Frequency of freeze-thaw cycles, bulk density and saturation effects on soil surface shear and aggregate stability in resisting water erosion

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Asare, S.N., Rudra, R.P., Dickinson, W.T. and Wall, G.J. 1997. **Frequency of freeze-thaw cycles, bulk density and saturation effects on soil surface shear and aggregate stability in resisting water erosion**. Can. Agric. Eng. **39**:273-279. Soil erodibility is the soil's inherent resistance to detachment and transportation by raindrops and runoff energy and is reflected in relative indices. Some of the factors from which these indices are calculated are surface shear strength and aggregate stability. These two soil properties were measured on remolded soil cores after subjecting them through a number of freeze-thaw cycles, a phenomenon which has been observed to aggravate stream sediment events in late winter and early spring periods. The three Southern Ontario soil textures chosen for the experiments were a Conestogo silt loam, a Brookston clay, and a Fox loamy sand. The surface shear strength and aggregate stability test was conducted to determine the influence of repeated freeze-thaw cycles on these properties and to incorporate the interactive effect of textural class, bulk density, and saturation on these variables. The mean weight diameter (MWD) method was used as an index to quantify aggregate stability. Surface shear strength was measured with a fall cone apparatus fitted with permanent magnetic suspension. Results of factorial analysis of variance indicate that the means of surface shear strength and aggregate stability proved to be significantly different among soil textural classes and bulk density. Also, the mean surface shear strength also indicated significant differences among the number of freeze-thaw cycles and saturation levels. **Keywords**: erodibility, erosion, freeze-thaw, bulk density, saturation ratio.

L'érodabilité d'un sol est définie comme la résistance naturelle du sol au soulèvement et au transport des particules par les gouttes de pluie et l'énergie du ruissellement, et est exprimée par des indices relatifs.Quelques uns des facteurs à partir desquels on calcule ces indices sont la résistance au cisaillement de la surface et la stabilité des agrégats.Ces deux propriétés des sols ont été mesurées sur des cylindres de sol remanié qui avaient été soumis à plusieurs cycles de gel-dégel, un phénomène qui semble faire augmenter les teneurs en sédiments des cours d'eau, tard durant l'hiver et tôt au printemps. Les trois sols du sud de l'Ontario qui ont été choisis pour les expériences sont un loam silteux Conestogo, une argile Brookston, et un sable loameux Fox. Des mesures de résistance au cisaillement et de stabilité des agrégats ont été faites afin d'évaluer l'influence de cycles répétés de gel-dégel sur ces propriétés, et d'inclure dans ces paramètres les effets interactifs de la classe texturale, de la densité apparente et de la saturation. On a utilisé la méthode des diamètres moyens des particules (DMP) comme indice pour quantifier la stabilité des agrégats. On a mesuré la résistance au cisaillement de la surface avec un pénétromètre à cône pourvu d'une suspension magnétique permanente. Les résultats de l'analyse factorielle de variance montrent que les valeurs moyennes de résistance au cisaillement de la surface et de stabilité des agrégats varient de manière significative selon la classe texturale et la densité apparente des sols. Les valeurs moyennes de résistance au cisaillement de la surface montrent des différences significatives selon le nombre de cycles de gel-dégel et le degré de saturation. **Mots-clés**: érodabilité, érosion, gel-dégel, densité apparente, degré de saturation.

INTRODUCTION

Significant sediment loads are transported by runoff in late winter and early spring periods in humid temperate regions (Dickinson and Wall 1976; Kirby and Mehuys 1987). The erodibility of some soils during these periods is greater than during other times of the year (Mutchler and Carter 1983). The increase in soil erodibility may be related to the occurrence of freeze-thaw temperature cycles, which occur frequently at this time of year and which have been shown to affect the physical characteristics of soils (Edwards 1991; Benoit and Voorhees 1990; Mostaghimi et al. 1988; Bisal and Nielsen 1964).

The impacts of periodic freeze-thaw on soil aggregation and surface shear strength are not well understood, as evidenced by the mixed results from previous studies. Many researchers have shown that freeze-thaw cycles are deleterious to soil structure and tend to reduce aggregation (Edwards 1991; Bisal and Nielsen 1967; Leo 1963). Others have shown that freeze-thaw processes improve physical properties of the soil (Gardner 1945; Sillanpaa and Webber 1961). Research has also demonstrated that the effect of freeze-thaw cycling on the physical properties of the soil depends on soil texture, compaction, water content, the rates of freezing and thawing, and biological factors (Benoit and Voorhees 1990; Mostaghimi et al. 1988; Chepil 1954).

