

Influence of vibration amplitude on the ultrasonic dispersion of soils

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A b s t r a c t. Ultrasonic dispersion is a powerful method of dispersing soil aggregates. Several procedures are described in the literature, which use absorbed ultrasonic energy as the main parameter for correlation with the process of soil dispersion. In the present work it is shown, that the dynamic of soil dispersion additionally depends on the magnitude of ultrasonic vibration. The vibration amplitude of the ultrasonic probe is an appropriate parameter in characterising the magnitude of loading, and a procedure to measure this value is described. Soil particle distribution in dispersion experiments is correlated to both, the absorbed ultrasonic energy per unit volume suspension and the amplitude of ultrasonic vibration.

K e y w o r d s: ultrasonic dispersion, soil aggregates, ultrasonic energy, vibration amplitude, particle size distribution

INTRODUCTION

Soils can be dispersed into smaller aggregates and particles using ultrasonic equipment. Edwards and Bremner [4], Ford *et al.* [7], Genrich and Bremner [10,11], Pritchard [18] and Watson and Parsons [25] used ultrasonic vibrations as pre-treatment for quantitative particle size analysis by subsequent pipette or sieve method approx. three decades ago. Edwards and Bremner [4] and Pritchard [18] showed that soil dispersion depends on the time the water-soil mixture is subjected to ultrasonic vibrations. The sand fraction decreases and the clay fraction increases the longer the solution undergoes ultrasonic vibrations. North [16] was the first author who correlated the refining of soil particles with the absorbed ultrasonic energy. In an energy balance calculation he considered the increase of temperature of soil and water, losses of heat and the energy to disperse soil particles. The ultrasonic energy absorbed per unit mass of dry soil [16,17] or the absorbed energy per unit volume of solution [12] or the absorbed energy in a defined solution

volume [15] are used to correlate the process of refining soil particles with energy criteria until now. The particle size distribution after different absorbed energies may serve as a parameter for the stability of microaggregates [3,12,16,17].

Models to describe the process of soil dispersion take the absorbed energy as a parameter for the effect of ultrasonic vibrations into account. Fuller and Goh [8] used a two-parameter model:

$$A = A_{\max} \cdot a^{-kE}, \quad (1)$$

to correlate the remaining undispersed clay (A) with the absorbed ultrasonic energy per millilitre solution (E). Raine and So [19] included the material dispersed before sonification (c) the applied energy (E) and two regression constants (a and b) to describe the relative fraction of dispersed material (D) by ultrasonic vibrations:

$$D = c + b \cdot \left(1 - e^{-aE}\right). \quad (2)$$

In a detailed study of five different soils, they show [20] in which way the regression function is influenced by several experimental parameters besides the ultrasonic energy (i.e., suspension concentration, temperature of solution, volume of suspension, gas content, soil wetting method, probe insertion depth and particle size distribution). Both models [8,19] imply that a large value of absorbed energy will lead to the complete dispersion of soil into particles.

Recommendations for an appropriate ultrasonic dispersion procedure described in the literature are based on energy criteria: Morra *et al.* [15] proposed a limitation of ultrasonic energy to obtain adequate particle sizes, since increasing ultrasonic energy above 3 - 5 kJ (50 ml water and 10 g soil) may affect organo-mineral complexes. Schmidt *et al.*

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[23] showed that absorbed ultrasonic energy must be 450 - 500 J ml⁻¹ to obtain a particle size distribution similar to standard analysis methods. However, smaller particle size fractions were found in a larger content [24], if soil containing coal or other particles from coal industry were analysed using this ultrasonic energy. Amelung and Zech [1] showed that different amount of ultrasonic energy is necessary to disperse aggregates of different diameters. Field and Minasny [6] divided between aggregate liberation (dominating the initial period of soil solution in ultrasonic segregation experiments) and aggregate dispersion (dominating the solution process at higher values of absorbed energy), and they defined a critical energy to initiate the second process.

Using the absorbed ultrasonic energy as the only parameter for breaking soil particles, however, is not appropriate to explain all the results described in the literature. Raine and So [21] showed that the same applied ultrasonic energy may cause different dispersion behaviour if ultrasonic power of 8.85 or 24.95 W, respectively, was used. Cerda *et al.* [2] found that a minimum amount of ultrasonic power is required to disperse different soils depending on their stability. Amelung and Zech [1] reported that sonifiers with different power outputs lead to different particle size distributions in ultrasonic dispersion experiments although the absorbed energies were similar.

