

Towards a fundamental understanding of soil aggregate breakdown under applied mechanical energies.

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1. INTRODUCTION

Soil aggregate instability and dispersion is the single most important process leading to problems associated with soil erosion, structural decline and land degradation. In the ordered systems described by aggregate hierarchy theory, breakdown occurs when sufficient mechanical stress has been applied to overcome the attractive forces within the aggregates. Smaller structural units also necessarily possess greater bonding energies than their larger counterparts. Where the stresses applied to the aggregate are less than the maximum stress required to fracture all of the structural hierarchical levels, incomplete disruption occurs. Traditional empirical techniques (e.g. end-over end-shaking, wet sieving) used in the measurement of clay dispersion and soil aggregate stability typically use only a single stability measurement taken after the application of an arbitrary energy for an arbitrary period of time. Hence, the results obtained and conclusions drawn are highly dependent on the nature of the mechanical energy applied. The stresses applied in these systems may also be different to those produced under field conditions (e.g. raindrop impact, cultivation) resulting in hierarchical breakdown inconsistent with field observations. This paper reports on the use of end-over-end shaking, ultrasonic and low frequency pressure waves to assess aggregate breakdown within dilute soil-water suspensions. It confirms the importance of quantifying the power, frequency and total mechanical energy applied in aggregation studies and reports on a method to measure the waveforms applied to soils under rainfall simulation and the potential to simulate these stresses in soil-water suspensions.

2. MATERIALS AND METHODS

Soils

The soils used throughout this work were a Red Ferrosol collected in Toowoomba and self-mulching Black and Grey Vertosols collected from Gatton (Lockyer Valley) and Pittsworth (Darling Downs), respectively. In each case, composite surface samples (0-10 cm) were collected, air dried, crushed to pass through a 2 mm mesh and homogeneously mixed before storage in an air-tight container until use. Except where indicated, the soil was used in an air-dried state and the mass reported is the oven-dried equivalent of the air dry soil. Particle size analyses (Table 1) were conducted using the method of Gee and Bauder (1986).

Table 1. Particle size analyses for the experimental soils

Soil	<2 μm	<2-20 μm	>20 μm
PRA1	0.68	0.08	0.24
Lawes	0.51	0.25	0.24
Ferrosol	0.44	0.27	0.29

Effect of power and total energy on dispersion

To confirm the effect of power and total energy on aggregate breakdown, the dispersion of PRA1 and Lawes soils was measured using both an end-over-end shaking (So *et al*, 1997) and ultrasonic technique (Raine and So, 1994). The end-over-end shaking technique consisted of

immersing 50 g of soil in 1 L of deionised water at 20°C within a 1.425 L cylinder (70 mm internal diameter). The cylinder was then shaken at 20 rpm for periods up to 120 minutes. The ultrasonic technique consisted of immersing 10 g of soil in 200 cm³ of deionised water within a 250 cm³ glass beaker. Ultrasonic energy (20 kHz) was then applied to the suspension at either 8.9 W or 25.0 W for periods up to 12 kJ/g using a Sonifier 250 (Branson, CT). After the application of the energy using either technique, the suspensions were mixed homogeneously, allowed to settle for the appropriate period, and subsamples extracted with a pipette to determine the quantity of <2 µm and <20 µm equivalent spherical diameter material (Jelinek, 1970). The pipette samples were oven-dried at 105°C for 48 hours and the dispersed material was determined by weighing. Negative exponential functions in the form outlined in Raine and So (1994) were fitted to the ultrasonic dispersion results.

Effect of frequency and power on dispersion

Two experiments were conducted using low frequency sinusoidal waveforms to investigate the effect of frequency and power on aggregate disruption. In each experiment, low frequency sinusoidal waves were applied to soil-water suspensions using an inverted V203 shaker table and PA25E amplifier (Ling Dynamic Systems, UK) controlled from a laptop computer interfaced with a DAQCard-1200 (National Instruments, USA). The shaker table was attached to a 12 mm diameter stainless steel probe fitted with a replaceable titanium alloy tip (surface area = 127 mm²). The probe was inserted into the soil-water suspensions so that the mode of operation was similar for both the low frequency and ultrasonic energy application.