Aggregate stability of a soil, which is a measure of the soil's resistance to change in pore structure, has been recognized as an important physical property governing soil resistance, or conversely, vulnerability to water erosion (Bryan 1968). Studies on aggregate stability have indicated that disintegration of soil aggregates can be directly related to water content and freezing rate (Benoit 1973; Bisal and Nielsen 1964; Benoit and Voorhees 1990). Both factors significantly affect the formation and growth of ice lenses in the soil during the freezing process. Periodic formation and thawing of ice lenses in the soil create forces that either strengthen or weaken the soil aggregation (Lehrsch et al. 1991). However, the circumstances which lead to the strengthening or weakening of the soil aggregates as a result of the freeze-thaw process in relation to other factors such as textural class, bulk density, and the degree of saturation have not been adequately explored.

Freezing and thawing, wetting and drying, and other alternating climatic extremes have been observed to significantly affect the strength of soil (Edwards and Burney 1987; Shiel et al. 1988). Water content and bulk density have been shown to influence the soil shear strength (Benoit and Voorhees 1990; Benoit and Bornstein 1970). These factors in turn are influenced by pore size distribution and the kind and location of particle bonds in the soil (Cruse and Larson 1977; Luk 1979).

Soil erodibility in the water erosion process represents indices which give an indication of the soil's inherent resistance to detachment and transportation by raindrops and runoff energy (Wall et al. 1988). Among some of the soil factors from which soil erodibility indices are estimated are surface shear strength and aggregate stability. These factor and other factors from which soil erodibility indices are estimated are usually treated as annual constants (Coote et al. 1988). Although such resultant indices are useful for spatial erodibility comparison, studies (Wall et al. 1988; Mutchler and Carter 1983) indicate that these indices could be refined to reflect seasonal variation. Coote et al. (1988) reported that shear strength and aggregate stability vary seasonally from the point of thaw to spring fallow, the period of time in Southern Ontario when the soil undergoes cyclical freezing and thawing.

The purpose of this study was to investigate the influence of repeated freeze-thaw cycles on the surface shear strength and aggregate stability of remolded top soil. The study also incorporated the interactive effects of selected textural class, bulk density, and saturation on these variables.

MATERIALS AND METHODS

Description of soil sample

The top soil from three agricultural soils in Southern Ontario were sampled: Conestogo silt loam (Grey Brown Luvisol), Brookston clay loam (Orthic Humic Gleysol), and Fox loamy sand (Grey Brown Luvisol). The loamy sand and the clay loam sites are located near the city of Guelph (Wellington County) and the silt loam site is located in Woolwich Township (Waterloo County). The detailed textural characteristics of these soils are presented in Table I. The textural analysis was conducted using the procedure outlined by McKeague (1978). Each soil textural class was considered as a block in each of two factorial experiments (for shear strength and aggregate stability) within randomized complete block designs with three levels for each of the three treatment factors: number of freeze-thaw cycles, bulk density, and saturation. Twelve samples analysed without replication were evaluated in each experiment.

Table I: Summary of textural characterization of the test

Soil textural class	Sand	Silt	Clay	Organic matter
	<————	(%wt)	————	—>
Conestogo silt loam	30	53	17	6
Bookston clay loam	27	39	34	5
Fox loamy sand	81	14	5	3

