass, 5) Water content, 6) Total unit weight, 7) Void ratio at 1 atmosphere of confining pressure and 8) Unified Soil Classification System (USCS) Symbol for Soil Type.

Laboratory testing

The normalized shear modulus and damping ratio curves of these materials were evaluated at the University of Texas at Austin using a combined resonant column (RC) and torsional shear (TS) device and cyclic-triaxial (CTX) device. The laboratory samples were reconstituted using the under-compaction method (Ladd 1978) to match in-situ density and water content. The RCTS tests were performed in a sequential series on the same specimen with isotropic confining pressures (σ'_0) ranging from 69 kPa to 1213 kPa. For each specimen, nonlinear RC tests were conducted at two or three σ'_0 over a shearing strain (γ) range from about 10^{-6} % to slightly more than 0.1%. CTX tests were conducted on these specimens at a single σ'_0 for each specimen, over a range from 303 kPa to 700 kPa, and over an estimated shearing strain range from about 0.01% to 1.4%.

The RCTS apparatus used in these tests is a computer-controlled RCTS device. This equipment has been developed at The University of Texas at Austin over the past several decades and a large number of RCTS tests (>900) have been performed on cylindrical soil and rock specimens. This equipment has a fixed-free configuration, with the bottom of the specimen fixed and torsional excitation applied at the top. The basic operational principle is to vibrate the cylindrical specimen in first-mode torsional motion. Sinusoidal torsional excitation is applied to the top of the specimen and swept over a range in frequencies, and the variation of the amplitude with frequency is obtained at the top of the specimen. Once first-mode resonance is established, measurements of the resonant frequency and amplitude of vibration are made. These measurements are then combined with equipment characteristics and specimen size to calculate shear wave velocities (V_s) and shear modulus (G_{max}) based on elastic wave propagation theory. Material damping is determined either from the width of the frequency response curve or from the free-vibration decay curve. The RCTS tests are performed at 5 confining pressures in order of increasing pressure. At the middle and highest pressure levels, nonlinear tests are conducted over a shearing strain range from about 10^{-6} % to slightly more than 10^{-1} %. In Figure 4, a schematic of the RCTS device is shown.

The CTX tests were performed based on the procedures presented in ASTM D3999 for measuring Young's modulus and estimating the shear modulus; damping ratio is also calculated. The testing procedures were modified to fit the specific needs of these projects. In particular, the tests were performed on drained instead of undrained saturated specimens. Additionally, local deformations were measured within the middle third of the specimens (along the height) using miniature LVDTs mounted to the specimen. Last, the load cell was placed inside the cell to eliminate friction between the piston and the cell that would otherwise be measured by the load cell. This was possible because the confining pressure was applied entirely with air and filling the cell with water to aid in saturating the specimen was not necessary. Both, tests with load control (at the lower strain levels) called "stress" and

displacement control (at the higher strain levels) called “strain”, were performed as part of the cyclic triaxial testing.

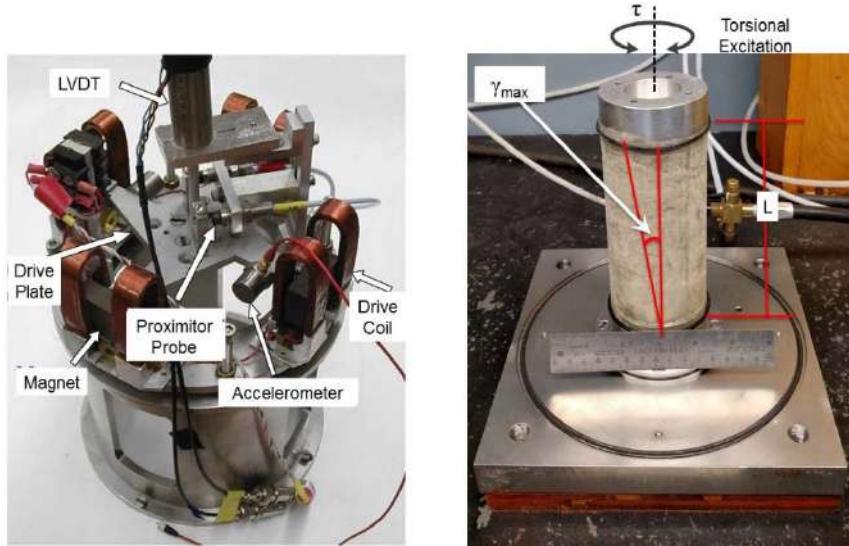


Figure 4: Resonant column torsional shear test device of The University of Texas at Austin

