Water Drop Impact Angle and Soybean Protein Amendment Effects on Soil Detachment

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ABSTRACT

To improve soil erosion prediction technology, the mechanics of each erosion process must be understood sufficiently to predict soil loss on an event basis. The mechanics of the initial erosion process, soil detachment caused by falling raindrops, requires greater understanding to improve mechanics-based prediction. This laboratory study addressed the effect of soil shear strength and raindrop impact angle on soil detachment. Loess (fine-silty, mixed, superactive, mesic Typic Hapludoll) and glacial till (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) A and C horizon soil materials were used. To vary soil shear strength, soybean protein material was added to each soil material at concentrations of 0.0, 0.5, and 1.0% by weight. Soil shear strength and soil detachment were measured on preformed soil cores. Soil detachment tests were performed at water drop impact angles of 90, 80, 70, and 60°. Soil strength increased and detachment decreased with increasing soybean protein concentrations. Shear strength of the loess C horizon increased 0.61 to 1.85 Mg m^{-2}, while that of the till C horizon material increased 0.57 to 0.98 Mg m^{-2} with addition of 1% soybean protein. A 1%–soybean protein addition reduced soil detachment 26% compared with unamended soil. Significant soil detachment interactions existed between waterdrop impact angle and the other variables. These interactions were due to different mechanical behavior of the soils and changing strength caused by soybean protein additions. Interactions observed are explained based on differences in the lateral jet for varying impact angles and for elastic vs. inelastic impacts.

ACCELERATED SOIL EROSION is a major agricultural production and environmental concern. Erosion and subsequent soil losses to rivers and streams cause major agricultural and environmental problems, such as loss of fertility and increased sedimentation. Annual damage caused by erosion alone in the United States has been estimated at $6 billion (Clark et al., 1985).

Interrill erosion is initiated by the soil detachment process (Ellison, 1947). This process is primarily caused by raindrop impact (Sharma et al., 1993; Young and Wiersma, 1973). Soil particles are detached from the soil surface if the raindrop impact force exceeds particle resistance to movement. Resistance to particle detachment is related to soil shear strength. Studies consistently indicate that as soil shear strength increases, the quantity of soil detached from a single water drop impact decreases (Cruse and Larson, 1977; Al-Durrah and Bradford, 1982). A water drop impact angle of 90°, with respect to the soil surface, was used in these studies. Water drop angles other than 90° were not found in the literature for single drop studies. As slope increases under multiple drop rainfall, total splash detachment and the proportion of downslope splash to upslope splash increases (Quansah, 1981; Grosh and Jarrett, 1994; Young and Wiersma, 1973; Bryan, 1979; Ellison, 1947; Ekern, 1950).

During most rainfall, raindrop impact angle varies considerably and will depend on wind velocity and soil topography. Intuitively, impact angle will seldom equal 90°, as was the case in most of the controlled studies that relate soil detachment quantity to soil shear strength. The force component acting horizontally along the soil surface will increase and the vertical force component will decrease as impact angle decreases. The relative importance of these two force components in soil detachment is yet undetermined, but will need to be understood to predict erosion on the basis of detachment and transport mechanics.

Soil application of organic polymers has reduced erosion in various studies (Kijne, 1967; Lentz and Sojka, 1994; Zhang and Miller, 1996). The mode of action seems similar to that of soil organic matter in stabilizing soil against erosion. Long chain organic polymers increase soil shear strength and consequently reduce soil detachment (Cruse and Larson, 1977).