These reports show that the same amount of absorbed ultrasonic energy can lead to a different particle size distributions, if the stressing of the particles caused by ultrasonic vibrations is different. Stressing of soil particles and breaking of aggregate bonds using ultrasonic dispersion equipment is mainly caused by high stresses due to cavitation of the fluid. Additionally, the turbulent flow of the soil water suspension may enhance the breakdown of particles. The main parameter whether acoustic waves cause cavitation or not is the acoustic pressure of the ultrasound, i.e., a minimum of acoustic pressure amplitude is necessary to stimulate cavitation, depending on the properties (temperature, purity etc.) of the fluid [5,22]. The acoustic pressure amplitude (p) depends on the density of the fluid (ρ) the sound velocity in the fluid (c) and the sound vibration velocity amplitude (v) [13]:

$$p = \rho \cdot c \cdot v. \quad (3)$$

Keeping the amount of water and the content of soil constant, the acoustic pressure varies therefore as a function of the sound vibration velocity amplitude. Depending on the vibration velocity the magnitude of cavitation bubbles varies, or even cavitation may be absent at low values of v . It may be therefore expected, that the magnitude of v has a pronounced influence on the process of particle breaking in the field of ultrasonic waves.

The sound vibration velocity amplitude can be taken into account using the vibration amplitude of the ultrasonic probe, which is inserted into the solution. Similarly, the velocity amplitude, which is proportional to the vibration

amplitude and the vibration frequency could serve this purpose. It is the aim of this work to show that the vibration amplitude (or the velocity amplitude) of the ultrasonic probe are easy measurable parameters for the magnitude of ultrasonic loading. Both, the absorbed ultrasonic energy per unit volume and the amplitude of ultrasonic vibration are necessary to characterise the dynamic of aggregate breaking during ultrasonic dispersion of soils.

MATERIAL AND METHODS

Principle of ultrasonic dispersion equipment

In this work ultrasonic equipment (Bandelin Sonoplus HD 2200) was used as shown in principle in Fig. 1. A piezoelectric ultrasonic transducer transforms a sinusoidal electrical voltage into mechanical longitudinal resonance vibration, where the resonance frequency of the equipment is 20 kHz. The equipment is mounted using a booster horn, which serves additionally to increase the vibration amplitude. The ultrasonic probe is inserted in a soil-water suspension. The booster horn and ultrasonic probe are manufactured using the commercially frequently used titanium alloy Ti-6Al-4V. The ultrasonic probe used had a cylindrical shape with a diameter of 12.7 mm.

The equipment allows experiments at different ultrasonic power. The power setting is reproducible within approx. 2% in different experiments. However, the ultrasonic power displayed as a percentage of the maximum power was used as a parameter only. In Fig. 2 the ultrasonic power displayed (in %) is compared with the power absorbed in 200 ml pure degassed water at an insertion depth of 10 mm. The power of ultrasonic vibrations emitted into

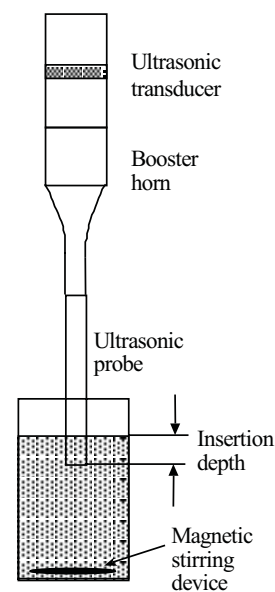


Fig. 1. Principle of the used ultrasonic dispersion equipment.

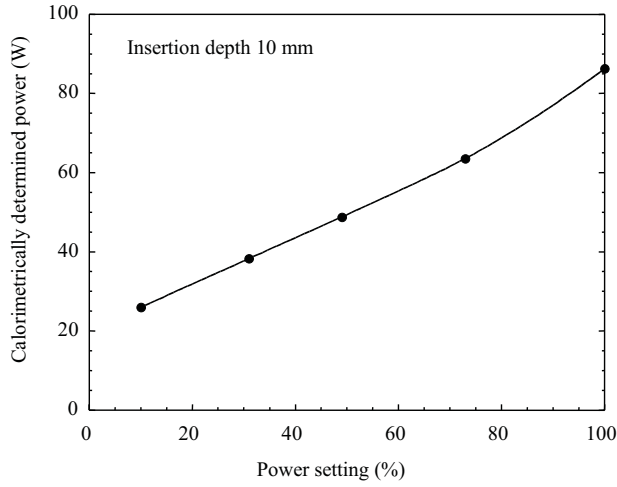


Fig. 2. Correlation of calorimetrically determined power and power displayed in ultrasonic dispersion equipment.

