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Causes of Severe Erosion in a Clayey Soil under Rainfall and Inflow Simulation

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Authors
Arabkhedri M.*[1] *PhD*,
Mahmoodabadi M.[2] *PhD*,
Taghizadeh Sh.[2] *MSc*,
Zoratipour A.[3] *PhD*

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[1]Soil Conservation & Watershed Management Research Institute, Agriculture Research, Education & Extension Organization, Tehran, Iran
[2]Soil Science Department, Agriculture Faculty, Shahid Bahonar University of Kerman, Kerman, Iran
[3]Nature Engineering Department, Agriculture Faculty, Khuzestan Agricultural Sciences & Natural Resources University, Khuzestan, Iran

***Correspondence**
Address: Soil Conservation & Watershed Management Research Institute, Agriculture Research, Education & Extension Organization, Tehran, Iran
Phone: . +98 (21) 44901214
Fax: +98 (21) 44905709
arabkhedri@scwmri.ac.ir

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ABSTRACT

Aims Soil erosion has been known as the most important land degradation feature in the globe and is also identified as a serious environmental threat due to its onsite and offsite effects. The aims of this study were to evaluate temporal changes of sediment concentration in a soil with high clay content under erosion by rainfall and inflow as well as interpreting the reasons for their very high erosion rate.
Materials & Methods This experimental study was done in the Rainfall and Erosion Simulation Laboratory of the Soil Conservation and Watershed Management Research Institute (SCWMRI). All experiments were performed at a 20% slope gradient under 55.9mm.h^{-1} rain intensity for 30 minutes. Four slope lengths (1, 6, 12 and 18m) were considered for erosion simulation. With regard to the 6m length of the flume, 1 and 6m lengths were simulated only under rainfall and the other two longer lengths by combining rainfall-inflow.
Findings Very high concentrations up to 80, 59, 40 and 9gr.l^{-1} were recorded in 18, 12, 6 and 1m slope lengths, respectively. Sediment concentration increased exponentially by increasing the length of the slope that could be explained by the influence of flow velocity increase on longer slopes. The high sediment concentration could be justified by the breakdown of the soil mass during rainfall and the formation of more than 65.0% of fine aggregates in the size of silt and very fine sand.
Conclusion The erodibility of clayey soil can be explained by the secondary aggregate size distribution rather than texture properties.

Keywords Marly Soil; Erosion Simulation; Slope Length; Tilting Flume

CITATION LINKS

[1] Soil erosion threatens food ... [2] Status of the World's Soil Resources ... [3] Influences of grass and moss on runoff and sediment ... [4] Iran, Islamic Republic of - cost assessment of ... [5] Water erosion and ... [6] A review on major water erosion factors ... [7] Interrill ... [8] Spatial patterns and temporal trends ... [9] Soil erosion atlas and landscape of the ... [10] Categorization of Marl units with new method ... [11] Dynamic modeling of soil erosion in Marl ... [12] Soil erosion and ... [13] Effect of rainfall intensity, slope and antecedent moisture content on sediment concentration ... [14] Effects of rain intensity, slope gradient and particle ... [15] Field investigation of rill and ephemeral gully ... [16] Effects of slope length, slope gradient, tillage ... [17] Impact of slope length on soil erosion of sloping farmland ... [18] Soil erosion in the anthropocene ... [19] Laboratory experiments on the influence of slope length on runoff, percolation and rill ... [20] Plot sizes dependency of runoff and sediment yield estimates ... [21] The impact of slope length on the discharge of sediment by rain impact induced saltation ... [22] Evaluation of GUEST and WEPP with a new approach ... [23] Soil erosion along a long slope in the gentle ... [24] Impact of slope length on red soil ... [25] Water erosion in different slope lengths on bare ... [26] The effect of row grade and length on soil erosion from concentrated flow in furrows of contouring ridge ... [27] Sediment concentration and hydraulic characteristics ... [28] WEPP calibration for improved predictions of interrill erosion in semi-arid to arid ... [29] A new expression of the slope length factor ... [30] Morpho-dynamic quantification of flow-driven rill erosion parameters based on physical ... [31] Method for measuring velocity of shallow water ... [32] Interrill soil erosion processes and their interaction ... [33] Size characteristics of sediments eroded from ... [34] Sediment transport and soil detachment on ... [35] Revegetation as an efficient means of increasing soil aggregate ... [36] An investigation of flow-driven soil erosion processes ... [37] Flow-driven soil erosion processes and the size selectivity ...