Organic polymer products are often derived from petroleum, a nonrenewable resource. Soybean protein has features similar to the petroleum-derived polymers and is also renewable. While similar agricultural products have been used as binders or adhesives for various industrial purposes (Myers, 1993), no studies have evaluated soybean protein impacts on soil mechanical and erosive properties. Furthermore, studies addressing polymer impacts on soil erosion have predominantly avoided using C horizon (very low organic matter content) material, a soil material likely to be exposed under highly eroded or construction conditions. Should a product such as soybean protein show effectiveness in minimizing erosion, likely targets for use of such a renewable polymer could be construction sites and similar areas that tend to be relatively small, highly erosive, and require temporary, but intensive, management for soil conservation. The objectives of this study were to identify the effect of (i) water drop impact angle on soil detachment for four different soil materials with a range of soil shear strengths and (ii) soybean protein amendment on soil shear strength and soil detachment from water drop impact.

MATERIALS AND METHODS

The A and C horizon of Monona (fine-silty, mixed, superactive, mesic Typic Hapludoll) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) soils were used in this

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Abbreviations: SPI, soybean protein isolate.

Table 1. Selected soil properties.

Soils (horizon)	Organic matter	pH	CEC	Exchangeable cations Ca	Mg	K	Na	Sand	Silt	Clay
	%		cmol kg^{-1}	% base saturation				%		
Monona (A) loess	**3.9**	**6.2**	**20.5**	**65.7**	**23.2**	**6.0**	**0.2**	**5.1**	**68.7**	**26.2**
Nicollet (A) glacial till	**4.2**	**7.0**	**22.2**	**74.4**	**24.1**	**1.2**	**0.3**	**37.7**	**38.1**	**24.2**
Monona (C) loess	**1.1**	**7.2**	**18.8**	**63.9**	**33.7**	**1.6**	**0.8**	**8.0**	**71.4**	**20.6**
Nicollet (C) glacial till	**0.6**	**8.3**	**23.2**	**84.2**	**14.6**	**0.7**	**0.6**	**50.9**	**33.5**	**15.6**

study. The Monona developed in loess and Nicollet developed in glacial till parent materials. Selected soil physical and chemical properties are given in Table 1. Particle-size distribution was determined by the pipette method (Day, 1965). Organic matter percentage was analyzed by the Walkley-Black method (Schulte, 1988). Soil pH was determined using the procedures of Eckert (1988) and a pH meter. Cation-exchange capacity and exchangeable cations were determined by the summation method (Brown and Warncke, 1988).

The soybean material used was Arpro-1100 soybean protein isolate (SPI; Archer Daniels Midland Co., Decatur, IL).[1] The material standard specifies that it contains >90% protein. Making a 10% solution involved slowly adding 100 g of SPI to 900 g of 90°C distilled water while stirring. After several minutes, 10.5 mL of 50% (v/v) NaOH solution was slowly added to bring the pH of the solution to ≈10. Raising the pH allowed the protein to better dissolve and mix with the water. The solutions were applied to soil using a fine-mist sprayer as described below.

Soil was sieved to obtain material <0.5 mm in diameter and then moistened uniformly with distilled water from a fine-mist spray bottle. Soil requiring SPI treatments was sprayed with a 10% solution of SPI to obtain the appropriate SPI concentration: 0.0, 0.5, or 1.0% by weight. Soil and soil–SPI mixtures having 10 to 15% gravimetric water contents were used to prepare soil cores 0.03 m long and 0.01 m in diameter. These were prepared for soil shear strength measurements, and soil cores 0.01 m long and 0.02 m in diameter were prepared for soil detachment tests. Both cores were prepared using phenolic plastic resin-lined brass cylinders. The phenolic plastic resin lining helped reduce soil–cylinder wall friction so as to optimize bulk density uniformity throughout the core. Soil bulk density for the soil shear strength test was to mimic that for the detachment test. Even though the brass cylinder was lined with a lower-friction resin, nonuniformity in bulk density existed in the longer and smaller-diameter shear strength core; that is, the bulk density of the core ends was higher than that in the core middle. This was determined by sectioning the cores axially into three segments. Bulk density was determined by measuring volume (dimensions determined with a micrometer) and oven-dry weight. Preliminary trials indicated that placing sufficient soil in the cylinder to develop an average core bulk density of 1.40 Mg m^{-3} resulted in a bulk density of 1.32 Mg m^{-3} in the middle of the core. This is the zone of shear plane development during the shear strength test. To produce these cores, soil was placed in the cylinder and compressed from above and below at a rate of 0.005 m min^{-1} with an Instron Universal Testing Machine (Grove City, PA). The detachment cores were prepared identically to those for the shear strength, except sufficient soil was added for a bulk density of 1.32 Mg m^{-3}, that which existed in the center of the shear strength cores. Greater uniformity in the detachment cores existed due to the shorter length and larger diameter design.