the fluid was determined with caloric measurements. The power displayed shows strong deviations from experimentally determined power. These experiments support the results of Schmidt *et al.* [23] that the power of ultrasonic devices displayed and calorimetrically determined power may be significantly different. The power displayed was only used as a relative value and did not serve as a parameter for evaluation of dispersion experiments therefore.

Determination of ultrasonic vibration amplitude

It is difficult to directly measure the vibration amplitude at the lower end of the ultrasonic probe, since it vibrates in the soil water solution. Capacity sensors mounted at the lower end of the ultrasonic probe for example disturb the emission of ultrasonic waves. However, the resonance vibrations cause cyclic straining of the mechanical components. Vibration amplitudes can be determined indirectly measuring the strain amplitudes, since strain amplitudes and vibration amplitudes are proportional. Cyclic strains can be measured at high accuracy using a strain gauge and an appropriate strain amplifier.

According to Mason [14], vibration amplitudes and strain amplitudes along bars of varying thickness stimulated to longitudinal resonance vibrations are correlated by a differential equation. The ultrasonic dispersion equipment used represents a system as described by Mason [14]. The vibration amplitude and the strain amplitude along the load train are shown in Fig. 3. Only the ultrasonic probe must be considered in the following, since it is the only vibrating component in contact with the soil water solution. In the following it is assumed, that the ultrasonic probe used has a cylindrical shape.

Vibration amplitudes of the ultrasonic probe vary along its length according to a cosine function and become maximal at the free end of the ultrasonic probe, where the ultra-

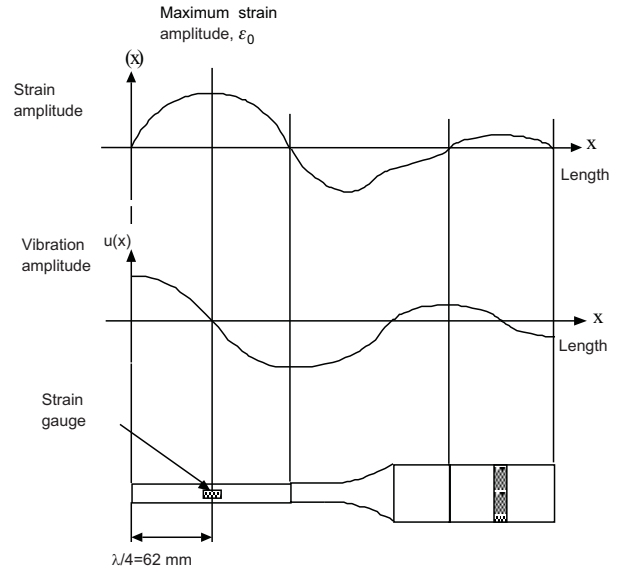


Fig. 3. Variation of the vibration amplitude, $u(x)$ and the strain amplitude, $\varepsilon(x)$ along the length x of the ultrasonic dispersion equipment.

sonic probe is inserted in the solution. Frequently, the length of the ultrasonic probe is approx. half of wavelength (λ) of the tension-compression ultrasonic wave, as shown in Fig. 3. If the length of the ultrasonic probe (l) is:

$$l = n \cdot \frac{\lambda}{2}, \quad (4)$$

and n is a natural number (1, 2, 3 ...) then the strains (and the stresses) at the junction to the booster horn are minimal, and the vibration amplitude at both ends are similar.