Nonlinear shear modulus and damping ratio in RCTS and CTX tests

The dynamic behavior at strain levels where the specimen tested exhibit linear, nonlinear-elastic, and highly nonlinear (plastic) behaviors, is shown by combining results from RC and CTX tests. This behavior is presented in terms of normalized shear modulus (G) by G_{max} and damping ratio versus the log of γ (G/G_{max} -logy and D-logy) plots shown in Figures 5, 6, 7, 8 and 9 for all the materials tested, which are separated by project and type of material. G_{max} values obtained from the resonant column tests were used to normalize the cyclic triaxial shear modulus values as well.

Curves generated from the equations developed by Menq (2003) for gravelly soils were used to compare the results of the nonlinear dynamic behavior of the materials evaluated by the RC and CTX tests. The equations developed by Menq (2003) were chosen due to their ability to predict G/G_{max} -logy and D-logy relationships using Cu values and different confining pressures. A brief discussion regarding the G/G_{max} -logy and D-logy relationships is presented below.

Crushed LO from Project 1 (Figure 5): The dynamic properties curves are not in agreement with those predicted by Menq (2003), showing a “stiffer” behavior for the G/G_{max} plot and much lower values when observing the damping ratio.

Blasted LO from Project 2 (Figure 6): Normalized shear modulus curves for a confining pressure of 200 kPa are in excellent agreement with those predicted by Menq (2003) for strains up to 0.01%. However, for the confining pressures of 700 kPa and 800 kPa, the curve predicted by Menq (2003) do not fit very well, particularly for high shear strains. On the other hand, damping ratio curves for both confining pressures are in general good agreement with those predicted by Menq (2003). Nevertheless, for high strains, damping ratio predicted by CTX is largely lower than the Menq's (2003) curves.

MW from Project 1 (Figure 7): In general, the normalized shear modulus curves for the range of confining pressures tested, fit pretty well with those predicted by Menq (2003). Regarding damping ratio curves, curves obtained in the RC testing are not in agreement with the Menq's (2003) curves, showing higher values for small strains in agreement with the findings of Yee et al. (2003). CTX tests were not performed for this material.

MW from Project 2 (Figure 8): Curves obtained from the testing and the predicted by Menq (2003) are in good agreement, mainly for small shear strains, for both normalized shear modulus and damping ratio. In addition, CTX results predict reasonably well the damping ratio but not the normalized shear modulus for strains higher than 0.01%.

MW from Project 3 (Figure 9): In general, curves obtained in laboratory and predicted by Menq (2003) are in good agreement, for both normalized shear modulus and damping ratio, except for the lowest confining pressure (85 kPa). CTX tests were not performed for this material.

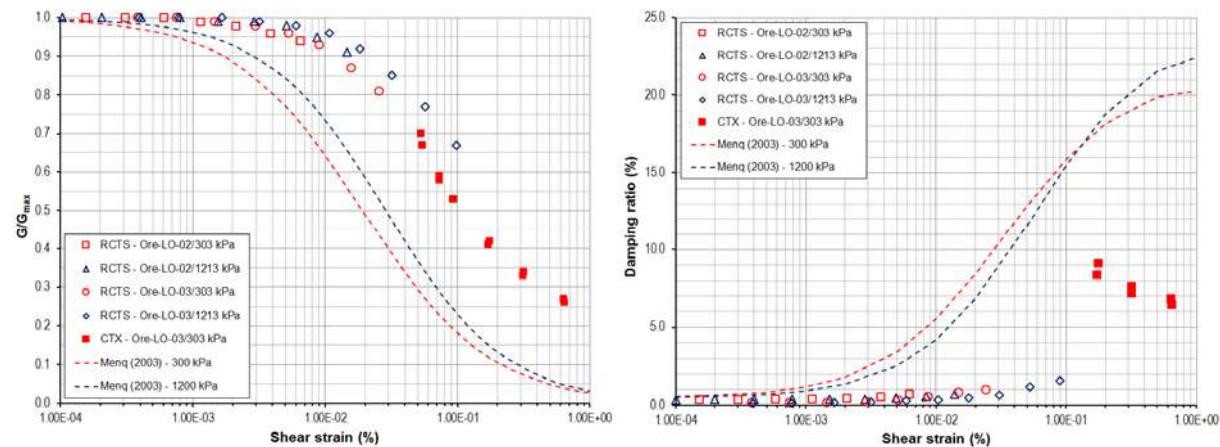


Figure 5: Crushed leached ore from Project 1. Normalized shear modulus and damping ratio versus shear strain and predictions of the dynamic property curves from Menq (2003)

