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Rainfall-induced soil erosion and sediment sizes of a residual soil under 1D and 2D rainfall experiments

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Abstract

Raindrop impact and surface flow trigger the downstream movement of soil particles by the processes of rainfall-induced soil erosion. A set of laboratory simulated rainfall experiments was carried out to study soil loss and size characteristics of discharged sediments of a soil under a rainfall intensity of 70 mm/h, controlled initial soil suctions and moistures. The rainfall simulation was instrumented with tensiometers and moisture sensors. A new device capable of deriving impact force, velocity, and kinetic energy of a falling waterdrop was developed. Sediment sizes in runoff were characterized by a laser particle size analyzer in order to correlate with the properties of rainfall. 1D simulated rainfall experiments were also employed to study soil detachment and soil susceptibility to rainfall under both saturated and unsaturated soil conditions. The processes of soil erosion and outflow size characteristics of sediments relating to effect of suction were discussed. The proposed set of experiments will be a viable tool for measuring soil loss, sediment runoff, and sediment sizes discharged from a farmland pertaining to properties of rain, soil and flow.

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Keywords: Soil erosion; Soil erodibility; Sediment sizes; Drop impact force; Unsaturated soil;

1. Introduction

Global warming effect triggers a change in climate and is likely to shift the characteristics of heavy and extreme rainfall in forms of pattern, amount, duration, frequency and intensity. The potential shift is strongly expected to influence the characteristics of soil erosion, surface runoff, and sizes of discharged sediments (Nearing et al. 2004). Rain is a natural dynamic movement of water that varies spatially and temporally under amounts and intensities. Rain is also considered as one of the most key erosion factors under all natural conditions in term of erosive and destructive power to cause soil particle detachment and movement from soil surface (Zachar, 1982). Rain-impacted soil detachment and flow are mutually responsible for sheet and interrill erosion areas. The size distributions of primary particles discharged by rain-impacted flows have been observed to be finer (including nutrient and chemical particles) than those in the soil matrix (Kinnell, 2009). Therefore, the soil erosion and removal of the fine particles affect farming productivities and water quality of the receiving aquatic environments.

Rainfall-induced soil erosion (RISE) for a bare soil is a complex energy-dependent process resulting from the combined effect of raindrop properties, soil components and soil-water interaction. Impact of raindrop is associated with the raindrop kinetic energy and has been widely studied to characterize soil resistance to impacting rainfall and runoff flow or soil erodibility (Hinkle, 1989; Nearing & Bradford,

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1984; Sharma & Gupta, 1989). The drop impact also attributes to the onset of particle movement through coupling soil detachment and sediment transport (Fig. 1).

Soil erodibility or susceptibility of a soil against erosive forces or erosion is a dynamic parameter of a soil that depends on hydraulics of raindrop and surface flow. Soil erodibility is temporally and spatially influenced by soil type, organic matter content, soil structure and permeability (Wischmeier & Smith, 1978). Antecedent soil conditions also influence soil erodibility and produce hysteresis in characteristics of soil loss and sizes of sediment discharged (Vilayvong et al. 2014). For example, cycles of wetting and drying of soils, which are partially underpinned by temporal variation of suction and soil moisture. Unsaturated soils with varying contents of air and water possess a negative pore water pressure or soil suction. Dry soils with high soil suction increases aggregate stability and shear strength of the surface soil. However, high soil moisture might increase aggregate slaking and breakdown during rainfall due to rapid wetting which is exacerbated by soil detachment and transport induced by rainfall and surface flow (Le Bissonais et al. 1989).