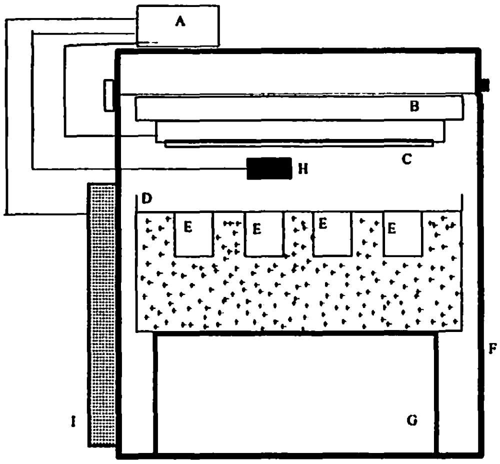
Sample preparation

Soil samples were collected from the top 0.20 m layer of each soil. Samples were air-dried and passed through a #10 (2 mm opening) sieve. The sieved samples were packed into aluminum cylinders, each 48 mm in inside diameter and 57 mm long with a hydraulic press at bulk densities of 1300, 1500, and 1600 kg/m^3. These bulk density values were selected based on typical bulk density values measured in the field. The packed soil columns were covered at the bottom with pieces of cloth to maintain the integrity of the packed samples within the cylinders. The samples were then saturated for 24 h from the bottom at atmospheric pressure by capillarity, followed by free or natural drainage for appropriate periods of times to attain high, medium, and low degree of saturation. Saturation expresses the volume of water present in the sample relative to the volume of pores. The high range included saturation greater than 90%, while the medium and low saturations were between 60 - 80%, and below 60%, respectively. Samples were weighed continually and saturation calculated until the required range was achieved. Samples were immediately transferred to the freezer to start the freeze-thaw cycle.

Freeze-thaw procedure

The freeze-thaw apparatus consisted of a domestic deep freezer with a portable heater fitted to the inside of the top lid (Fig. 1). The controls for the freezing coils from the freezer and the heating elements of the stove were wired into the thermostat which had a temperature reading gauge to control the temperature settings. The temperature sensor which also was wired to the thermostat was placed inside the freezer between the samples and the stove. The periods of freezing and thawing were conducted independently. Each soil column was enclosed on the sides and bottom with an insulator and covered at the top with a plastic sheet to prevent evaporation. Soil columns were then placed in an insulated foam cell in a single layer. This arrangement helped to simulate a one-dimensional freeze-thaw process.

Samples were frozen at a temperature of -20°C for an average duration of 24 h and thawed at a temperature of 40°C for the same amount of time. These temperatures are greater in magnitude than those generally observed during freeze-thaw conditions in Southern Ontario. However, relatively large negative and positive temperatures were required for the penetration of freezing and wetting fronts to the bottom of the samples within a reasonable length of time. The freeze-thaw treatments included one, three, and six freeze-thaw cycles.



A Thermostat control unit with temperature setting mechanism
B Portable stove
C Heating element of stove
D Closed cell foam system for holding core sample
E Repacked samples
F Deep freezer
G Stand
H Temperature sensor
I Deep freezer coils

Fig. 1. Schematic diagram of freeze-thaw apparatus.

Aggregate stability

After having undergone the designated number of freeze-thaw cycles, one soil sample from each treatment combination was taken out of its cylinder, air-dried, and split into two equal parts (A and B) of approximately 100 g each. The aggregate size distribution of part A was determined using a nest of sieves (4.0, 2.8, 2.0, 1.0, 0.5, 0.25 mm diameters). The soil samples were sieved for two minutes on a Rototap testing sieve shaker (Model 11695) after which each size separate was weighed and expressed as a percentage of the total initial sample mass.

The other part of the air-dried sample (B) was exposed to simulated rainfall using The Guelph Rainfall Simulator (Tossel et al. 1987). A 13 mm full-jet nozzle placed at a height of 1.5 m above the sample and operated at a pressure of 49.3 kPa was used to produce a simulated rainfall for 20 minutes at an intensity of 160 mm/h. This intensity represented a short duration 100-year return period storm in Ontario. Samples were evenly spread over a 250 µm mesh and 0.20 m diameter screen. The screens were arranged on a platform with a common radius of 0.50 m. A high-precision motor was used to rotate the platform at a speed of 0.75 rpm to ensure a reasonably uniform distribution of rainfall on all the samples. Samples were air-dried and the aggregate size distribution was determined by the sieving process described earlier.

The mean weight diameter (MWD) of soil aggregates (Van Bavel 1949) was used to index the aggregate stability for statistical comparison because this approach characterizes the whole range of size distribution of aggregates by a single representative value. The MWD was obtained by calculating the area under the inverse of the particle size distribution curve obtained from sieving each sample. The particle size distribution curves were developed by plotting the upper limits of the sieve sizes on the x-axis and the fraction of the total mass passed through each sieve on the y-axis. The difference between the MWD of the sample with no raindrop impact (MWD_A) and the MWD of the sample after raindrop impact (MWD_B) was used as an index of aggregate stability.