In each experiment, the suspensions were prepared by immersing 3 g soil in 15 cm³ of deionised water within a 25 cm³ beaker. A 10 mm x 3 mm magnetic stirrer bar rotating at approximately 120 rpm was used to ensure uniform mixing within the suspension. The first experiment used a randomised complete block design with the wave applied at amplifier power setting 2, 4 or 6, frequencies of 100, 200 or 400 hz, and for periods of up to 900 sec. Two replications of each treatment were conducted. The second experiment used a completely randomised design with 3 replications where the pressure wave was applied for 600 s at either 800, 1600 or 3200 hz using amplifier setting 6, and for 600 s at 800 hz using amplifier setting 8. In each case, the release of <2 µm and <20 µm material was measured using the pipette withdrawal technique described above.

Comparison with rainfall simulation

The mechanical energy and aggregate disruption associated with raindrop impact was assessed using a rainfall simulator similar to that used by Loch (1989). The Ferrosol was packed into 0.25 m² trays, capillary wet and exposed to 100 mm/hour rainfall for periods up to 60 minutes. Surface samples were taken after the appropriate period of rainfall and the amount of <2 and <20 µm material measured using the sedimentation technique described above. The impact waveform produced by the rainfall was recorded using a PCB Piezotronics accelerometer mounted magnetically beneath a metal plate (1.5 mm thick and diameter = 100 mm) at the same distance from the sprays as the soil surface. The waveform sequence was subsequently applied to a suspension consisting of 10 g capillary wet soil and 10 cm³ of deionised water using the shaker table at power setting 2 or 6. The same number of waveforms were applied to the suspension as had been applied to the soil using the rainfall simulator and the aggregate breakdown produced by the application of these waveforms to the suspensions were compared to that measured after three periods of rainfall simulation using paired T-tests.

3. RESULTS AND DISCUSSION

Ultrasonic energy applications to the PRA1 soil were found to produce a significant ($P < 0.05$) increase in < 2 and $< 20 \mu\text{m}$ dispersion with total energy applied (Fig 1a). Similarly, increasing the period of end-over-end shaking significantly increased the amount of < 2 and $< 20 \mu\text{m}$ material released (Fig 1b). However, where the equivalent ultrasonic energy required to produce the same amount of < 2 and $< 20 \mu\text{m}$ material as the end-over-end shaking treatment was plotted against the corresponding period of shaking, a non-linear relationship was found (Fig 2). This suggests that the mechanical energy applied by each technique has a different ability to disperse this sized material. Furthermore, the relationships plateau with increasing periods of shaking. This indicates that as the period of shaking increases, the mechanical energy applied by shaking becomes progressively less effective at dispersion. The amount of < 2 and $< 20 \mu\text{m}$ dispersion produced by the end-over-end shaking treatment is also significantly less than the total amount of < 2 and $< 20 \mu\text{m}$ sized material present in the soil (Table 1). Hence, at least some of the aggregates composed of this material are able to withstand the stresses imposed by the shaking treatment.

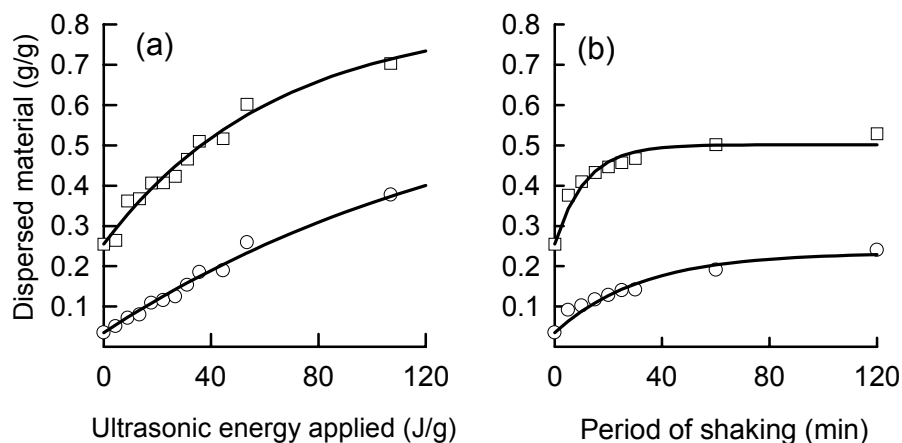


Figure 1. Dispersion of $< 2 \mu\text{m}$ (O) and $< 20 \mu\text{m}$ (□) material for PRA1 with the application of (a) ultrasonic energy and (b) end-over-end shaking. (after Raine and So, 1997)