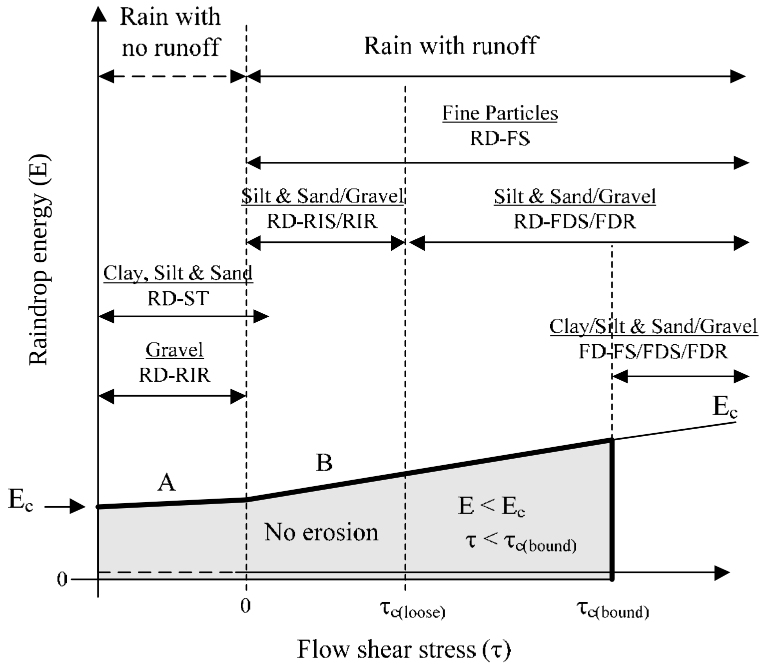


Fig. 1. Mechanism of soil erosion due to impact of rainfall and flow (Kinnell, 2009)

Nomenclature

E_c = critical raindrop energy to cause detachment.
$\tau_{c(loose)}$ = critical flow shear stress required to transport loose (pre-detached) soil particles.
$\tau_{c(bound)}$ = critical shear stress required to detach particles bound within the soil surface (held by cohesion and inter-particle friction).
RD–ST = raindrop detachment and splash transport.
RD–RIR = raindrop detachment and raindrop induced rolling.
RD–RIS/RIR = raindrop detachment and raindrop induced saltation or rolling.
RD–FDS/FDR = raindrop detachment and flow driven saltation or flow driven rolling.
RD–FS = raindrop detachment and flow suspension.
FD–FS/FDS/FDR = flow detachment and flow suspension or flow driven saltation or flow driven rolling

Many process-based soil erosion models such as WEPP (Flanagan & Nearing 1995) consider the effect of runoff on erosion explicitly and require the rainfall properties (the drop size distribution, velocity, kinetic energy and intensity) and soil properties (soil moisture, soil suction, and permeability) to be addressed. Measurement of soil erosion and the discharged sediment sizes pertaining to raindrop impact and soil conditions is a challenge in practice and measurement data are scarily limited. Therefore, it is viable that determination procedure and method need be developed. The objectives of this study are (a) to conduct a preliminary study for continuous determination of impact force or kinetic energy of a falling waterdrop for soil erodibility study and (b) to investigate the grain size distribution of discharged particles from laboratory rainfall-impacted soil erosion using a residual soil, heavy rainfall intensity of 70 mm/h, and impact force of the falling waterdrop under controlled initial soil suctions.

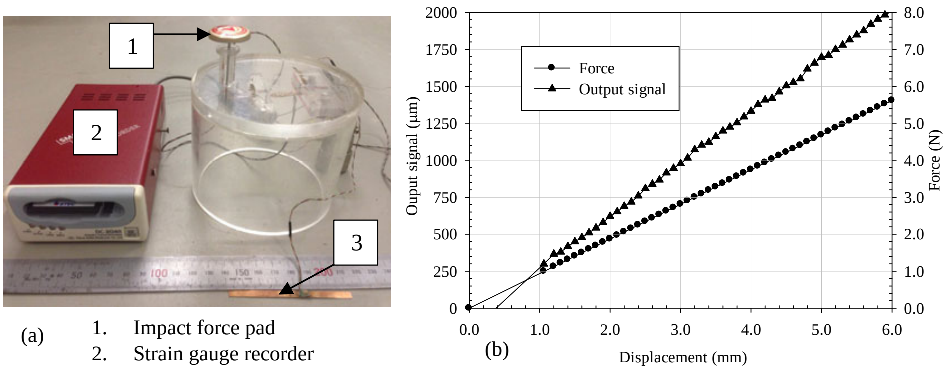
2. Materials and Method

2.1. Determination of impact force from a falling waterdrop test

Impact force of a simulated waterdrop was measured by using a strain gauge-based cantilever strip. The copper alloy strip of 50 mm (length), 4.0 mm (width) and 0.2 mm (thickness) was mounted with a miniature strain gauge sensor (Fig. 2a). A light circular aluminum pad was placed on the tip of the strip vertically by a frictionless pin. When a raindrop strikes the surface of the pad, the cantilever strip experienced deflection and the strain gauge sensor picked up the surface displacement signal. The sensor was first calibrated against vertical displacement. The output signal was acquired using a dynamic strain recorder. The displacement and output signal were then converted by equation (1) to obtain the impact force. Fig. 2b shows the results of calibration of displacement, output signal and impact force using material properties of the copper (modulus of elasticity, E = 117 GPa).

$$F = \frac{3EI}{L^3}\delta \quad (1)$$

Where F: force, L: length of cantilever, E: modulus of electricity of material, I: moment of inertia, EI: stiffness of the strip and δ: deflection at the tip of cantilever.