The wavelengths of the tension compression waves depend on the resonance frequency (f) and the velocity of sound (c). In a cylindrical bar, the velocity of sound may be expressed using Young's modulus (E) and the mass density (ρ):

$$\lambda = \frac{c}{f} = \frac{1}{f} \cdot \sqrt{\frac{E}{\rho}}. \quad (5)$$

Using a co-ordinate system as shown in Fig. 3 it may be assumed that the lower end (free end) of the ultrasonic probe ($x=0$) vibrates with a vibration amplitude u_0 . Then the displacement $u(x,t)$ at a length x of the ultrasonic probe at a time t is:

$$u(x,t) = u_0 \cdot \cos\left(\frac{2\pi}{\lambda} \cdot x\right) \sin(2\pi f \cdot t). \quad (6)$$

The vibration amplitude at the length x , $u(x)$ is:

$$u(x) = u_0 \cdot \cos\left(2\pi f \cdot \sqrt{\frac{\rho}{E}} \cdot x\right). \quad (7)$$

The strain amplitude at the length x , $\varepsilon(x)$ is the deviation of the vibration amplitude:

$$\varepsilon(x) = \frac{du(x)}{dx} = -u_0 \cdot 2\pi f \cdot \sqrt{\frac{\rho}{E}} \cdot \sin\left(\frac{2\pi}{\lambda} \cdot x\right). \quad (8)$$

The strain becomes maximal at the length where the vibration amplitude is minimal, i.e., at a distance of $\lambda/4$ from the free end of the ultrasonic probe, as shown in Fig. 3. The strain amplitude in a distance of $\lambda/4$ from the free end (ε_0) is proportional to the vibration amplitude at the end of the ultrasonic probe according to:

$$u_0 = \frac{\varepsilon_0}{2\pi f} \cdot \sqrt{\frac{E}{\rho}}. \quad (9)$$

In the present investigation, a cylindrical ultrasonic probe made of Ti-6Al-4V (Young's modulus $E=110$ GPa and mass density $\rho=4500$ kg m⁻³) was used. The ultrasound equipment worked at a resonance frequency of 20 kHz. The strain amplitude, ε_0 had to be measured at a distance of $\lambda/4$:

$$\frac{\lambda}{4} = \frac{1}{4f} \cdot \sqrt{\frac{E}{\rho}} \cdot 62 \text{ mm}, \quad (10)$$

of the lower end of the ultrasonic probe (Fig. 3). At this place the strain amplitude was measured with a strain gauge. Commercial strain gauges have been used.

To determine the vibration amplitude at the lower end of the ultrasonic probe (u_0), the following relation was used:

$$u_0 = \varepsilon_0 \cdot \frac{1000}{2\pi \cdot 20000} \cdot \sqrt{\frac{110 \cdot 10^9}{4500}} = \varepsilon_0 \cdot 39.3 \cdot 10^{-3}. \quad (11)$$

The vibration amplitude (in micrometers) is correlated to the measured strain amplitude (in mm m⁻¹) according to:

$$u_0 \text{ (in } \mu\text{m)} = \varepsilon_0 \text{ (in mm m}^{-1}\text{)} \cdot 39.3. \quad (12)$$

The strain amplitude and the resonance frequency can also be used to determine the velocity at the place x of the ultrasonic probe, $v(x,t)$ since the velocity is the deviation of the displacement:

$$v(x,t) = \frac{du(x,t)}{dt} = 2\pi f \cdot u_0 \cdot \cos\left(\frac{2\pi}{\lambda} \cdot x\right) \cos(2\pi f \cdot t). \quad (13)$$

The velocity amplitude at the lower end of the ultrasonic probe (v_0), where it is inserted into the solution, is therefore:

$$v_0 = 2\pi f \cdot u_0 = \varepsilon_0 \cdot \sqrt{\frac{E}{\rho}}. \quad (14)$$

In the actual investigation, a cylindrical ultrasonic probe made of a titanium alloy was used and the resonance frequency was 20 kHz. Therefore, the velocity amplitude at the

lower end of the ultrasonic probe, the vibration amplitude at the lower end and the strain amplitude in a distance of 62 mm from the free end are proportional with the following factors:

$$v_0 = \left(\text{in ms}^{-1}\right) = 0.126 \cdot u_0 \text{ (in } \mu\text{m)} = 4.94 \cdot \varepsilon_0 \text{ (in mm m}^{-1}\text{)}. \quad (15)$$

The determination of cyclic strain amplitudes is possible with high accuracy, if strain amplifiers adequate to determine strain signals at resonance frequency (20 kHz) are used. The main limitation is that the equations described above are valid only, if the ultrasonic probe has a cylindrical shape. Otherwise, the vibration amplitude and the strain amplitude do not follow simple trigonometrical functions but have to be considered in more detail [14].