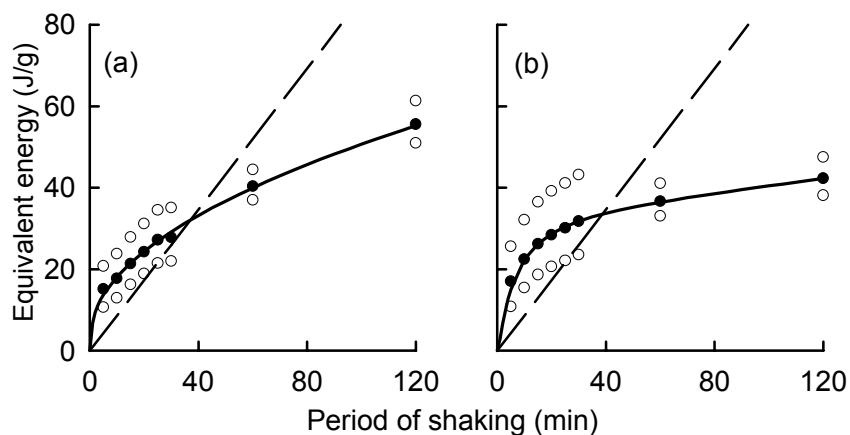


Figure 2. The equivalent ultrasonic (—, ● x_{best} , o 95% CI) and kinetic (- -) energy applied by end-over-end shaking to PRA1 soil for (a) $< 2 \mu\text{m}$ and (b) $< 20 \mu\text{m}$ sized material. (after Raine and So, 1997)

The dispersion produced by the range of total energies applied to the Lawes soil using both the ultrasonic and end-over-end shaking treatments is shown in Fig 3. Complete dispersion of the <2 and <20 μm material was ultimately achieved in each of the ultrasonic treatments. However, a reduction in the ultrasonic power application from 25 W to 8.9 W produced a significant decrease in the rate of aggregate breakdown. The lower power applied by the end-over-end shaking treatment was unable to completely disperse the <2 μm material. This undispersed <2 μm material must have been aggregated into micro-aggregates 2-20 μm in size, as the end-over-end shaking treatment produced a similar amount of <20 μm material as the 8.9 W ultrasonic treatment for all total energies and ultimately dispersed all aggregates >20 μm (Fig 3). Hence, these results indicate that for this soil, 0.33 g/g of aggregated <2 μm material was dispersed by the end-over-end shaking. However, an additional 0.18 g/g of aggregated <2 μm material was able to withstand the stresses applied by the end-over-end shaking treatment but were unable to withstand the stresses applied by the 8.9 W ultrasonic treatment. The ability of both the ultrasonic and end-over-end shaking treatments to disperse the <20 μm material completely, but not the <2 μm material, is consistent with the hierarchical model of aggregate breakdown and bond strength (Dexter, 1988, Oades and Waters, 1991).

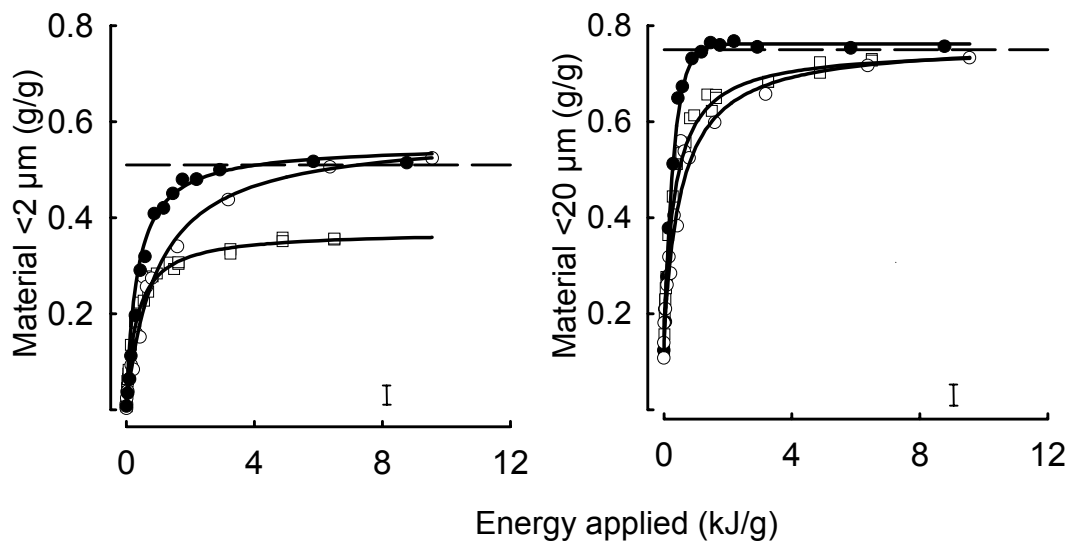


Figure 3. Soil dispersion curves for Lawes soil with energy applied at 1.92 W (\square) by end-over-end shaking and at 8.9 W (\circ) and at 25.0 W (\bullet) by ultrasound. Complete dispersion (---) measured by Gee and Bauder (1986) method. Vertical bars represent l.s.d. at $P=0.05$. (after Raine and So, 1997)