(a)
1. Impact force pad
2. Strain gauge recorder
3. Copper strip with strain gauge

Fig. 2. Impact force device: (a) strain gauge for impact force, (b) calibration of impact force

2.2. Soil sample and soil preparation for rainfall-induced soil erosion (RISE) study

Shino et al. (2013) reported that change in rainfall erosivity for soil erosion of farmlands in Japan due to potential impact of future climate. Their results suggested that rainfall erosivity will increase in many parts of farmland areas and soil erosion of farmlands will be elevated on an average rate of more than 20%. Rainfall intensity of more than 20 mm/h is classified as heavy rain in Japan. The number of days with rainfall of 1.0 mm or more is descending and the number of days with rainfall intensity of 100 mm or more is on the rise and the frequency of hourly heavy rains of 50 mm or more is highly likely occurred (JMA, 2012). The most frequent occurence of the events was observed in the southern part of Japan, the highest is in Okinawa island, followed by Kyushu island (JMA, 2013).

A residual soil derived from weathered and decomposed granitic rocks was used as a soil sample. Masa soils (by local name in Japan) are residual soils which are widely distributed in the southern part of Japan. In general, Masa soils are susceptible to erosion by water because composition of the soil are coarse-grained soils with low soil cohesion and little organic matter content (Egashira et al. 1984). Basic index properties of the soil are listed in Table 1. Air-dried soil sample passing 2.0 mm sieve was used and the grain size distribution curve of the soil depicted in Fig. 8c.

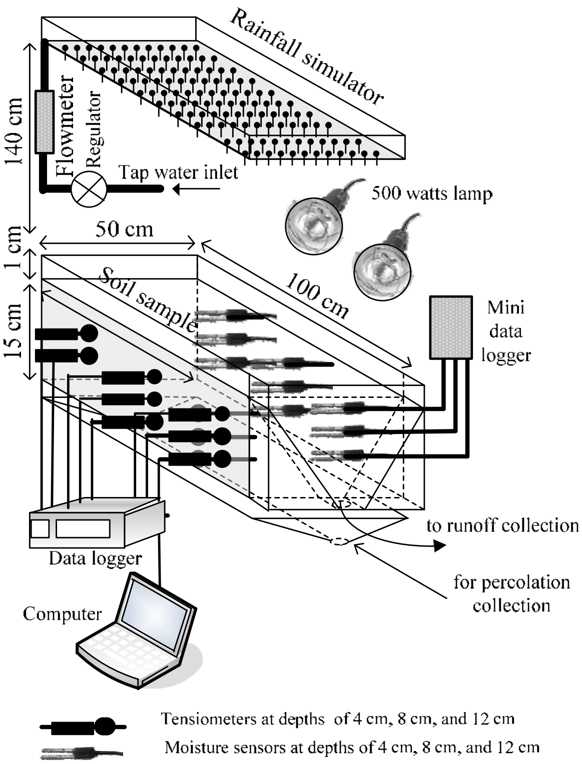


Fig. 3. Schematic diagram of the rainfall experiment setup

Table 1. Basic properties of the Masa soil

Properties	Masa soil
Soil classification (USCS)	SGP
Specific gravity, G_s	2.74
Bulk density before saturation (Mg/m^3)	1.22
Atterberge’s limit test	
Liquid limit (%)	30.23
Plastic limit (%)	24.96
Plasticity index (%)	5.27
Organic matter content (OMC) (%)	2.78
Saturated permeability (m/s)	2.19×10^{-5}

The sample soil is classified as a poorly-graded soil with a percentage of sand (JIS A 1204/JGS 0131) of 96%, of which 32%, 30%, and 34% are coarse-grained sand (0.850-2.0 mm), medium-grained sand (0.25-0.850 mm) and fine grained sand (0.075-0.250 mm), respectively. Silt (0.005-0.075mm) and clay (<0.005 mm) are accounted for 3% and 1%, respectively. Coefficient of uniformity (C_u) and coefficient of curvature (C_c) are 8.75 and 0.25, respectively. Air-dried soil sample was compacted by self-consolidation from water drain by gravity after saturation. Saturation was carried out by gravity-fed water supply using a tap water through a tube connecting the bottom of the soil box with 10 cm height of pore water level to enhance moisture distribution and bonding of soil.