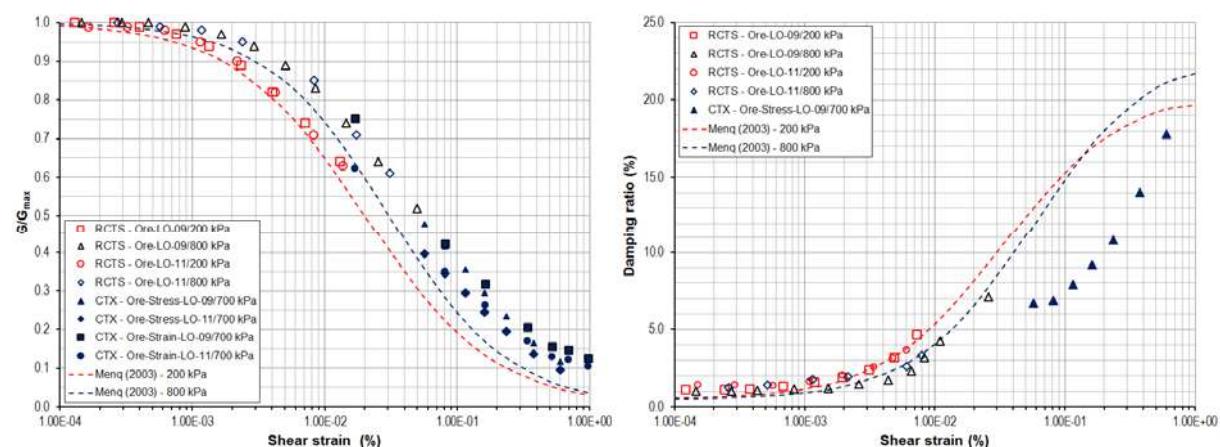


Figure 6: Blasted leached ore from Project 2. Normalized shear modulus and damping ratio versus shear strain and predictions of the dynamic property curves from Menq (2003)

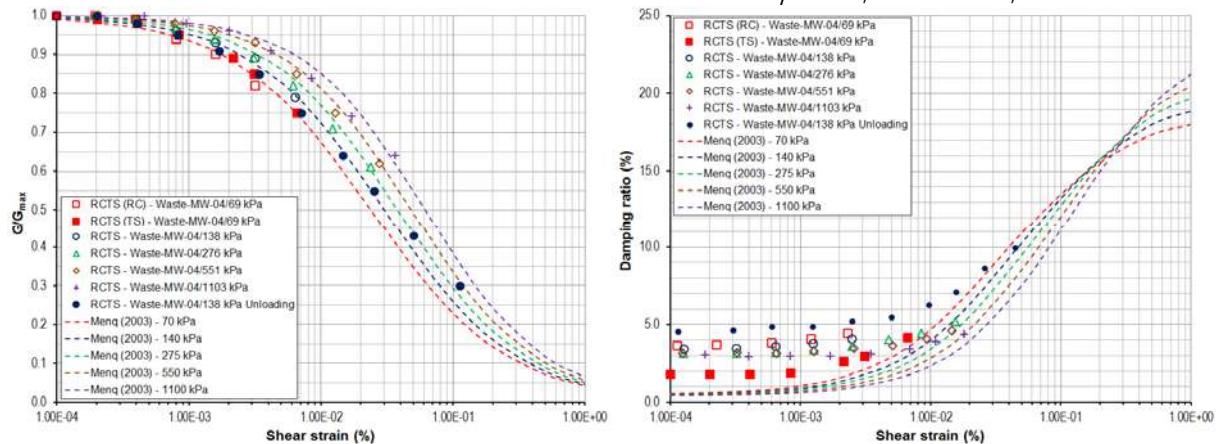


Figure 7: Mine waste from Project 1. Normalized shear modulus and damping ratio versus shear strain and predictions of the dynamic property curves from Menq (2003)