Where mechanical energy was applied to the Ferrosol using the low frequency shaker table operating at <200 hz, there was no significant difference in the amount of <2 μm and <20 μm sized material released due to changes in either frequency or power (Table 2). However, increasing the frequency from 200 to 1600 hz increased the amount of <20 μm sized material but did not affect the amount of <2 μm sized material released (Tables 2 & 3). Increasing the power within the 800-3200 hz frequency range also increased only the amount of <20 μm sized material released. However, increasing the frequency from 1600-3200 hz increased both <2 and <20 μm sized material released. In all cases, the amount of <2 and <20 μm sized material released was substantially less than that released by the application of the same amount of ultrasonic energy.

Table 2. The effect of wave frequency (100-400 hz), power and period of application on the aggregate breakdown of a FerrosolWithin columns, means followed by the same letter are not significantly different at $P = 0.05$.

Main effects		<2 μm (g/g)	<20 μm (g/g)
Period of application (s)	0	0.0034 ^a	0.0521 ^a
	300	0.0200 ^b	0.1677 ^b
	600	0.0268 ^b	0.2136 ^c
	900	0.0504 ^c	0.2378 ^c
Frequency (hz)	100	0.0320 ^b	0.1861 ^b
	200	0.0202 ^b	0.1964 ^b
	400	0.0350 ^b	0.2366 ^c
Power setting	2	0.0323 ^b	0.1973 ^b
	4	0.0287 ^b	0.2104 ^b
	6	0.0362 ^b	0.2114 ^b

Table 3. The effect of pressure wave frequency (800-3200 hz) and power on aggregate breakdown of a FerrosolWithin columns, means followed by the same letter are not significantly different at $P = 0.05$.

Power setting	Frequency (hz)	Period (s)	<2 μm (g/g)	<20 μm (g/g)
6	800	600	0.0031 ^a	0.1846 ^c
	1600	600	0.0148 ^a	0.2581 ^d
	3200	600	0.0331 ^b	0.2603 ^d
8	800	600	0.0114 ^a	0.2686 ^d

There was no significant difference between the amount of <2 μm and <20 μm sized material released under rainfall and that produced when similar mechanical waveforms and total energy were applied using the shaker table (Table 4). This suggests that it is possible to accurately reproduce mechanical stresses experienced in the field under laboratory conditions and that there is the potential for the development of rapid, quantitative aggregate stability assessment techniques.

4. CONCLUSIONS

Aggregate breakdown in soils is a function of the frequency and amplitude of the applied mechanical wave and the total energy applied. Hence, to quantitatively simulate in the laboratory the aggregate breakdown at each hierarchical level that occurs under field conditions, the mechanical stresses imposed in the field need to be reproduced exactly. A method of simulating the mechanical energy associated with raindrop impact has been proposed.

Table 4. Aggregate breakdown produced by rainfall simulation and a shaker table applying the equivalent mechanical waveform sequence to a Ferrosol
Within columns, means followed by the same letter are not significantly different at $P = 0.05$.

	600 s ^A		1200 s ^A		1800 s ^A	
	<2 μ m (g/g)	<20 μ m (g/g)	<2 μ m (g/g)	<20 μ m (g/g)	<2 μ m (g/g)	<20 μ m (g/g)
Shaker table - setting 2	0.0047 ^a	0.0841 ^a	0.0071 ^a	0.0882 ^a	0.0032 ^a	0.0799 ^a
Shaker table - setting 6	0.0091 ^b	0.0722 ^a	0.0129 ^b	0.0990 ^a	0.0144 ^b	0.1234 ^b
Simulated rainfall	0.0210 ^b	0.0665 ^a	0.0209 ^b	0.0769 ^a	0.0219 ^b	0.1007 ^b

^A Period of simulated rainfall or equivalent number of waveform sequences

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