Introduction

Overall, the soil erosion rate has been estimated to be 10-40 times higher than the soil formation rate [1]. Soil erosion has been recognized as the most important land degradation feature in the globe [2] and is also known as a serious environmental threat [3] due to its onsite and offsite effects.

The annual cost of environmental degradation in Iran, which includes soil erosion as the main factor, was estimated at about 10 billion US$, that equals 8.8% of the Gross Domestic Product of Iran [4]. Water and wind erosion are common in many parts of Iran [5], the former is dominant in 120Mha out of the total 164Mha area of the country [6].

Erosion involves three main processes, including detachment, transport, and deposition [7]. Several factors, including erosivity of rainfall and runoff, erodibility of soil, topography, vegetation cover and, land management, influence these processes and consequently control soil erosion [7].

Despite low annual precipitation in most parts of Iran [7], heavy showers occasionally occur [8] as an important contributing factor in the erosion of Iran [7]. The erosion rate is higher in places where the soil is erodible and there is not enough vegetative cover to protect the slopes. In arid and semiarid regions of Iran, marls and some other formations (Such as loess and marine silts), create hilly bare landscapes with very sparse vegetation and various features of the sheet, rill, and even gully erosion. These sensitive formations constitute about 20% of Iran [9], they have been known as the main source of sedimentation in many river basins (e.g. Sefidroud basin). Based on the texture analysis of 67 topsoils taken from various marl formations that were reported by Shaban *et al*. [10], in the most samples, the amount of silt fraction is greater than clay and sand fractions which could explain the reason for high erodibility of them. In contrast, high rates of interrill and rill erosion, especially in clayey marly soils, create a big question. Zoratipour [11] reported severe erosion especially in steep slopes of clay-calcareous gy_1 marl in Taleghan District, Iran. Basically, the high percentage of clay should prevent erosion due to its high cohesion force [12]. Therefore, *further investigation* is *needed* in this *area*.

Rainfall intensity has been known as the controlling factor of interrill erosion [13, 14], however, rill erosion is mostly related to the concentrated overland flow due to natural topography, For example, Di Stefano *et al*. [15] reported the rill erosion as the dominant feature compared to the interrill erosion in Sparacia experimental area, Sicily, Italy.

The rate of erosion on a particular slope gradient acts as a function of its length. Slope length refers to the distance between the origin of runoff and sedimentation point [16]. Other factors remaining the same, runoff per unit area may decrease with an increase in slope length. A better understanding of the effect of slope length on soil erosion processes will improve soil loss modeling as well as soil conservation at slope scale [17]. To some extent, slope length expresses the effect of scale on erosion [18].

Despite numerous studies on the effect of slope length on runoff and erosion, we could not find any report about the effect of slope length on erosion of clay-textured soils. Poesen [18] has emphasized the need for research on soils having textural extremes. In the following paragraphs, a review of the studies on the effect of slope length on the erosion of other types of soil is presented.

Based on rainfall simulation experiments, Bryan and Poesen [19] found that the behavior of runoff discharge is affected by rainfall excess, slope length, surface sealing, rill development, and head cut incision. Sadeghi *et al*., [20] found a decreasing trend for area-specific runoff based on collected data in natural erosion plots. The time of concentration is more on the longer slopes than shorter ones [21]. Therefore, compared with shorter slopes, more runoff infiltrates the soil in longer ones [16].

On the other hand, slope length enhances soil loss through increasing runoff discharge and flow velocity and the consequent increase in sediment transport capacity [22]. Basically, it is expected that by increasing the length of slope (in long enough slopes), total runoff increases, which leads to rill erosion in downslope areas and higher mean of erosion rates. Ming *et al*. [23] found that under mild precipitation, rill cannot form within the top 50m of the slope length, while under intensive rains, it can be made starting even at 15m from the top of the slope. Fu and Zhang [24] simulated different rain intensities ranging from 30-150mm.h^{-1} on slope lengths of 1, 2, 3, 4, 5m with the gradient of 20°.