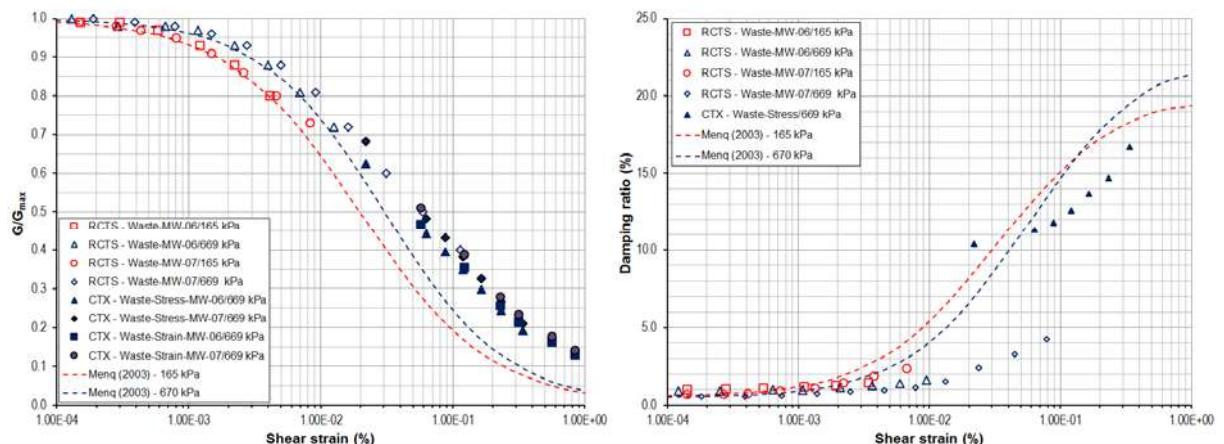


Figure 8: Mine waste from Project 2. Normalized shear modulus and damping ratio versus shear strain and predictions of the dynamic property curves from Menq (2003)

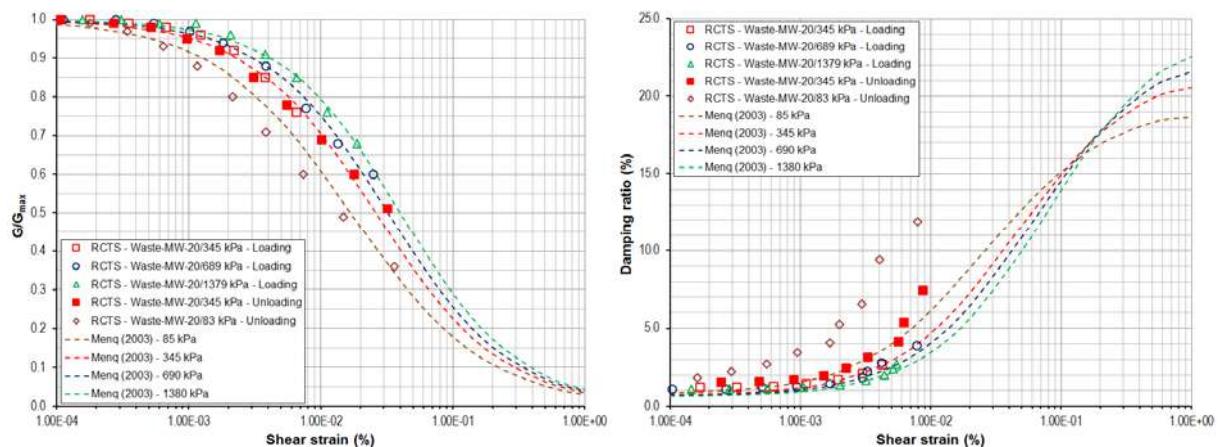


Figure 9: Mine waste from Project 3. Normalized shear modulus and damping ratio versus shear strain and predictions of the dynamic property curves from Menq (2003)

Crushed samples

The only crushed material tested in the RC and CTX laboratory programs were LO samples LO-02 and LO-03 from Project 1. The G/G_{max} -logy and D-logy relationships were quite different from the ones predicted by Menq (2003). An analysis of the mineralogy of the LO material indicates a volcanic origin. Consequently, the Senetakis et al. (2013) formulation for dynamic properties of volcanic crushed sands was chosen for comparison purposes. As we can observe in Figure 10, the curves of normalized shear modulus obtained in the laboratory and the predicted are in good agreement, mainly for the lower confining pressure; for damping ratio the laboratory curves and the predicted are in agreement just for shear strain lower than $3 \times 10^{-3}\%$, but not for higher stains.