The prepared cores were placed on a tension table (Cruse and Larson, 1977) for wetting. The hanging water column of the tension table was adjusted so that the core center, upon matric potential equilibration, would be −0.5 kPa for 1 h. After 1 h, the matric potential applied to the shear strength cores was adjusted so that the core center would have a matric potential of either −0.5, −1.0, or −1.5 kPa. This allowed determination of soil shear strength characteristics, as discussed below. Because all detachment tests were conducted at matric potentials of −0.5 kPa, the detachment cores remained at the −0.5 kPa setting. The cores remained at the testing matric potential for 10 h to ensure equilibrium conditions existed.

Triaxial Compression Test

Bishop and Henkel (1962) discussed the unconfined-drained triaxial compression test used in this study. The soil cores remained on the tension table during the compression test to help ensure that matric potential in the soil core remained constant during the test. The minor principal stress within a core during the test was assumed to equal the absolute value of the matric potential imposed by the hanging water column on the tension table (Childs, 1955; Towner, 1961).

A slow rate of major principal stress application was used (0.0002 m min^{-1}) to ensure minimal matric potential changes in the core during load application. A pressure transducer continuously recorded stress applied to the core during the compression test. Major principal stress increased slowly prior to soil failure, after which stress decreased. The maximum applied stress was assumed to coincide with soil failure. Major principal stress at failure is given by:

$$\sigma_1 = \psi + (s + 0.5M_s)/0.000078 \text{ m}^2 \qquad [1]$$

where σ_1 is the major principal stress (Mg m^{-2}), ψ is the matric potential at the top of the core (kPa), s is the mechanical stress applied by the loading mechanism (Mg m^{-2}), M_s is the mass of soil in the core (Mg), and 0.000078 m^2 is the cross-sectional area of the soil core.

Compression tests for each combination of SPI and soil material treatment were conducted at matric potentials of −0.5, −1.0, and −1.5 kPa. Each compression test was replicated three times. Mohr Coulomb failure envelopes were developed from the imposed minor principal stresses and the observed major principal stress. The major principal stress used was the average value of σ_1 for the three replications of each treatment combination.

The experimental design was a split-plot with the three matric potentials as the whole plots and the 12 combinations of soil material and SPI treatment as the split plots. Three replications were used. Data were analyzed with analysis of variance, and orthogonal contrasts were done to evaluate interactions and main effects.

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[1] Mention of trade name does not imply endorsement by Iowa State University

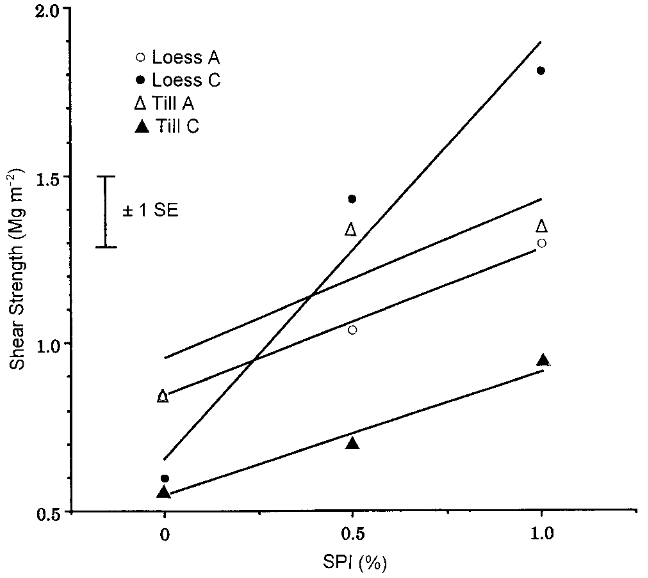

Fig. 1. Shear strength vs. soybean protein concentration for A and C horizons of both loess and till soil materials, averaged across all matric potentials. Lines represent regression lines fit to each of the four soil types.