2.3. Rainfall-induced soil erosion (RISE) experiments

Rainfall-induced soil erosion (RISE) experiment consists of a rainfall simulator, a soil box, and a support frame. Rainfall simulators are widely used device to investigate the process of soil erosion and surface hydrology. In this study, a dripping-type rainfall simulator capable of forming a uniform waterdrop size was used. The simulator consists of 396 numbers of hypodermic needles with inner diameter 1.0 mm, spacing at 30 mm and maximum drop size of 3.00 mm in diameter. Artificial rain using tap water was dropped at a height of 1.40 m above the soil surface. A soil box of size of 100 cm length, 50 cm width and 15 cm thickness with a perforated base was tilted at 5 degrees (9% slope). The set-up of the RISE experiments is shown in Fig. 3.

Runoff was collected at 1-minute interval for the duration of 60 minutes. Aluminum containers derived from discarded soft drink cans were used as sampling collectors. The collected runoff was oven dried at 105ºC for measuring amount of soil solid. Eight numbers of small tensiometer (UNSUC model from Sankei Rika Company) were installed below soil surface for measuring soil suction at depths of 4 cm, 8 cm and 12 cm. The tensiometers were wired to a data logger (TDS-302 model from Tokyo Sooki Kenkyujo Company) for recording and monitoring soil suction over time. Nine numbers of volumetric water content sensors (EC5 moisture sensor from Decagon Company) were installed at the opposite side of the soil box with the same depths and locations as those of the tensiometers. The moisture sensors were connected to a mini A3 battery-powered data logger for storing data.

2.4. Determination of soil hydro-mechanical properties

Soil water retention curve (SWRC) of a soil or a material represents the amount of water holding in its pores under stress conditions (e.g. soil suction). Determining SWRC is a cumbersome process and requires tedious handling, high cost equipment, quality technicality and monitoring. Fine soils with high contents of silt and clay exhibits a high suction range that requires a special apparatus for measuring the high suction. A compact high speed refrigerated centrifuge (6500 model from Kubota corp.) was used in this study because the SWRC is obtained with short time operation. The device is capable of inducing suction in the soil specimen up to 2000 kPa. Suction conversion in centrifuge device was obtained by the equation from Gardner (Gardner, 1937) (2). The equation from van Genuchten (1980) (3) was used to predict SWRC beyond measured data.

$$\psi = \frac{\rho\omega^2}{2g}\left(r^2{}_2 - r^2{}_1\right) \quad (2)$$

Where ψ is suction (kPa), r_1 is radial distance to the free water surface (cm), r_2 is radial distance to the midpoint of the soil specimen (cm), ω is angular velocity (rad/s), ρ is density of the pore fluid (g/cm^3), g is a gravitational acceleration (981 cm/s^2)

$$\theta = \theta_r + \left(\theta_s - \theta_r\right)\left[1 + \left(\alpha h\right)^n\right]^{-m} \quad (3)$$

Where θ is the volumetric water content, h is the water pressure (kPa), θ_s and θ_r are the saturated and the residual volumetric water contents, α, n and m are empirical parameters.

In general, permeability function of unsaturated soils can be estimated from empirical equations, macroscopic models and statistical models (Leong & Rahardjo, 1997). Due to rigorous mathematical derivation, statistical models perform the best when no database for permeability function of a local soil is available, otherwise, the empirical equations are recommended. Permeability function of the Masa soil was indirectly derived from the statistical model proposed by Childs & Collis-George (1950). The model was selected because only data from SWRC and saturated permeability, k_s, can be incorporated to correlate the coefficient of permeability and soil suction. The model has been employed successfully with high accuracy to obtain the permeability function of natural soils. The technique for obtaining the permeability functions of unsaturated soils using the model is described by Fredlund & Rahardjo (1993).