They observed that at a certain rain intensity, soil loss increased by increasing the slope length and the relationship was described as a power function (R^2>0.80). In addition, the increment of sediment mass was found not to be proportional to the same slope length increase. Bagio *et al.* [25] examined the impact of slope lengths of 11, 22, 33, and 44m, with an average degree of slope of 8% and found that soil losses are increased with increasing slope length.

The effects of specified slope length on erosion rate depend on the runoff velocity [16], which itself is a function of the runoff depth. Kinnell [21] states that sediment concentration increases when the slope length is increased from 150 to 600mm. Liu *et al.* [26] also found a positive correlation (but not statistically significant) between sediment concentration and length of slopes. In contrast, Sadeghi *et al.* [20] found that concentration is lower for longer plots. The opposite results on average sediment concentration regarding to the slope length may depend on the presence or absence of vegetation as well as availability of erodible material. Lal [16] stated that the length effect may be easily altered by soil and crop management, for example by the quantity of crop residue, methods of seedbed preparation, the canopy characteristics, and percentage of ground cover. In this regard, Arjmand Sajjadi and Mahmoodabadi [27] claimed that surface roughness is very important agent affecting the impact of slope length, because this factor depends on soil surface characteristics such as aggregate size distribution, gravel surface, plant residue, rows construction, etc. [28].

Kinnell [21] and Liu *et al.* [26] found exponential relationships between slope length and amount of sediment transferred. In comparison, a linear relation was explored in the experiments conducted by Bagio *et al.* [25]. Interestingly, Sadeghi *et al.* [20] did not find any relation between plot length and unit area sediment production. Bagarello *et al.* [29] found that unit area sediment production does not increase with plot length. Generally, the effect of slope length on erosion rate of susceptible clayey soils has been less studied.

The aims of this study were to evaluate the temporal changes of sediment concentration in a soil with high clay content under erosion by rainfall and inflow as well as interpreting the reasons for their very high erosion rate.

Materials and Methods

This experimental study was carried out in the Rainfall and Erosion Simulation Laboratory (Figure 1) of the Soil Conservation and Watershed Management Research Institute (SCWMRI). It has 4 main components as follow:

1- Six movable nozzles on a 7 meter rail at a height of 10 meters above the ground with the ability to produce rain intensity up to 130mm per hour. The Christiansen uniformity index of rainfall was 83.3%.

2- A tilting flume with the length and width of 6×1m, adjustable up to a 60% slope

3- An inflow system upstream of the flume and adjustable taps to supply steady flow into the flume

4- A funnel at the outlet of the flume system for collecting runoff

Figure 1) Erosion and rainfall simulation laboratory (a), Tilting Flume and inflow tank (b), Nozzle (c), Eroded soil after treatment (d), and Runoff tank (e)

First, about 10 tons of soil sample was taken from the upper 25cm of gy_1 marl formation in Taleghan District, Alborz Province, Iran and transported to the SCWMRI. The climate in Taleghan is semiarid with an annual average precipitation of about 500mm. Its weather is very cold in winter and hot in summer. Most of the precipitation occurs as snow in winter. The high percentage of clay and severe rill and interrill erosion features are the dominant properties of this formation (Figure 2) [11].

Figure 2) A view of severe erosion in gy_1 Marl

Air-dried soil was crushed and it passed through a 10mm sieve, then a representative 2kg sample was carried to the laboratory for physical and chemical properties analysis. In addition, a sample from the water used for the rainfall simulator was also analyzed.

In order to perform the planned experiments, before transferring soil, the bottom of the flume is normally filled by coarse gravels with a thickness of 5cm as a drainage layer which was then covered by a layer of textile fiber [30]. Subsequently, the sieved soil was poured layer by layer (each 5-7cm) into the flume and compacted, using a roller until it got to a thickness of 20cm with field bulk density of $1.35gcm^{-3}$.