Shear strength

The surface shear strength (τ) of each soil sample was measured with a fall-cone apparatus (Geoner A/S g-200) fitted with permanent magnetic suspension. A 100 g 30° cone was used for all tests. One sample of each combination of factors, soil bulk density, saturation ratio, and number of freeze-thaw cycles was used for surface shear strength analyses. Samples were placed on a pedestal underneath the cone holder which was adjusted vertically until its apex just come in contact with the surface of the soil sample. The cone was then dropped on the sample. The depth of penetration was read on a gauge with the assistance of a magnifier attached to the lever arm. Four readings were taken for each sample and the average depth (*h*) obtained was used to calculate the shear strength using the semi-empirical equation (Hansbo 1957):

$$\tau = cM/h^2 \tag{1}$$

where:

τ = shear strength (N/m^2),
M = mass of the cone (g),
h = depth of penetration of the cone (mm), and
c = constant (m/s^2).

The constant *c* was obtained from experimentally determined values for seven soil textural groups given by Towner (1973). The values of the constant *c* used for the clay loam, silt loam, and loamy sand were 5.4, 10.0, and 12.0 m/s^2, respectively.

RESULTS AND DISCUSSION

Shear strength

Results of the factorial analysis of variance indicate that the mean surface shear strength proved to be significantly different ($P < 0.01$) among soil classes, bulk density, and number of freeze-thaw cycles. Saturation main effects were also significant at the 0.05 probability level (Table II). Figures 2, 3, and 4 present the effects of freeze-thaw cycles on surface shear strength for the three soil textural classes averaged across the saturations. These results indicate a trend of decreasing surface shear strength with increasing number of freeze-thaw cycles in all three textural classes. This implies that the strength of the sieved surface soil decreased as the soil went through increasing cyclical freeze-thaw changes. The initial bulk density of the soil samples significantly influenced surface shear strength (Table II), but not in the same manner for all freeze-thaw cycles (Figs. 2, 3, and 4). It was also observed in this study that at every freeze-thaw cycle, an increase in bulk density tended to increase the surface shear strength as well. Averaging over the three levels of saturation, the silt loam indicated a decrease of 66%

Table II: Results of a 3^4 factorial analysis of variance on surface shear strength (τ) and change in mean weight diameter (ΔMWD) for soil textural class (Soil), bulk density (ρ_b), saturation (s), number of freeze-thaw cycles (FT)

Source of variation	Degrees of freedom	<——Mean Squares——>	
		τ	ΔMWD
Soil	2	259726.414**	1.643**
ρ_b	2	98274.945**	0.244**
s	2	13012.857*	0.016
FT	2	21400.366**	0.022
ρ_b x s	4	7858.253	0.097
ρ_b x FT	4	3649.769	0.014
s x FT	4	640.299	0.020
ρ_b x FT x s	8	1652.067	0.048
Error	52	3936.472	0.048

* Significant at 0.05 probability level

** Significant at 0.01 probability level

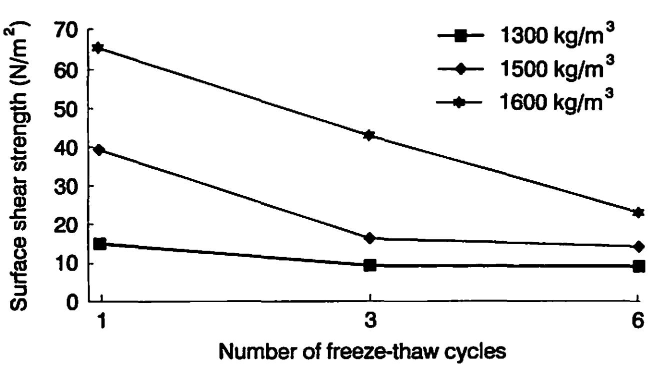


Fig. 2. Effects of freeze-thaw cycles and bulk density on surface shear strength of a silt loam averaged over the three saturation levels.

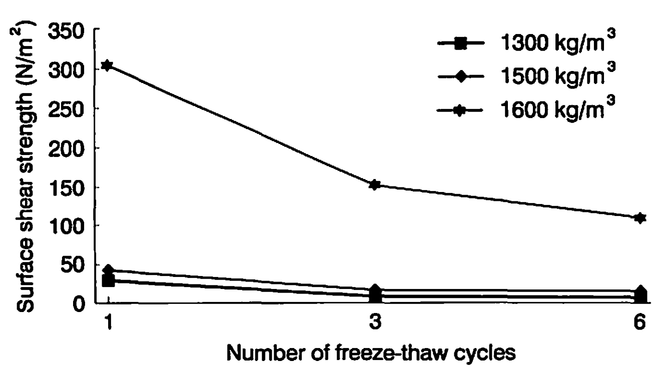


Fig. 3. Effects of freeze-thaw cycles and bulk density on surface shear strength of a clay loam averaged over the three saturation levels.

in the surface shear strength at bulk densities of 1500 and 1600 kg/m^3 between one and six freeze-thaw cycles. The decrease at bulk density of 1300 kg/m^3 was 22% for the same range of freeze-thaw cycles. Similar relative decreases were observed with different percentages in the clay loam (Fig. 3) and the loamy sand (Fig. 4).