It is important to note that MW sample MW-04 from the same Project 1 than the crushed ore material, is also of the same volcanic origin, however, dynamic properties do not seem to be influenced by this aspect. Therefore, a preliminary conclusion seems to indicate that the effect of the crushing process, which influences the angularity and texture of coarse particles, would be affecting the dynamic properties obtained in the dynamic laboratory testing. As we only tested one crushed LO sample, it is not possible to conclude regarding the effects of the geological origin or the crushing process. More testing is needed for future research.

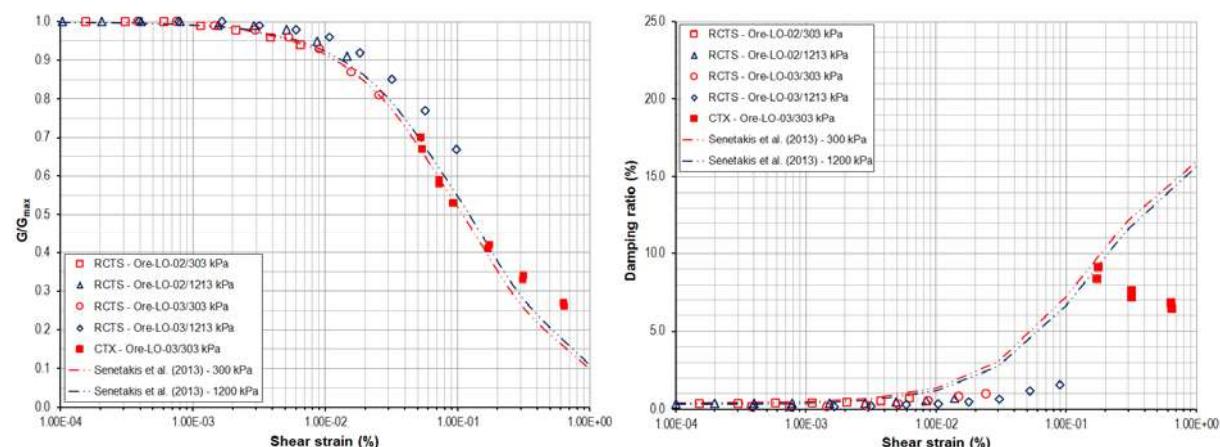


Figure 10: Crushed leached ore from Project 1. Normalized shear modulus and damping ratio versus shear strain and predictions of the dynamic property curves from Senetakis et al. (2013)

Proposed normalized shear modulus and damping ratio

Figures 11 and 12 show the summary of all the testing performed in LO and MW in this study, respectively. As shown in Figure 11, samples LO-02 and LO-03 of crushed LO show a different trend when compared with the other samples. However, blasted LO samples LO-09 and LO-11 behave similar to the MW materials for both normalized shear modulus and damping ratio.

As shown in Table 1, MW samples Cu values ranged from 12 to 28. Although variability of Cu when the material is mined by blasting in an open pit and their influence on the dynamic properties are expected, the testing program results shown in Figure 12 indicate very similar trends for both normalized

shear modulus and damping ratio. No such conclusion can be obtained for the blasted or ROM LO samples since only one set of samples from the same project was evaluated.