2.5. Soil erodibility and sediment sizes analysis.

A one dimensional (1D) waterdrop test was employed to study soil resistance against impact force of a falling waterdrop. The waterdrop test uses a hypodermic needle (1.0 mm inner diameter with 3.0 mm drop size diameter) to generate artificial rainfall with intensity of 70 mm/h, similar to the intensity used in the RISE experiments. A stainless steel ring (50 mm inner diameter and 50 mm height) was used to extract soil samples from the soil box of the RISE experiment after the end of the experiments. The soil specimens were then transferred to a small centrifuge device for determining soil-water retention curve. After an initial soil condition induced by the centrifuge device was established, the specimen was then individually moved to the 1D waterdrop test. Soil erodibility can then be assessed in terms of amount of soil loss under varying impact forces and soil suction. 5 minute test was selected due to observed response of results of tensiometers installed nearest to the soil surface in the RISE experiment. Soil detachment due to the impact of falling waterdrops was collected and oven dried at 105°C to obtain dried soil solid mass. The dried soil mass was then analyzed by a laser diffraction (LD) particle size analyzer (SALD 3100 model from Shimadzu Company) for the outflow sediment size distribution in the range of 0.05-3000 μm (Yasufuku et al. 2015). From the RISE experiment and 1D waterdrop test, runoff was collected and dried in oven at 105°C. The dried mass of the eroded soil was mixed with 10 ml of distilled water. 100 μl of volume of suspended sediments were pumped by using a pipette method before operating the LD device.

3. Results

3.1. Dynamic properties of a falling waterdrop for 1D waterdrop test

Extensive soil erosion researches have been conducted to study the erosive and destructive forces of rainfall to soil surface. It was recognized that the capacity of the rain to detach and transport soil particles is a function of rainfall energy or rainfall erosivity. Erosivity of the waterdrop is represented by impact force, kinetic energy ($0.5\ mv^2$) and momentum (mv); where m is the mass and v is the velocity of an impacting drop. Fig. 4 shows the result of the impact force converted from a falling waterdrop of 3.0 mm in diameter and 0.02 g dropped from 1.40 m at a constant rate of 2.5 mL/min. The output from the strain gauge sensor was captured at a rate of 5 μm at a frequency of 10 kHz. The rise time of the signal to the peak can be reliably used to derive the drop momentum, kinetic energy, velocity and impact force. Numerous studies have derived the drop impact force using piezoelectric impact force sensors equipped with signal amplifier and a digital oscilloscope that converts drop impact signal at high frequency and records time in microsecond. Some researchers (Hinkle, 1989; Nearing et al. 1986) employed empirically based impact sensors to indirectly obtain output signal that varies with drop sizes and velocities to study waterdrop force, kinetic energy and momentum.

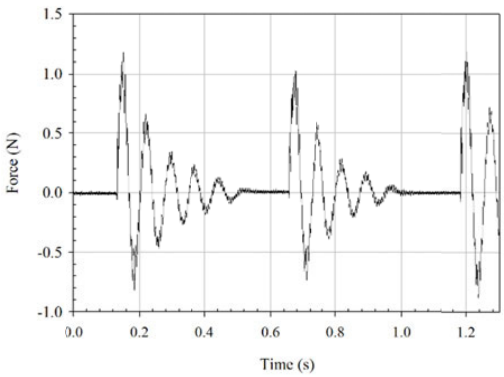


Fig. 4. Derivation of impact force from output signal

3.2. Monitoring of unsaturated soil conditions during rainfall

Soil suction contributes to soil resistance against raindrop impact and shear stress of flow by altering shear strength, soil stability, cohesion, permeability, soil structure, and infiltration. Fig. 5a and Fig. 5b show the responses of soil moisture and suction, respectively, at different depths at 4 cm, 8 cm and 12 cm at the center section of soil slope. Results showed good response between the changes in soil moisture and soil suction. Increase in dryness reduced volumetric water content (VWC) and increased soil suction. The influx of soil moisture at the surface at a wet rate of 70 mm/h rainfall can be observed through the change in VWC. The results also indicate that it took about 5 minutes to cause the soil suction to disappear under the applied rainfall intensity. The difference in the profiles of VWC and soil suction with depths was due to the nonhomogeneous distribution of factors affecting them such as the permeability function (Fig. 6b). In addition, the response time of the volumetric water content for the 4 cm depth changed slightly and the elapsed time from tensiometer responded around 3-5 minutes. It was noted that the saturated volumetric water content (0.417 m^3/m^3) could not be fully reached during 60 minutes of the rainfall event. Therefore, it was clear that the soil surface was still in transition from unsaturated to saturated conditions.