Ultrasonic experiments

To standardise ultrasonic procedure the following experiments were performed:

- To investigate the role of the suspension volume on the absorbed ultrasonic power (or ultrasonic energy), caloric measurements at different vibration amplitudes were performed using 3 different volumes of pure degassed water (100, 200 and 400 ml). An increase of the temperature of water from typically 20°C to typically 25°C was evaluated.
- To investigate the role of insertion depth on the absorbed ultrasonic power, two insertion depths (10 and 40 mm) were used. The experiments were performed using 200 ml of pure degassed water.

Ultrasound dispersion experiments should serve to evaluate the role of both, absorbed energy and vibration amplitude on the process of ultrasonic dispersion of soil. These experiments were carried out on a laboratory referenced soil material (EUROSOL 7) [26]. Ultrasonic dispersion experiments were performed using 200 ml of pure degassed water and 10 g of soil. The insertion depth was constant at 10 mm. The temperature of the solution remained constant at $20 \pm 2^\circ\text{C}$ using a cooling device. In addition to the ultrasonic vibration, the solution was stirred with a magnetic stirring device (2 Hz, cylindrical shape with length 25 mm and thickness 8 mm).

To investigate the process of ultrasonic dispersion at different vibration amplitudes, two series of experiments were performed. In the first series the vibration amplitude was $23 \mu\text{m}$ (which means that the velocity amplitude was 2.9 m s^{-1}) and in the second series the vibration amplitude was $42 \mu\text{m}$ (velocity amplitude 5.3 m s^{-1}). The following experiments were carried out:

- The ultrasonic dispersion of sand particles was studied at different absorbed ultrasonic energies using two different vibration amplitudes.
- To decide whether or not ultrasound is appropriate to completely disperse soils into particles, the relative weight content of different sand fractions obtained at a high ultrasonic energy (1000 J ml^{-1}) was compared to the particle size distribution obtained with the chemical dispersion method.

Soil treatment and particle size analysis

Laboratory reference soil material (EUROSOL 7)[26] was used in dispersion experiments. The soil was sieved (maximum diameter 2 mm) and dried by air. Before dispersion testing, the soil was pre-wetted at 60 hPa matrix potential at 24°C for 24 h in a pressure chamber.

The wet sieving method served to determine soil particle size distribution after different treatments. The entire sand fraction was analysed with standardised sieves and classified in different particle sizes: coarse sand (2000 to $630 \mu\text{m}$), medium sand (630 to $200 \mu\text{m}$), and fine sand (200 to $63 \mu\text{m}$). Determination of mass fractions (accuracy 0.001 g) was performed after drying the soil fractions at 105°C for 24 h.

The first series of experiments served to characterise the soil particle distribution after pre-treatment and prior to ultrasonic or chemical dispersion. In ultrasonic dispersion experiments, particle size distribution was determined at different amounts of absorbed energy by sieving the solution immediately after ultrasonic treatment. Chemical dispersion [9] was performed using 0.4 M tetra-sodium-diphosphate-decahydrate as a dispersion agent and overhead shaking (1 Hz , radius 40 mm) for 6 h at a temperature of 20°C .

RESULTS AND DISCUSSION

Influence of solution volume

In Fig. 4a, the absorbed ultrasonic power using 100, 200 and 400 ml of degassed water and an insertion depth of 10 mm is compared. The vibration amplitude was kept constant, and the ultrasonic power was determined calorimetrically. All experiments were repeated twice, and the respective symbols show the mean values of the absorbed ultrasonic power.

It may be recognised that no influence of solution volume on the absorbed power was found, within the scatter range. This means that similar ultrasonic energy is absorbed varying the solution volume by a factor of four, if the ultrasonic vibration amplitude and the insertion depth are kept constant. The approximation line (assuming a second order polynomial function) shows the dependence between vibration amplitude and ultrasonic power for a suspension volume of 200 ml.

Influence of insertion depth

The influence of the insertion depth of the ultrasonic probe into the water solution was determined using two insertion depths, 10 and 40 mm in 200 ml of pure degassed water. Figure 4b shows the absorbed power for different vibration amplitudes approximated using second order polynomial functions.