Four treatments associated with 1, 6, 12, and 18m flume lengths were designed. All experiments were carried out under simulated rainfall ($55.9mm.h^{-1}$) for a 30 minute period. The first two treatments (1 and 6 meters length) were only under rain impact. However, for the 12 and 18m flume length treatments, the final outflow (Discharge at the 30th minute) of the 6 and 12m treatments were also added up through the inflow system in addition to the rainfall.

The prepared soil in the flume was saturated thoroughly from the bottom, 24 hours prior to each experiment. Then, by setting the flume gradient at 20% (The slope of marly hills with the worst erosion features) [11], enough time for draining out the saturation water was created. Instantly after ending the drainage, each experiment was run. Runoff samples (each one up to 1 liter) were taken once every minute, in the first eight minutes. Afterwards, sampling continued once every 2 and 3 minutes until the 18th and 30th minutes, respectively. The volume of collected runoff was measured and then sent for determining the amount of sediment. These data were used for studying the trend of discharge, concentration and transported sediment.

In addition to the 1 liter samples, whole runoff and sediment of every 10min, were collected on 3 large tanks separately. Immediately after sediment deposition, the clear water siphoned out and the deposited silt was weighted. Then about 100g of wet sediment was dried in an oven at 105°C for 24h and weighed which then used for calculating the average sediment concentration of each 10min time period.

During simulation experiments, the flow velocity was measured, using the tracing dye method [31] on the 5th, 15th, and 25th minutes. For the 1m flume length the velocity was only measured at the outlet. However, the velocity was measured for other experiments every 1.5m (that is 1.5, 3, 4.5 and 6m). Two different velocities were measured based on a simple assumption as follows:

1) The maximum velocity was measured when the first red sign reaches to the measuring section.

2) The minimum velocity was measured after the color fades away.

These two velocities were interpreted as rill and interrill flow velocities. The measured velocities were used to describe the variation of sediment production of studied treatments.

Findings

The soil texture was clayey, and clay constituted 50% of the whole soil (including gravel fraction) and 56% of the fine earth (less than 2mm). The soil had considerable amounts of equivalent $CaCO_3$. It had a neutral pH and a low organic carbon (OC) content (Table 1). Based on chemical characteristics, this soil did not have limitations in regard of salinity and alkalinity. A relatively low cation exchange capacity, alongside high clay content suggests a coarse clay size.

Table 1) Physico-chemical properties of the studied soil

Soil Property	Amount
Clay (%)	50.0
Silt (%)	31.0
Sand (%)	9.0
Gravel (%)	10.0
Bulk density ($g.cm^{-3}$)	1.32
Total porosity	46.2
Saturation (%)	42.2
Organic carbon (%)	0.3
EC ($dS.m^{-1}$)	0.3
pH	7.1
Equivalent $CaCO_3$ (%)	19.0
Gypsum (%)	11.3
CEC (meq $100g^{-1}$ Soil)	26.8
ESP (%)	4.5

Based on chemical characteristics, this soil did not have limitations in regard to salinity and alkalinity.
A relatively low cation exchange capacity alongside high clay content suggested a coarse clay size.
EC= Electrical Conductivity
CEC= Cation Exchange Capacity
ESP= Exchangeable Sodium Percentage

In the water that was used in the simulation experiment, pH was almost neutral and salinity was low. The amounts of calcium and sodium were more than the quantity of other soluble cations (Table 2).
Table 3, shows the amounts of discharge, runoff volume and sediment concentration and weight obtained in the three 10min intervals as well as the whole period.
In the all of treatments, flow volume and the average of discharge in the three 10min intervals gradually increased while the average of concentration and sediment production decreased. The third 10min interval had a 1.3-1.5 time discharge increase compared to the first 10min period, while the concentration was half of the amount in the first period.
The ratio of area-specific flow volume and the average of sediment concentration of the 18m simulated length to the 1m length were 18.2 and 6.4 times respectively. In other words, 117 times more specific sediment produced from the longest length compared to the shortest treatment mainly relates to the flow volume increase rather than concentration rising.