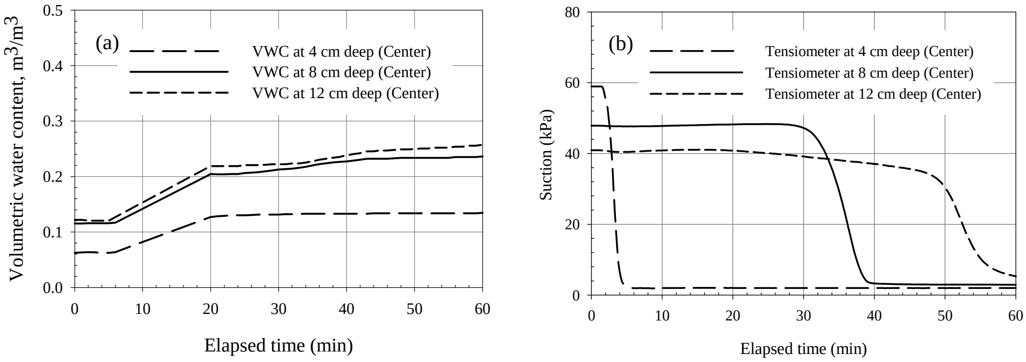


Fig. 5. Unsaturated state of soil under rainfall intensity of 70 mm/h: (a) variation of soil moisture, (b) variation of soil suction

Fig. 6 shows the result of the hydro-mechanical properties of the Masa residual soil. The measured data for water retention curve was obtained from the centrifuge device. The complete variation of soil moisture across higher suction values can be predicted by fitting the measured data using the van Genuchten's equation (3). Results indicate that the soil has low capacity to retain water because water in the soil pore can drain at relatively low suction (i.e., 0.01 kPa). Variation of soil moisture influences the rate of water filtration and permeability. Decrease in the soil moisture, as described by decrease in the VWC or reduction in the soil suction, the coefficient of permeability was also synchronously decreased as shown in Fig. 6b. As the soil permeability decreased, it is expected that the soil surface becomes consolidated and denser, affecting impact force of rainfall, runoff and soil loss.

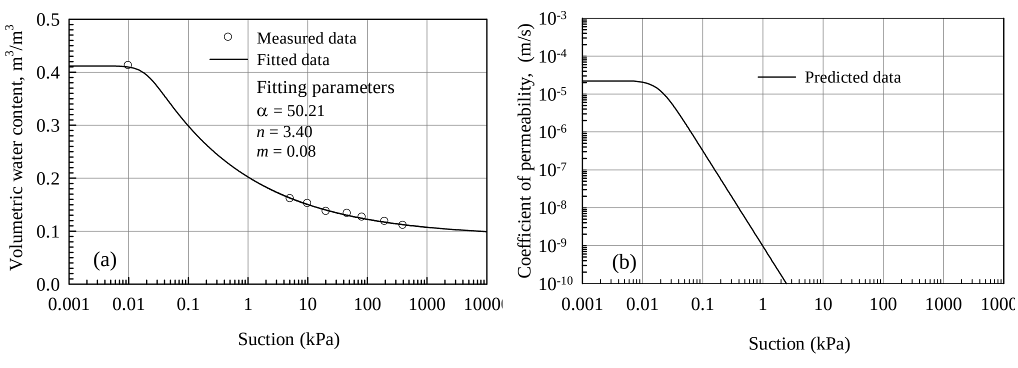


Fig. 6. Unsaturated soil properties: (a) soil-water retention curve, (b) predicted hydraulic conductivity