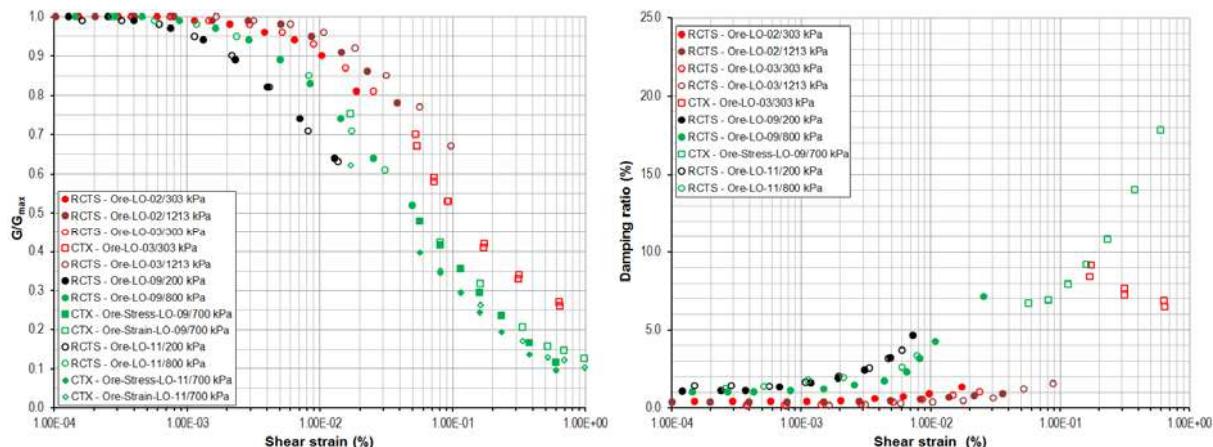


Figure 11: Normalized shear modulus and damping ratio versus shear strain for leached ore

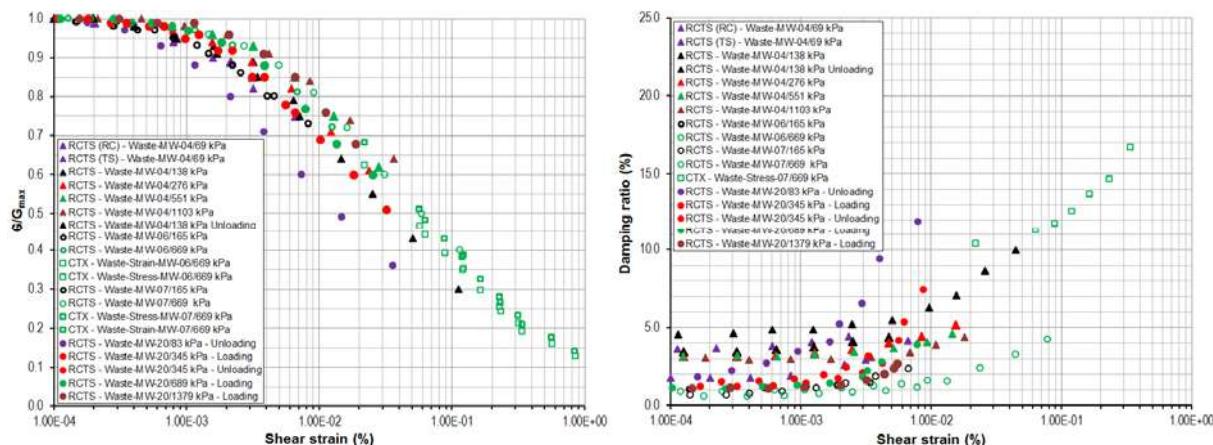


Figure 12: Normalized shear modulus and damping ratio versus shear strain for mine waste

Based on the discussion above, the authors propose normalized shear modulus and damping ratio curves for MW materials based on the results of the RC and CTX testing program. The proposed curves are shown in Figure 13 over a range of confining pressures ranging from 100 to 1200 kPa. The proposed curves for normalized shear modulus are similar to those predicted by Menq (2003) up to 0.01%.

It is important to mention that the damping ratio proposed for small-strain is based both on the testing results, as well as in the findings of Yee et al. (2013). By performing validations of seismic response analysis, this author suggested values of small-strain damping ratio from 2 to 5%, rather than the ones obtained in the resonant column tests presented in this study.

Since ROM ore and MW are obtained by blasting in the open pit, they can be considered similar materials. Consequently, the testing program results of blasted LO were compared with the dynamic property curves proposed in this study for MW, as shown in Figure 14. It can be observed that the proposed curves nicely fit the test results of the blasted LO of this study (samples LO-09 and LO-11 from Project 2), but are different from the crushed samples testing results (samples LO-02 and LO-03).