Each of the soil textural classes behaved differently in terms of the range of magnitude of the surface shear strength. The clay loam had the highest range of surface shear strength with averages of 187 and 14.5 N/m^2 at bulk densities of 1600 and 1300 kg/m^3, respectively. This trend was followed by the loamy sand with averages of 257 and 150 N/m^2 for the highest and lowest bulk densities and the silt loam with averages of 43 and 11 N/m^2 between the two bulk densities. The differences in magnitudes of the surface shear strength values could be attributed to the differences in textural classes of the soils (Table I and II). The medium texture, having highest clay content, tended to possess the highest value of surface shear strength. Maybe this relates to the number of small size particles in the presence of organic matter which can provide a binding effect and enhance cohesion and continuity of the particle network more than soils such as silt loam and loamy sand which have relatively lower clay contents.

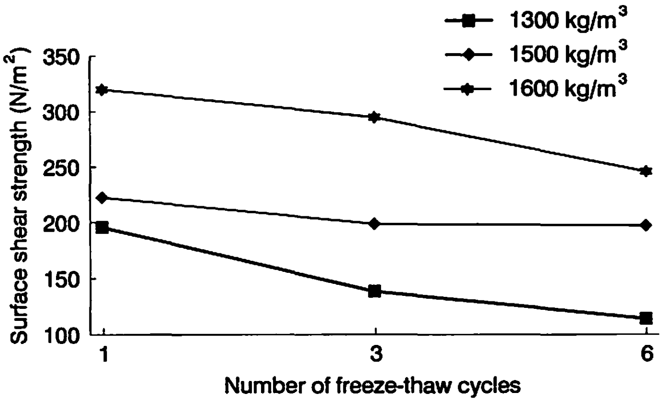


Fig. 4. Effects of freeze-thaw cycles and bulk density on surface shear strength of a loamy sand averaged over the three saturation levels.

The data also indicated an increase in surface shear strength with an increase in bulk density in all the soils. With increasing bulk density the samples were more compacted and consolidated especially with the remolded samples. The natural structure was altered during remolding resulting in structureless soil samples.

Results from laboratory studies such as this can serve as a guide in providing information on how natural soils might be affected by seasonal freeze-thaw cycles. In a field experiment, Kok and McCool (1989) observed similar trends of a decrease in shear strength after snow and frost had occurred a number of times. Freezing and thawing has been observed