Soil Detachment Tests

A raindrop tower designed after that of Cruse and Larson (1977) was constructed so that a single 0.0064-m-diameter water drop fell 2.0 m through a 0.07-m-diameter acrylic tube. The acrylic tube helped minimize water drop drift, thereby helping to ensure that the drop hit the soil core placed below the tower. The velocity of water drops at impact was ≈5.9 m s^{-1} (Laws, 1941).

During the detachment test the soil core remained on the tension table. Aluminum cupcake tins with a circular opening cut slightly larger than the detachment cores (approximately 0.022 m) were used to collect the soil detached by water drop impact. Prior to the test, the tins were oven-dried, cooled in a desiccator, and weighed on an analytical balance to 1×10^{-4} g. The cupcake tins were placed over the cores such that the core protruded through the circular opening in the tin bottom. The cupcake tin walls, thus, surrounded the soil core. The tin walls extended above the cores ≈5 cm.

One water drop was allowed to fall onto each soil core. After water drop impact, the tin was removed, oven-dried, cooled in a desiccator, and weighed. To accommodate the effect of impact angle on detachment, one end of the tension table was raised immediately before the test. Water drop impact angles (the angle from the soil surface) used in this experiment were 90, 80, 70, and 60°. A split-plot design was used with the four impact angles as whole plots and the 12 combinations of soil material and SPI treatments as split plots. Three replications were used. Analysis of variance and orthogonal contrasts were used to evaluate the interactions and main effects of the three factors.

RESULTS AND DISCUSSION

Soil Shear Strength

Analysis of variance of the shear strength data revealed that matric potential was not involved in any interactions with soil type, horizon, and rate of SPI ($P > 0.09$) and that there was a strong, positive, and linear relationship between matric potential and shear strength ($P < 0.001$) (data not shown). There was a substantial three-way interaction among the other factors: soil type, horizon, and SPI rate ($P < 0.001$). As shown in Fig. 1, there was generally a moderately strong linear relationship between amount of SPI and average shear strength for each soil type and horizon combination, but the slopes of the linear lines representing the four combinations were quite different ($P = 0.002$). This is responsible for most of the interaction, although there was also a noticeable nonlinear component of the interaction ($P = 0.042$), which can be seen by noting the very linear relationship for till C and loess A, a somewhat curvilinear relationship for loess C, and a weak relationship for till A. Despite the interaction, as SPI rates increased, soil strength also increased, except for the highest level of SPI for the till A horizon material.

Table 2. Average soil shear strength for loess and till A and C horizons, averaged across all matric potentials and soybean protein rates.†

	Shear strength	
Soil material	**A horizon**	**C horizon**
	Mg m^{-2}	
Monona loess	1.06	1.28
Nicollet till	1.17	0.74

† Standard error = 0.058 Mg m^{-2}.

There was a strong soil type × horizon interaction ($P < 0.001$) with average shear strength for the till A, till being somewhat greater than for the loess A, while the average shear strength of the till C was much less than the loess C (Table 2). For both comparisons, the material with the highest organic matter content had the highest strength, even though organic matter content differences were quite small (see Fig. 1, 0% SPI treatment).

Soil Detachment

Soil detachment for loess (average = 0.00860 g) was clearly smaller than for till (average = 0.0147 g) ($P < 0.001$). Because of this and many strong interactions of soil type with the other factors ($P < 0.001$), the data for the soils were analyzed separately to obtain a clearer picture of the response for each soil.