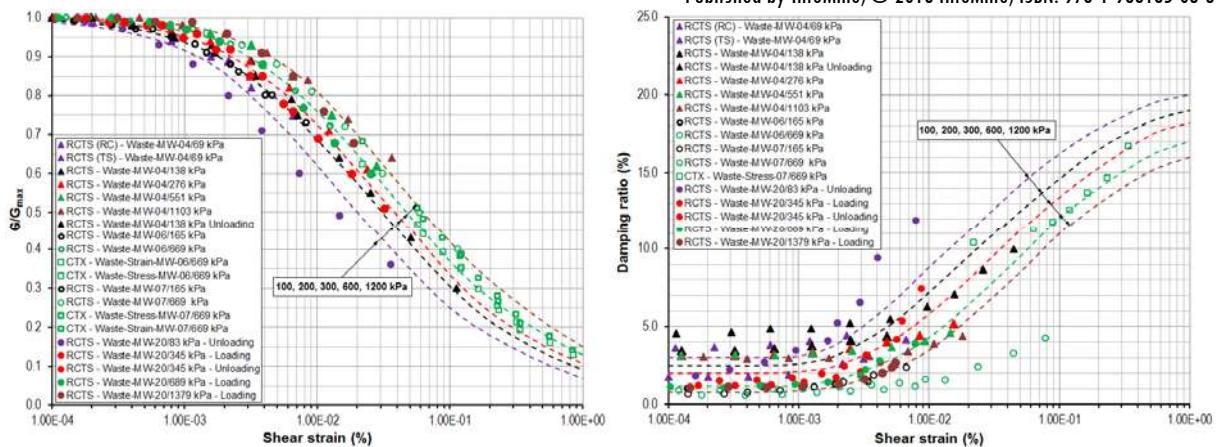


Figure 13: Proposed curves for normalized shear modulus and damping ratio for mine waste materials tested in this study

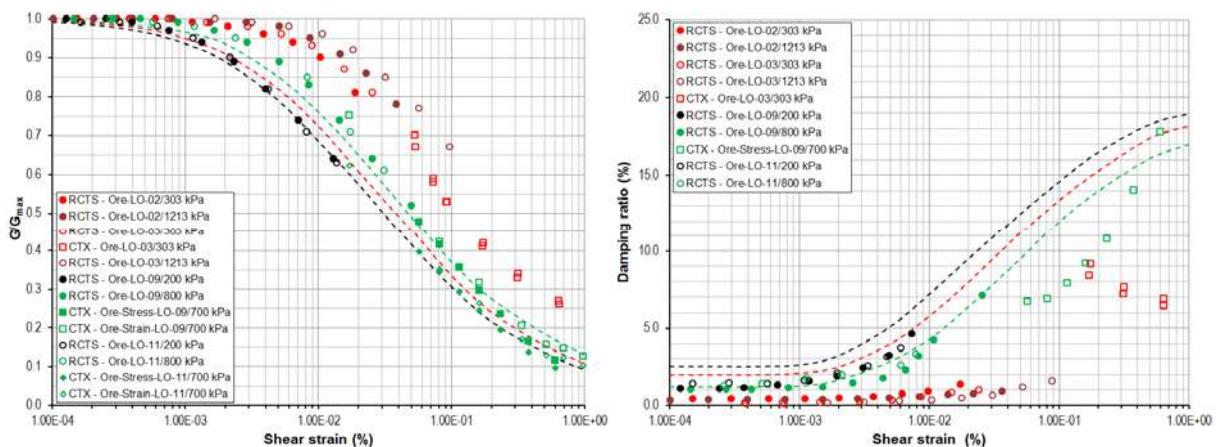


Figure 14: Comparison of the proposed curves for normalized shear modulus and damping ratio for mine waste materials with testing results of leached ore materials