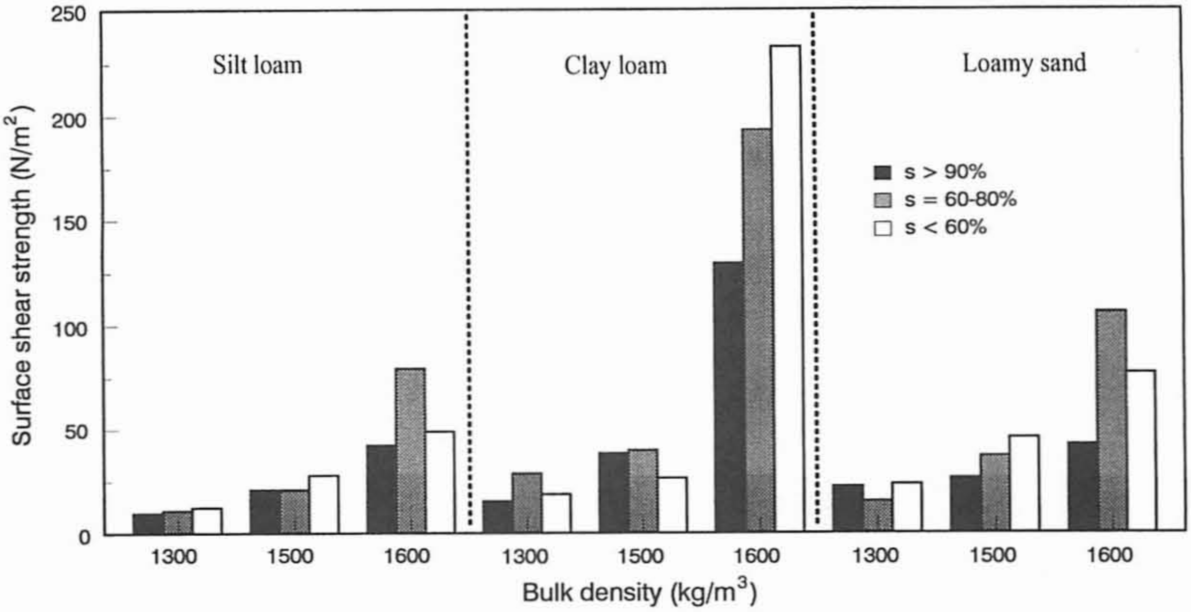


Fig. 5. Effect of bulk density and degree of saturation on surface shear strength for silt loam, clay loam, and loamy sand.

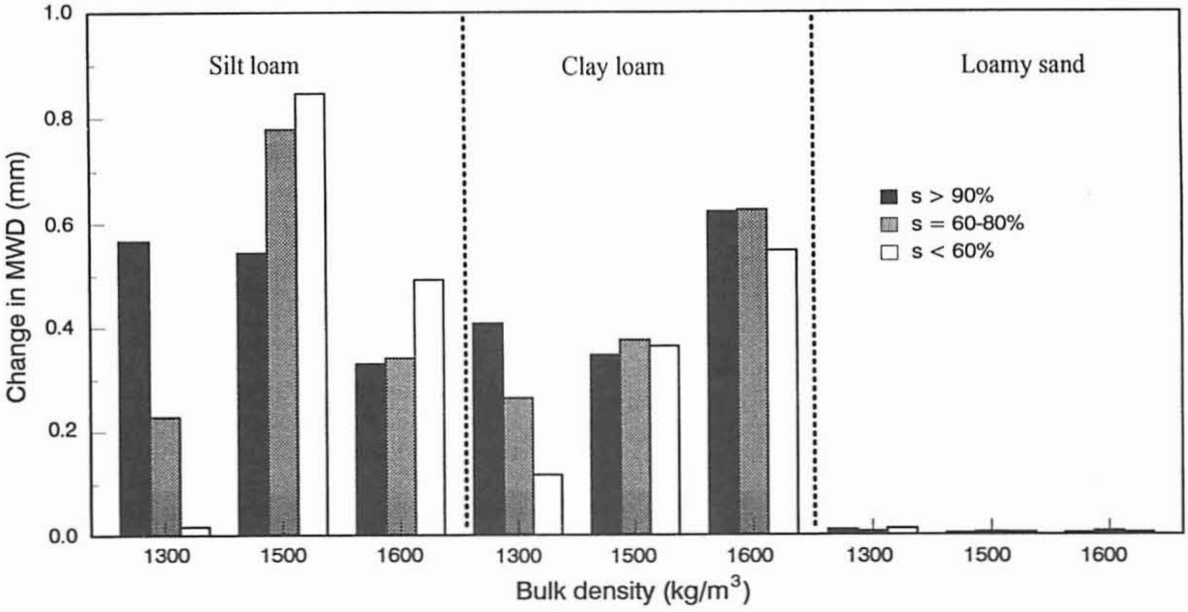


Fig. 6. Effect of bulk density and degree of saturation on the change in mean weight diameter for silt loam, clay loam, and loamy sand.

to affect soil characteristics like soil moisture, bulk density, and porosity and the change in magnitude of these characteristics dependents on the particular mix of initial conditions (Benoit and Voorhees 1990). Saturation significantly affected surface shear strength at the 0.05 probability level. This we postulate relates to an increase in the volume of water relative to the volume of void space in the sample. Although the wide variability observed in our study may have hidden any significant interactions among the factors, we suspect that saturation affects the relationship between surface shear and aggregate stability. Kok and McCool (1989) observed that the near-surface shear strength on a natural soil subjected to freeze-thaw can be inversely related to the water content of the top 10 mm of the soil surface. This means that the moisture content of the surface layer is very critical in determining the surface shear and the stability of surface particles will change with decrease in degree of saturation. Data in Fig. 5 show this trend for a silt loam at bulk densities of 1300 and 1500 kg/m^3, for a clay loam at a bulk density of 1600 kg/m^3, and for a loamy sand at a bulk density of 1500 kg/m^3. The rest of the samples did not follow this linear and inverse trend. This inconsistency could be attributed to the fact that during the freeze-thaw process continuous free drainage from samples might have been substantial enough to affect the moisture content of the samples, especially close to the surface.