Table 2) Characteristics of the water that used in erosion simulation experiments

Characteristics of the water	Amounts
Temperature (°C)	18
Magnesium ($Meq.l^{-1}$)	0.9
Calcium ($Meq.l^{-1}$)	3.2
Potassium ($Meq.l^{-1}$)	0.03
Sodium ($Meq.l^{-1}$)	2.2
pH	7.2
EC ($dS.m^{-1}$)	0.6

Table 3) Collected data during three 10min, simulation intervals and whole period

Simulated length (m)	**Time interval** (min: sec)	**Discharge** ($ml.s^{-1}$)	**Runoff volume** (ml)	**Sediment Concentration** ($g.l^{-1}$)	**Sediment mass** ($g.m^{-2}$)
1	10:29-20:00	0.9	506.7	9.6	4.9
1	20:00-31:00	1.2	766.9	5.5	4.2
1	10:29-31:00	1.0	1273.6	7.1	9.1
6	02:10-10:00	18.4	8648.8	37.3	53.8
6	10:00-20:00	25.4	15228.0	19.8	50.4
6	20:00-31:00	28.5	18811.3	14.1	44.3
6	02:10-31:00	24.7	42688.0	20.9	148.5
12*	00:45:10:00	42.5	23614.1	59.4	233.9
12*	10:00-20:00	48.1	28869.0	34.8	167.6
12*	20:00-31:00	55.4	36544.4	26.1	159.1
12*	00:45-31:00	49.1	89027.4	37.8	560.5
18**	00:45:10:00	65.7	38575.7	68.0	437.5
18**	10:00-20:00	76.5	45906.5	43.4	331.7
18**	20:00-31:00	83.3	54962.7	32.8	300.0
18**	00:45-31:00	75.5	139444.9	46.0	1069.2

* and ** show Simulated flume lengths by entering extra inflow equal to final runoff discharge of 6 and 12m experiments in addition to the $55.9mm.h^{-1}$ rainfall impact

The runoff occurred earlier by increasing the simulated length. Despite the low fluctuations of discharge in all four experiments, in general, it showed the upward trend at first which then followed by a stable tendency (Diagram-1a).
The trend of area-specific sediment of 12-meter simulated length was reduced by time, whereas the other three treatments showed an incremental trend in the first minutes which followed by a decreasing trend (Diagram-1b).
The maximum flow velocity increased along the flume extends from the head of the flume as

well as passing the time (Diagram 2).

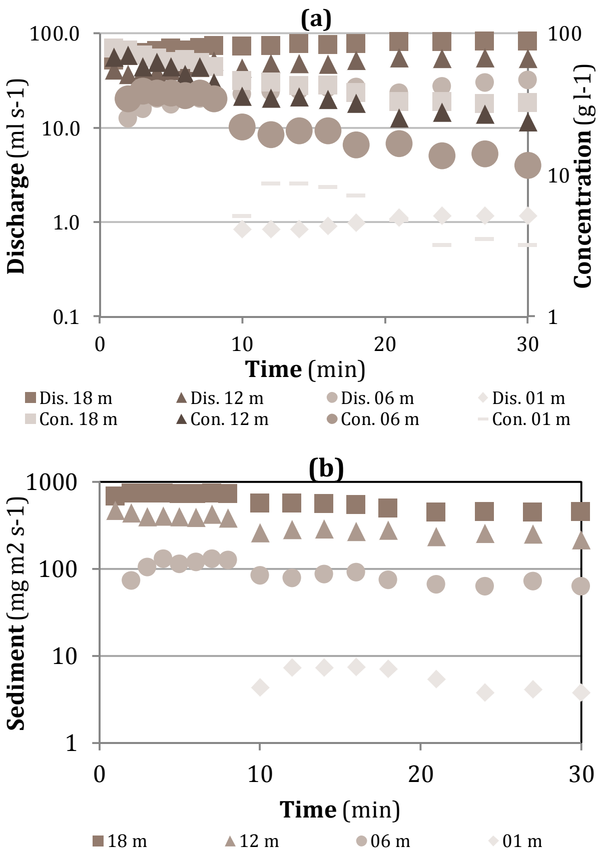

Diagram 1) The variations of discharge, sediment concentration (a) and sediment load (b) by time for simulated 1, 6, 12 and 18m slope lengths

With increasing length and discharge, the average of flow velocity in the simulation lengths of 18, 12 and 6 meters were 13, 8 and 5 times higher than 1-meter treatment, respectively (Table 4). The median of wet aggregate size distribution was 0.036mm and the content of silt and very fine sand sized aggregates was more than 65% (Diagram 3), which most probably explains the reason of high erosion rate on this soil.