The insertion depth has a pronounced influence on the absorbed power, i.e., at a certain vibration amplitude the absorbed ultrasonic power increases with increasing insertion depth. This may be explained assuming two kinds of release of ultrasonic energy into the solution: Emission of ultrasonic sound waves which is accomplished mainly at the

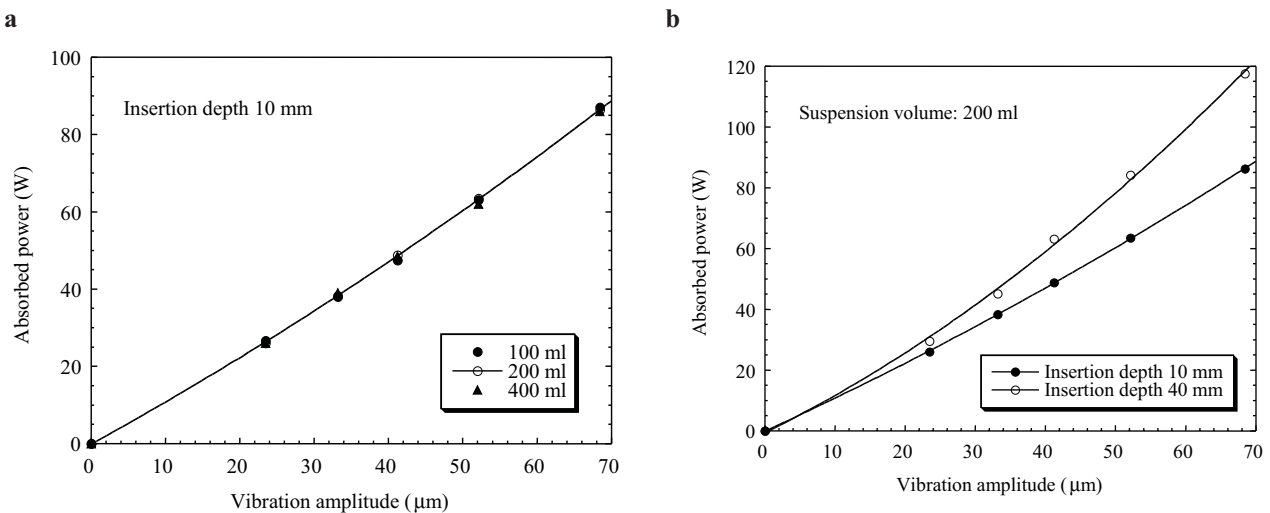


Fig. 4. Absorbed ultrasonic power: in different volumes (a) and at different insertion (b) of water at constant vibration amplitude.

bottom of the ultrasonic probe, and heating caused by surface friction of ultrasonic probe and solution. Since larger insertion depths mean larger areas of surface friction, the absorbed power increases with increasing insertion depth.

Influence of absorbed energy and vibration amplitude on dispersion

In Fig. 5 (a-d) the sand fractions obtained after pre-treatment and different times of sonification using vibration amplitudes of 23 and 42 μm , respectively, are shown. The velocity amplitudes were 2.9 and 5.3 m s^{-1} . The abscissa shows (in logarithmic scale) the absorbed ultrasonic energy per unit volume suspension. The ordinate shows the content

of coarse sand (Fig. 5a), medium sand (Fig. 5b), fine sand (Fig. 5c), and entire sand fraction (Fig. 5d) at different absorbed ultrasonic energies. Dash-dotted lines show the respective contents of coarse, medium, fine and entire sand fraction, respectively, determined prior to ultrasonic sonification, i.e., after the pre-treatment of the soil. Dashed lines show the respective content as obtained with chemical dispersion.

As shown in Fig. 5a, the content of coarse sand decreases with increasing absorbed ultrasonic energy for both investigated vibration amplitudes. However, the dispersion of coarse sand is accelerated, if the higher vibration amplitude is used. A relative weight content of 20% of coarse sand, for example is obtained at an absorbed ultrasonic energy of approximately 3.3 J ml^{-1} at a vibration