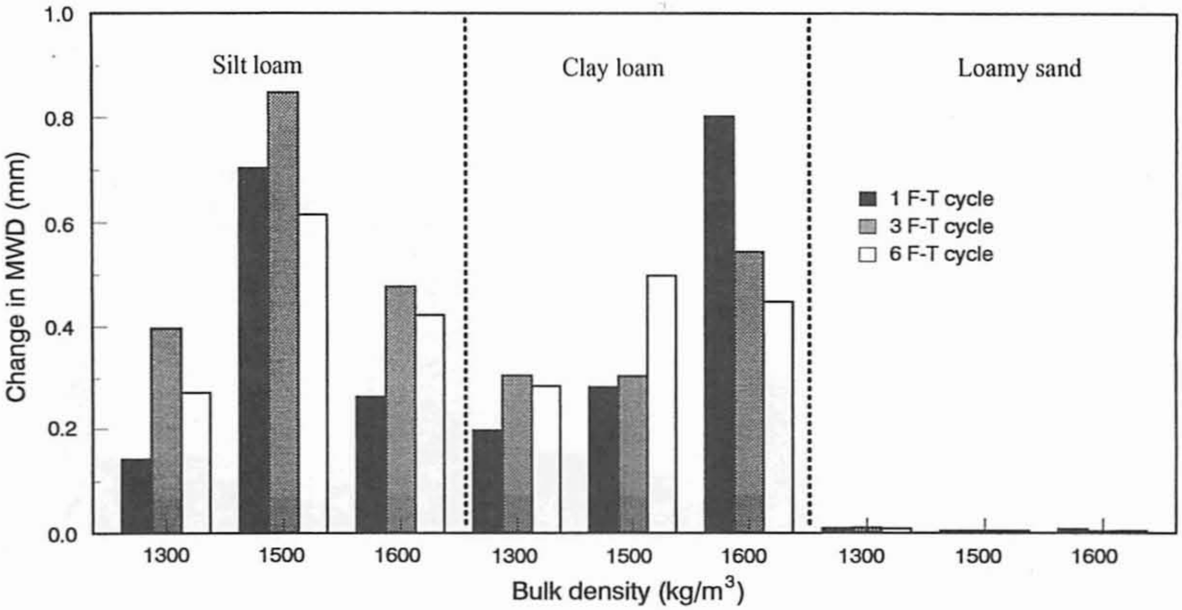


Fig. 7. Effect of bulk density and number of Freez-thaw (F -T) cycles on the change in mean weight diameter for silt loam, clay loam, and loamy sand.

Aggregate stability

The aggregate stability results indicated significant differences among the bulk density and soil textural class data at the 0.01 probability level (Table II). Beside textural class and the bulk density, the rest of the main effects, namely the saturation and freeze-thaw cycle as well as their interactions, were found not to be significant and hence inconclusive. The data in Figs. 6 and 7 also indicate no significant trend in the different textural classes in relation to the effect of saturation and freeze-thaw cycles. However, one could deduce from the data on the aggregate stability that the loamy sand disintegrated least and was the most stable of the three textural classes (Figs. 6 and 7). The stable aggregates of the loamy sand will be less susceptible to erosion and will require heavy storms and runoff for erosion to occur.

CONCLUSIONS

For repacked samples of three soil textural classes (loamy sand, silt loam, and clay loam), surface shear strength was found to be significantly dependent on the bulk density and the number of freeze-thaw cycles. An increase in bulk density results in an increased surface shear strength. As the number of freeze-thaw cycles increased, the surface shear strength tended to decrease. Although saturation was also significant, no conclusive trend could describe its effect on surface shear strength.

Soil textural class and bulk density have significant effect on aggregate stability and aggregate stability can be related to the bulk density of each soil class. The loamy sand was relatively less susceptible to erosion than the silt loam or clay loam.

It is difficult and perhaps inappropriate to extrapolate these laboratory results to field conditions. However, observations made in the field regarding increase in soil erosion and sediment loads during late winter and early spring periods (Dickinson and Wall 1976; Kirby and Mehuys 1987) could be related to soil partly frozen at shallow depths and undergoing freeze-thaw cycles at the surface.

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