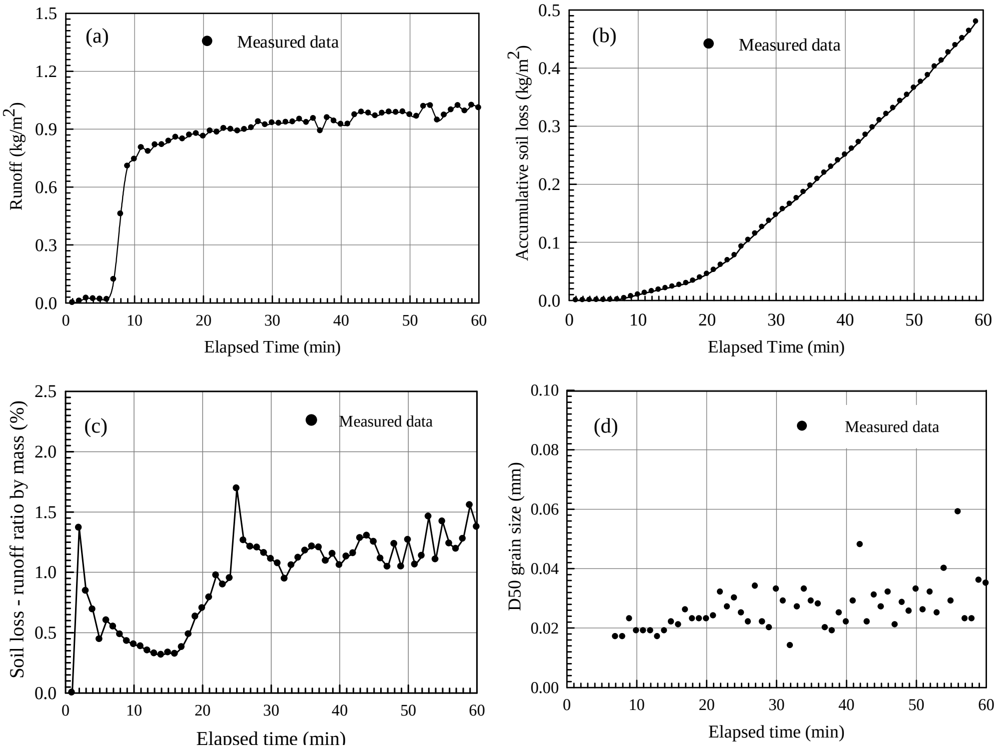


Fig 7. Runoff and soil loss under rainfall intensity of 70 mm/h: (a) runoff generation, (b) soil loss concentration, (c) accumulative soil loss per area and (d) Median sizes (D50) of suspended sediment

3.3. Soil loss and outflow sediment size distributions

3.3.1. Soil loss and outflow sediment size distributions from the RISE experiments

Fig. 7 shows the results of soil erosion under rainfall intensity of 70 mm/h. Fig. 7a show the runoff generation with respect to time. After a rapid rise of the runoff about 10 minutes after rainfall applied, there was a slight change in runoff rate. Fig. 7b shows the rate of the soil loss-runoff ratio. At the beginning, there is high soil loss and subsequently soil loss-runoff ratio showed a little fluctuation. Fig. 7c shows the accumulative soil loss per unit area. After 20 minutes of applied rainfall, it was observed that the soil lost at constant amount, which can be observed by the degree of linearity in the graph of the accumulative soil loss. Fig. 7d shows the results of median sizes (D50) of the suspended sediments of the soil loss from the RISE experiments. The results showed that the D50 of about 0.03 mm was average median sizes of the suspended sediments from the downstream of the soil box.

3.3.2. Soil loss and size distributions of the outflow sediment from the 1D waterdrop test

Fig. 8 shows the result of the grain size distribution of the detached particles due to 1D waterdrop test. Fig. 8a shows the total soil loss from 1D waterdrop test for 5 minutes. It found that under a single waterdrop test and controlled soil suction, small sized soil particles (sizes less than 0.1 mm) were detached from the soil surface. Results from a laser diffraction device revealed that the median sizes of the detached soil under a single waterdrop test was found to be within 0.01-0.05 mm in diameter (Fig. 8b). There was a difference in sizes of the detached particles due to varying initial soil suctions. At near saturation or zero suction, fine particles of D50 size were 0.013 mm. The maximum size of D50 for the detached particles was 0.047 mm occurred when 5 kPa of soil suction presented before the waterdrop test. For the range of suction of 40-400 kPa, D50 of detached soils increases slightly with the increase in soil suctions (Fig. 8b).

4. Discussion

The soil loss or sizes of detached particles are largely dependent on rainfall energy, soil properties, and surface flow. Nearing (1987) proposed a theoretical method for assessing the relative effect of soil suction, porosity and saturation on impact pressures from waterdrop on soil surfaces. It was found that the soil surface low soil suction was highly unstable under raindrop impact and the soil surface will be subject to liquefaction. In comparison to the rigid soil surface, the impact force from rainfall is higher than the saturated soil surface due to protection layer of water, which absorbed the energy from rainfall. This result is similar to the result shown in Fig. 8d. Primary soil loss and sediment sizes discharge for the Masa soil for saturated condition under 1D test is primarily dependent on the surface soil conditions such as initially saturated or unsaturated condition. It was found that initially saturated soil specimen produced the finest discharged sediment sizes for the Masa soil. Subsequently, the sizes of outflow sediments are usually found to be finer particles, which are governed by raindrop and flow detachment (Fig. 7c). With unsaturated soil surface condition, the primarily sediments discharge is of coarser particles (Fig. 8c).