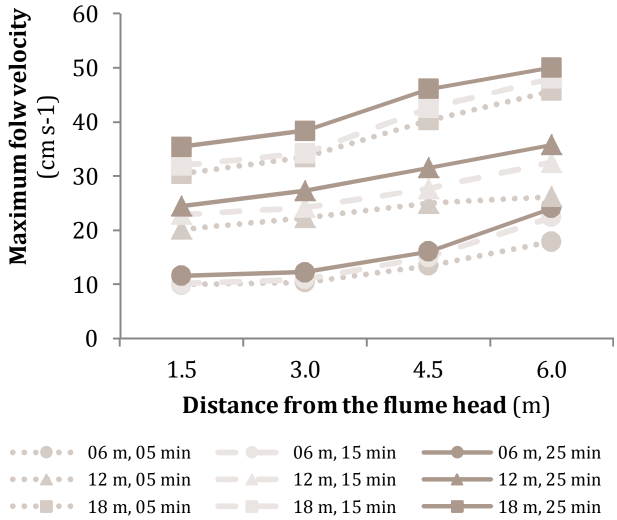

Diagram 2) Maximum flow velocity over flume length in three times

Table 4) Flow velocity at flume outlet

Flume length (m)	Measurement time (min)	Maximum velocity at outlet (cm s^{-1})	Minimum velocity at outlet (cm s^{-1})	Average velocity at outlet (cm s^{-1})
1	15	4.2	1.8	3.0
1	25	4.8	2.1	3.5
6	5	17.9	9.5	13.7
6	15	22.5	11.7	17.1
6	25	24.1	11.1	17.6
12*	5	26.3	15.3	20.8
12*	15	32.6	17.2	24.9
12*	25	35.9	17.9	26.9
18**	5	45.8	24.1	34.9
18**	15	48.1	25.1	36.6
18**	25	50.1	28.9	39.5

* and ** Simulated treatments by entering extra inflow equal to final discharge of 6 and 12m experiments in addition to the 55.9mm.h^{-1} rainfall impact

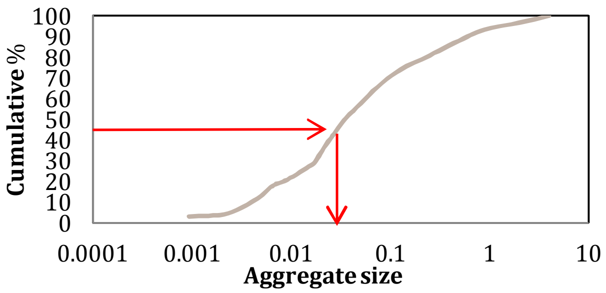

Diagram 3) Wet aggregate size distribution curve for studied clayey soil

Discussion

The aims of this study were to evaluate the temporal changes of sediment concentration in a soil with high clay content under erosion by rainfall and inflow as well as interpreting the reasons for their very high erosion rate.

It is apparent that the runoff occurs earlier by increasing the simulated length. Despite the low fluctuations of discharge in all four experiments, in general, it showed the upward trend at first which then followed by a stable tendency. According to the study done by Asadi *et al*., [32] the weaker the soil stability aggregates, the longer the time to reach steady conditions. The reason for the increase of flow rate is the decrease in the infiltration of the soil with the continuity of the test. In contrast, the sediment concentration showed a strong downward trend in the first minutes, which eventually its trend becomes gentler. This is due to the rinsing of the material ready for erosion at the beginning of the flow. The gradual reduction of sediment concentration at the beginning of the experiment and its achievement to a relatively stable state has been observed in many studies [13, 14].