For the loess soil there was a three-way interaction between SPI rate, horizon, and impact angle ($P = 0.036$). A graph of the data (Fig. 2) clearly showed that the interaction was due to the marked difference in impact angle influence on detachment for the zero rate of SPI vs. this relationship for the other treatment combinations. For the C horizon with 0.0% SPI, there was a strong increase in detachment with decreasing impact angle. For the A horizon with 0.0% SPI, there seemed to be no change in detachment with changing impact angle, while the other four combinations showed a general increase in detachment with increasing impact angle. After removing the 0.0% SPI data, an analysis of variance of the detachment data revealed no apparent rate × horizon × impact angle interaction ($P = 0.47$). Although, on average, detachment for the 0.5 and 1.0%

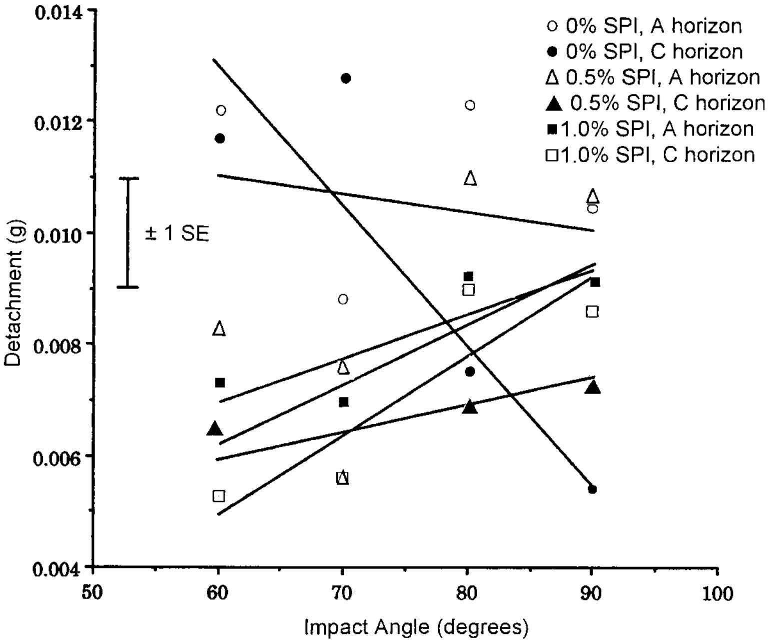

Fig. 2. Detachment vs. impact angle for combinations of soybean protein treatments on loess A and C horizons. Lines represent regression lines fit to each of the six treatments.

SPI rate samples were almost identical at each impact angle, the horizons behaved very differently. For 0.5% SPI the A horizon detachment was much higher than the C horizon detachment at each impact angle, but for 1.0% SPI the A and C horizons had more similar detachments, particularly at the two highest impact angles.

For the till soils, analysis of variance revealed that SPI rate was not involved in any interactions with impact angle or layer ($P > 0.67$) and that there was a strong, negative, and linear relationship between detachment and SPI rate ($P < 0.001$). Detachment values were 0.0133 g for 0.0% SPI, 0.00117 g for 0.5% SPI, and 0.0099 g for 1.0% SPI, with a standard error of 0.0005 g. There was an interaction between impact angle and horizon (Table 3). The interaction was due to the difference in the slope of linear lines that could be fit to the A and C horizon data ($P = 0.013$). For the C horizon sample there was a notable increase in detachment with increasing impact angle, while for the A horizon there was only a small increase in detachment with increasing impact angle.

Strength vs. Detachment

The relationship between shear strength and detachment was evaluated by comparing the shear strength for the 12 combinations of soil type and SPI rate, averaged across the four impact angles, with the detachment for the same twelve. The 0.0% SPI loess C sample was eliminated from this analysis (see discussion below). The correlation of the two characteristics was strongly negative ($r = -0.80$, $P = 0.031$).