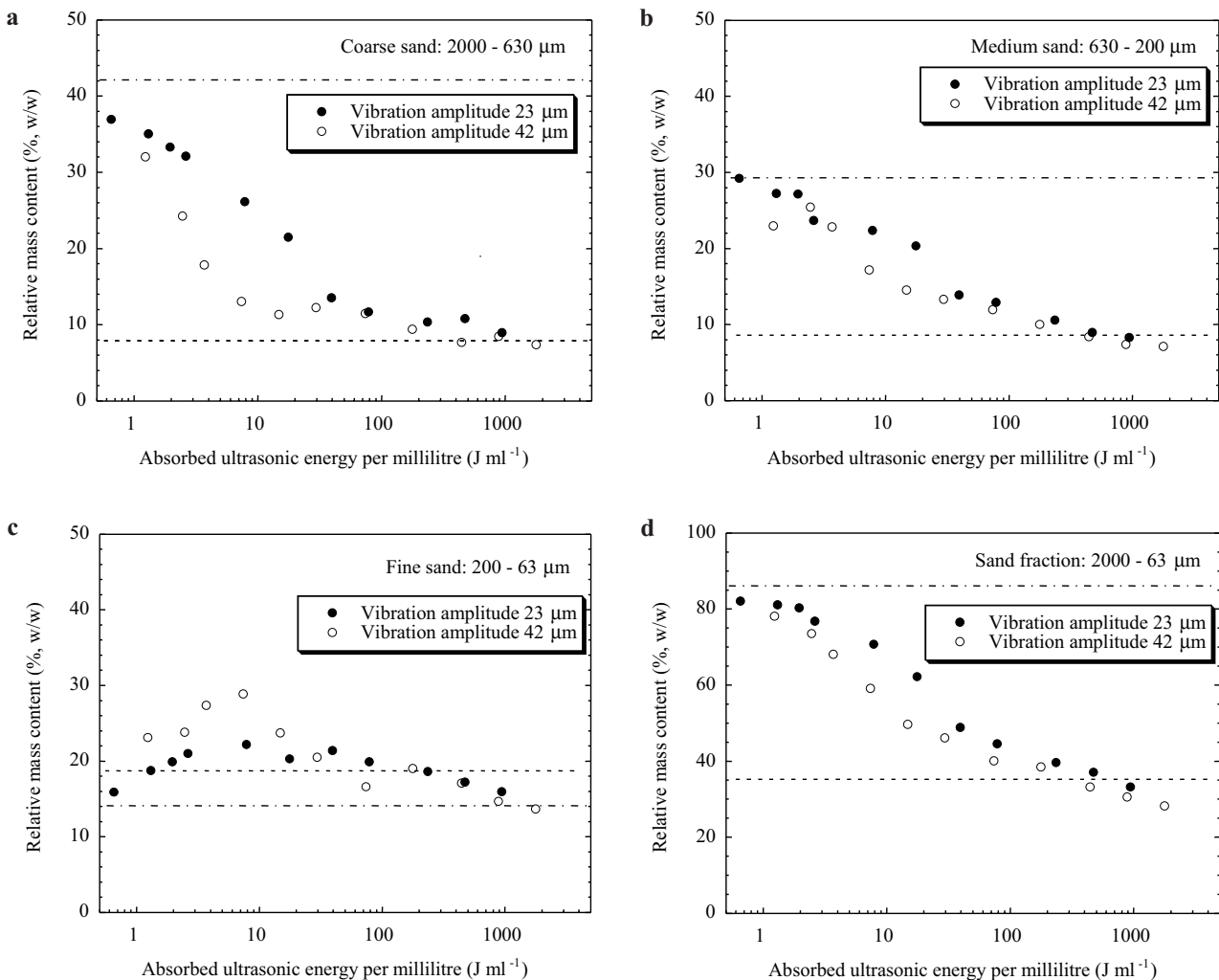


Fig. 5. Relative mass content of sand particles (coarse particles (a), medium particles (b), fine particles (c), and overall sand fraction (d)) obtained by sonification at different absorbed energies. Dots represent measurements at vibration amplitude of 23 μm (velocity amplitude of 2.9 m s^{-1}) and circles represent measurements at a vibration amplitude of 42 μm (velocity amplitude of 5.3 m s^{-1}). Dash-dotted lines show the relative mass contents of different sand fractions determined prior to ultrasonic sonification, and dashed lines show contents as obtained with chemical dispersion.

amplitude of $42\ \mu\text{m}$ whereas $20\ \text{J ml}^{-1}$ of absorbed energy is necessary to obtain the same relative weight content at a vibration amplitude of $23\ \mu\text{m}$. The dispersion of coarse sand into sand with a finer grain size needs less absorbed energy when the ultrasonic vibration amplitude is higher.

The relative weight content of medium size sand fraction obtained at different absorbed energies is shown in Fig. 5b, and Fig. 5c shows the relative weight fraction of fine sand. Absorbed energies of approximately $10\ \text{J ml}^{-1}$ lead to a different relative content of both, medium and fine sand fraction depending on the vibration amplitude, whereas this difference diminishes at higher absorbed energies. The relative weight content of the entire sand fraction obtained at different absorbed energies is shown in Fig. 5d.