There were significant differences in the flow rate and sediment concentration of the four simulations. The highest instantaneous runoff from one meter long flume was 1.2ml s^{-1} which reached to 32.2, 55.8 and 84.4ml s^{-1} in the three other treatments, respectively. The maximum concentration values for the four tests were 8.8, 39.5, 71.0 and 79.5g l^{-1} correspondingly. According to the result of ten minute intervals, it was obvious that with 70 times increase in the flow discharge, sediment concentration increased only nine times, that indicated a limitation in the supply of erodible particles to the flow [33]. The highest soil loss rate of these four treatments was about 8, 131, 473 and 754mg $s^{-1}m^{-2}$, that indicated a 94-fold difference in instantaneous sediment transport. In addition, the rate of average concentrations were 7.1, 20.9, 37.8 and 46.0g l^{-1} for 1, 6, 12 and 18m flume lengths respectively. Increased concentration due to runoff increase and flume length have also been confirmed in several other studies [21, 26, 34].

The difference in velocity of four treatments was due to the difference in flow depth. The results of the present study showed that the maximum velocity was almost twice of the minimum velocity. Due to the 13 times difference between the minimum velocity of 1 meter and 18 meters treatments, it seems that the minimum velocity assumption was not the correct interrill flow velocity, because, almost same interrill flow velocities were expected.

In this study, the maximum flow velocity increased along the flume extends from the head of the flume as well as passing the time, due to the fact that the depth of runoff increased by getting close to the outlet of flume and therefore as the velocity increases. According to the result, the maximum flow velocity occurred at the end of the flume; the amount of velocity for 12m length simulation was 49.0% more than 6m, and for 18m treatment was 40.0% in excess of 12m. Higher values of flow depth and flow velocities was accompanied by greater stream power and sediment transport [22, 33]. All experiments were conducted on a 6-m flume by simulating rainfall or concurrent rainfall and inflow. By plotting measured flow velocity, sediment concentration and soil loss vs. the three studied slope lengths (6, 12 and 18m.), the hydrological and erosion condition along an 18m slope were well simulated. In other words, these three experiments are representative for 1st, 2nd and 3rd six-meter sections of an 18m slope. In this way, it is possible to simulate longer slope lengths by increasing the amount of inflow.

In the present study, the average sediment concentration from marly clayey soil was much higher than that of other soils reported in earlier studies. An important reason for the high erosion rate of clayey soil in this study was low organic matter content, which prevents the formation of large and stable aggregates [35]. Low infiltration rate due to the heavy texture of soil also affects the amount of runoff and soil loss too. Refahi [5] suggests that with an increase in clay content of about 40%, the size and stability of aggregates increases because its role as cementing factor in the production of aggregates. If the clay content is more than 40%, smaller aggregates will be greater, especially in areas where the surface soil is alternately frozen and melted in the winter period. The greater the amount of fine aggregates resulted in more erosion. In fact, as Asadi *et al*, [36] showed sediment leaving an eroding area is a combination of primary soil particles and aggregates. The size of secondary soil particles (Soil aggregates) plays an important role in erosion processes [37].

Regarding the possibility of intense summer rainfall as well as rapid melting of snow in the early spring in Taleghan area, severe erosion due to the formation of rills particularly in the foot slopes of gy_1 Marls is expected. Due to the importance of soil mass breaking to fine secondary aggregates on severe erosion, further research on grain aggregate measurement over time and ways to increase its resistance are recommended.

The limitation of this study was the use of clear water as the inflow due to the impossibility of injecting suspended sediment therein.

Conclusion

The most important finding of this research is the necessity of paying attention to the distribution of secondary aggregate size rather than primary particle size distribution for studying the erosion processes in clayey soils.

Some other important findings of this research are as follows:

1) The concentration of sediment is high at first, and over time, its amount decline to a fairly stable condition.

2) The amount of soil loss increases exponentially with increasing flume length. The minimum velocity are not yield a rational result for the velocity of sheet flow.

3) The occurrence of high concentrations up to $80gl^{-1}$ reflects the extreme sensitivity of the studied clayey soil.

4) A large amount of clay with low organic matter leads to the production of small aggregates in the size of silt and very fine sand which justifies its high erosion rate.

5) The erodibility of clayey soil can be explained by the secondary aggregate size distribution rather than texture properties.

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