A dominant factor causing selected interactions was the behavior of the loess C material. A unique detachment pattern for the loess C material was observed for impact angles of 90 and 80° (Fig. 2). At these impact angles, soil detachment increased with increasing SPI rates. The results are contrary to those observed for other soil materials in this study and also opposite of results from other studies that used polymers to reduce soil detachment or erosion rates (Cruse and Larson, 1977; Lentz and Sojka, 1994). Two factors affecting soil transport from the impact zone seem critical to explaining these contradictory results: (i) elasticity of waterdrop–soil collision and this effect on waterdrop impact lateral jet (Huang et al., 1983) and (ii) influence of water impact angle on waterdrop impact lateral jet. The 0.0% SPI loess C material had the lowest strength characteristics. Visual inspection of the water drop impact zone indicated that an elastic impact occurred with 0.0% SPI loess C; that is, the impact zone took the form of an indented surface with a bulging soil ring surrounding the indentation. Greater visual change occurred on this soil material than on other soils. However, soil was not dislodged by water drop impact and projected onto the collection tin.

The lateral jet of water resulting from water drop impact (Huang et al., 1983) will be greater on rigid surfaces and for lower impact angles than that lateral jet or splash occurring on a soft, elastic surface with perpendicular impact (Mutchler, 1967). Mutchler (1967) showed that for waterdrops falling on water, an elastic collision, water is lifted in a cylindrical shape around the point of impact with little if any lateral jetting. Energy in the falling water drop that is dissipated in an elastic collision as observed for the loess C material will result

Table 3. Soil detachment from till A and C horizon soil material for different impact angles, averaged across all soybean protein rates.†

	Soil detachment			
Horizon	60°	70°	80°	90°
	g			
A	0.0117	0.0130	0.0143	0.0123
C	0.0122	0.0159	0.0189	0.0191

† Standard error = 0.0014.

in sheared soil but low lateral jet forces. Little measured detachment results. As the raindrop impact angle decreases, greater force components act parallel to the surface and lower force components act perpendicular to the surface. With increasing SPI rates, soil strength increased, which will probably reduce the elasticity of the water drop impact. This resulted in dislodged particles being transported to the collection pan due to increased lateral jetting.

The apparent increased sensitivity of detachment to shear strength at lower impact angles probably results from a lateral jet more efficient at transporting detached particles from the point of impact. Stronger evidence of this concept results from observations with the loess C material. As mentioned above, the detachment pattern as influenced by SPI additions and soil strength measures was not consistent with recognized principles until impact angles were 70° and below. At these angles the lateral jet velocity probably increased so that dislodged particles were transported away from the point of impact to the collection tin even with the weakest soil. With the weak loess soil and perpendicular impacts, lateral jet development, rather than shear strength controlled measured detachment.

It is important to recognize that the 0.0% SPI till C horizon had a shear strength similar to that of the loess C horizon (Fig. 1), yet this material responded to SPI and impact angle treatments much differently than did the loess C material. The till impact zone had little evidence of an elastic impact and little evidence of lateral jet limiting detachment values. This suggests shear strength influences on detachment may vary between contrasting materials and that factors influencing impact hydraulic processes (Froese and Cruse, 1997) and soil elastic behavior must be considered.

CONCLUSIONS

Water drop impact angle influenced measured soil detachment through impact angle effect on lateral jet development. This is particularly important with weak soils for which an elastic, vs. inelastic, collision occurs between the water drop and soil material. Additions of soybean protein to remolded soil resulted in stronger soils, which increased resistance to soil detachment from waterdrop impact. As resistance to detachment increased, increasing impact angle caused a general increase in detachment.

This study suggests soybean-derived products may hold potential for temporary soil stabilization, although the product used in this study was not developed for this purpose. It is conceivable that research development in this area could lead to a product significantly superior to that used here.

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