The most pronounced influence of the vibration amplitude on the dynamic of soil dispersion is found at low absorbed energies. In this regime the relative mass content of coarse sand is smaller and the content of fine sand is higher at larger vibration amplitudes. With increasing vibration amplitudes, cavitation and subsequent stressing of soil particles increases and causes more frequent fracture of soil particles. Ultrasonic dispersion experiments at different vibration amplitudes and low absorbed energies may serve therefore to separate microaggregates of different stability.

Comparison of ultrasonic and chemical dispersion

In Fig. 6 the relative weight fraction at large absorbed ultrasonic energies ($1000\ \text{J ml}^{-1}$) using vibration amplitudes of 23 and $42\ \mu\text{m}$ (velocity amplitudes of 2.9 and $5.3\ \text{m s}^{-1}$), respectively is compared to the relative weight content obtained with chemical dispersion. The relative weight fractions of coarse and medium sand determined with the

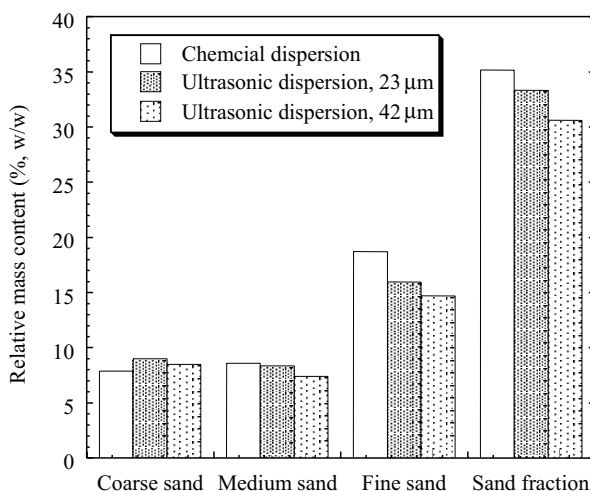


Fig. 6. Relative mass content of coarse, medium and fine sand particles and overall sand fraction obtained with chemical dispersion, ultrasonic dispersion at a vibration amplitude of $23\ \mu\text{m}$ and an absorbed energy per millilitre of $1000\ \text{J ml}^{-1}$, and ultrasonic dispersion at $42\ \mu\text{m}$ and $1000\ \text{J ml}^{-1}$, respectively.

ultrasonic and the chemical method differ by a maximum 1.2%. This means that ultrasonic experiments and chemical dispersion lead to a similar relative weight content of coarse and medium sand, and ultrasonic energy is able to completely disperse coarse and medium size sand particles. This coincides with the predictions of the models of Fuller and Goh [8] and of Raine and So [19].

However, the relative weight content of fine particles at absorbed energies of $1000\ \text{J ml}^{-1}$ is approx. 14.7% (vibration amplitude $42\ \mu\text{m}$), 16.0% (vibration amplitude $23\ \mu\text{m}$) and chemical dispersion experiments lead to a relative weight content of 18.7%. This means that ultrasonic dispersion at large absorbed energies may disperse small particles more effectively than chemical dissolution.

Two advantages of the ultrasonic dispersion method in comparison with the chemical method should be noted: About 1-2 h are necessary to perform an ultrasonic dispersion experiment at absorbed energies of $1000\ \text{J ml}^{-1}$. A chemical dispersion experiment needs about one day, which shows a significant saving of time using ultrasonic dispersion. Additionally, soil components are not in contact with chemical substances during the ultrasonic dispersion [3], allowing the further chemical and biochemical analysis of different components or fractions of a soil.

CONCLUSIONS AND OUTLOOK

The dynamic of soil dispersion depends on the absorbed ultrasonic energy per unit volume and the amplitude of ultrasonic vibration. Both parameters can be varied in order to characterise the different dispersion behaviour of soils.

1. Since soil aggregation is closely related to the erodibility of soils, further investigations on the relationship between soil dispersion and soil erosion should be carried out.

2. Moreover, the ultrasonic method seems to be an appropriate application for the dispersion of soils without chemical additives. This is of particular importance when nutrient losses (i.e., phosphorous) in run-off experiments should be determined.

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