When no runoff was generated, soil suction was dominant and did not abruptly disappear as rainfall continued (Fig. 5b). In this stage, soil suction exists in the soil and affects rainfall infiltration. The rate of water percolates into the soil controls by gravity and soil suction. The higher the soil suction will reduce the soil permeability and increase the runoff. Whereas process of soil erosion when rainfall and runoff are presented, soil loss and outflow sediment size distribution are more complex. In this stage, the presence of flow depth reduces the impact from raindrops and it is required the higher rainfall energy to extract soils beneath the layer of flowing water. A limiting moisture content is the important control for runoff production on many soils might

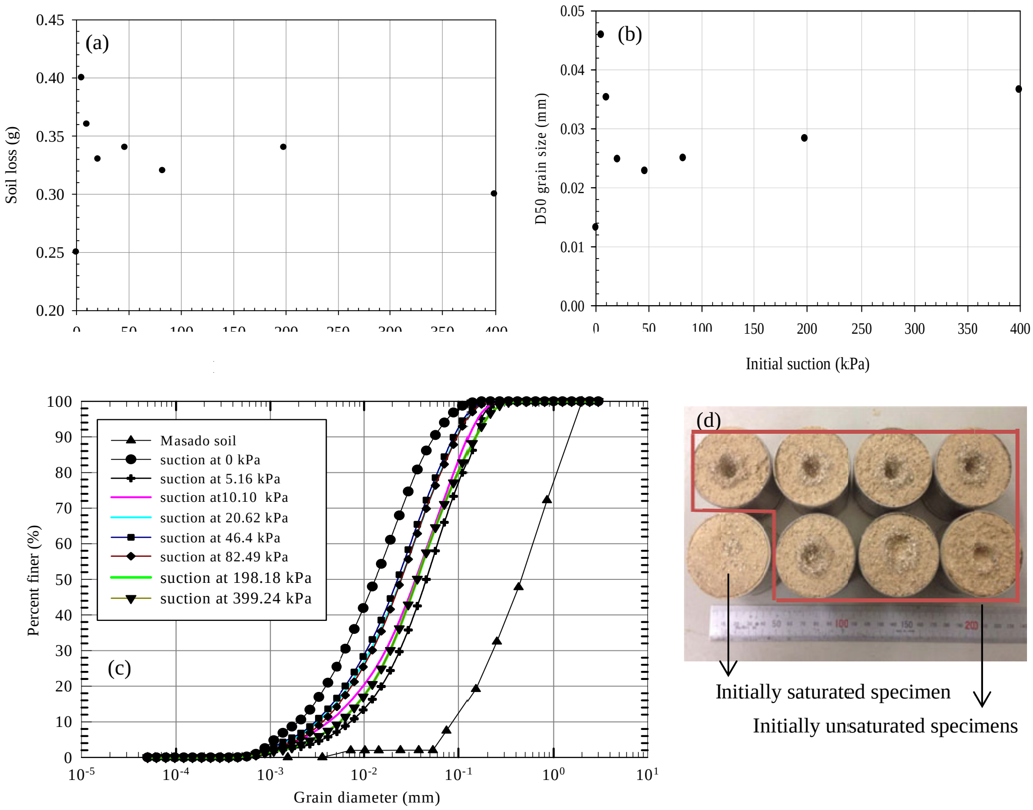


Fig. 8. Effect of waterdrops on size distribution of surface soil: (a) soil loss due to impact force of waterdrop, (b) D50 grain size of the suspended sediments discharged, (c) grain size distributions of the soil sample and detached particles due to 1D waterdrop test, and (d) surface condition after 1D waterdrop test.

5. Conclusions

This research was focused on the preliminary laboratory investigation of rainfall-induced soil erosion (RISE) experiments and the outflow sediment size characteristics of a Masa residual soil. A portable developed device is potentially an alternative for measuring the dynamic properties (kinetic energy, velocity, momentum, impact force) of a falling waterdrop. Small centrifuge device was effective to obtain the variation of soil moisture contents and suction. The device can reproduce uniform initial conditions in terms of soil moisture and suction for 1D waterdrop test. The use of 1D waterdrop with the laser diffraction device was useful method for soil erodibility study under varying initial soil conditions. Median sizes (D50) of suspended sediment and eroded soil from soil erosion experiment and 1D waterdrop test was found to be within 0.01-0.05 mm in diameter.

This research was focused on a single rainfall intensity or rainfall kinetic energy with a single slope gradient and a single soil type. Variability of rainfall kinetic energies need to be compared with natural rainfall kinetic energy for assessing the effect of rainfall energies to soil detachment and sediment outflow of different soils. The use of the RISE experiments and the 1D waterdrop tests for soil erodibility study will further be carried out for soil erosion hazard and mapping study, and potentially leading to the soil erosion prediction using physical parameters of rainfall, soils, and hydraulic flow.

Acknowledgments

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