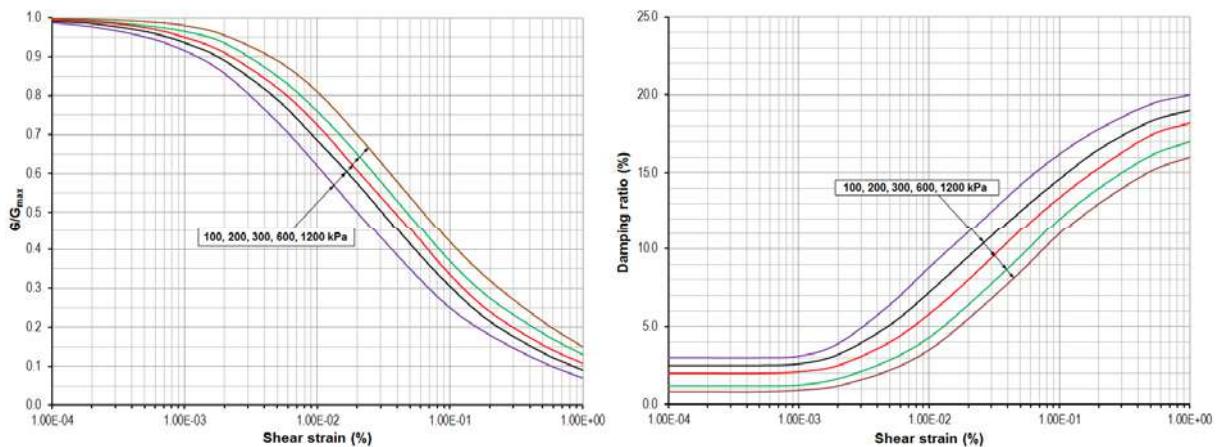


Figure 15: Proposed curves for normalized shear modulus and damping ratio for blasted leached ore and mine waste materials

The proposed normalized shear modulus and damping ratio curves for blasted (ROM) LO and MW materials are presented in Figure 15. Those curves may be taken as a preliminary and as a reference for obtaining dynamic property curves for seismic response and dynamic analysis of HLP and MWD. This

should be combined with an adequate calculation of G_{max} based on geophysical surveys or accepted empirical relationships. However, a proper determination of these dynamic properties based on dynamic laboratory testing always is needed in any case.

Conclusions

Currently, several empirical curves for dynamic properties exist in the literature for different types of soils. However, for leached ore or mine waste, typical materials of mining operation, there is no testing previously performed and therefore no database available. Hence, when dealing with the seismic design of structures such as heap leach pads and mine waste dumps, cyclic testing is required to verify any existing dynamic curve to be used in it.

In order to assess the dynamic properties of these materials, samples from two heap leach pads and three mine waste dumps from three mining operations were reconstituted in laboratory using the parallel-gradation technique, tested during the design stages of each project and summarized for this study. The linear and nonlinear shear modulus and damping ratio of these materials were evaluated at the University of Texas at Austin using tests that involved a combined resonant column and torsional shear device and cyclic triaxial device.

The laboratory testing results for obtaining the variation of normalized shear modulus and damping ratio with shear strain of blasted (ROM) leached ore and mine waste materials show a reasonable agreement with the curves generated from the equations developed by Menq (2003) for sandy gravelly soils. A close fit is observed for shear strains up to 0.01%, while some deviation is observed for damping ratio in some of the materials tested. For higher shear strains, Menq's (2003) curves represent more degradation than that of the laboratory results.

As for the case of the crushed leached ore of volcanic origin, the laboratory results were quite far from the curves predicted by Menq (2003) but rather close to the ones predicted by Senetakis et al. (2013) for volcanic crushed sands; however, the laboratory results of the mine waste material from the same Project 1, and also of volcanic origin, indicate that dynamic properties do not seem to be influenced by this aspect. Therefore, this appears to indicate that crushed nature of the ore may influence the dynamic properties.

Normalized shear modulus and damping ratio curves for blasted (ROM) leached ore and mine waste materials are proposed in this study over a range of confining pressures, which are similar to those predicted by Menq (2003) for shear strains up to 0.01%. Since current state-of-art of seismic design of earth mining structures, such as heap leach pads and mine waste dumps, in highly active seismic zones suggests, the use of seismic response analysis and calculation seismic-induced permanent displacements, these proposed curves become a useful tool when performing seismic response as well as fully-coupled dynamic analysis. Proper determination of the maximum shear modulus using geophysical surveys or accepted empirical correlations is also needed.

More dynamic testing is needed for confirming or adjusting the dynamic properties curves proposed in this study. Those tests should use the parallel-gradation technique to reconstitute samples in laboratory. Additional effort should be made for testing crushed leached ore to verify the aspects that may influence its dynamics properties, such as the geologic origin and the crushing process.

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