Effect of bulk density, age, and water content on the erosional strength of streambank soils

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Abstract. The purpose of this study is to investigate the influence of physical properties, more specifically the bulk density and water content, to the erosional strength of streambank soils. Thirty (30) soil samples were extracted from the crest, midbank and toe of the bank at Clear Creek in Iowa City, Iowa. Out of those thirty (30) samples, six (6) samples were tested in the standard soil laboratory for obtaining their bulk density and particle size distribution, six (6) samples were tested their bulk density and heterogeneity using Gamma radiation scanning, and eighteen (18) samples were tested their erosional strength. In addition, six (6) pure Kaolinite-clay samples were constructed with various degrees of consolidation or age and water content for measuring their using conduit flume technique. The results of the conduit flume tests revealed an increasing trend in magnitude of moving from the crest to the toe of the bank. The $T_{ef}$ values were 1.57, 1.53, and 1.92 Pa for the crest, midbank, and toe soils from the left bank. In similar order, the $T_{ef}$ values were 1.46, 1.47, and 1.83 Pa for the soils from the right bank. A similar trend was obtained for the bulk density based on standard laboratory test and gamma radiation scanning. According to standard laboratory test, the average bulk density values for the crest, midbank, and toe of the right bank were 1299, 1618, and 1880 kg/m$^3$. Similarly, based on gamma radiation technique, the average bulk density values for the crest, midbank, and toe of the right bank soils were 1273 kg/m$^3$, 1594 kg/m$^3$ and 1863 kg/m$^3$, respectively. This agreement in the trend of $T_{ef}$ and bulk density suggests a positive correlation between those to parameters. The results of Kaolinite-clay sample experiments demonstrated that samples with higher degree of consolidation or more age would have higher $T_{ef}$. In addition, the Kaolinite-clay samples with higher water content would have lower $T_{ef}$. These findings suggest the presence of spatial and temporal variability in $T_{ef}$ of streambank soils. Therefore, incorporating this $T_{ef}$ variability in modelling streambank erosion will give more accurate results.

1. Introduction

One of the important key soil parameters that determine the rate of streambank erosion is the erosional strength, $T_{ef}$ [1], [2]. Soils with higher $T_{ef}$ will be more resistant to fluvial erosion and less erodible [3]. This parameter is a surrogate measure of the inter-particle cohesive attraction force affected by complex and interrelated physical, geochemical, and biological properties of soil [3], [4], [5]. The physical properties include particle size, particle size distribution, bulk density, water content, age, and temperature. The electro-chemical attraction of soil particles is influenced by clay mineralogy, organic content, and water geochemistry. On the other hand, biological activities of benthic organisms can change the composition and structure of soil, which in turn, affect the $T_{ef}$ value.
The $\tau_{c,f}$ is one of input parameters in several streambank erosion models, such as Bank Stability and Toe Erosion Model (BSTEM) and CONservational Channel Evolution and Pollutant Transport System (CONCEPTS), for predicting soil erosion rate and streambank retreat. Not rarely, only a single $\tau_{c,f}$ value is applied for modelling soil erosion in a site scale or even in the watershed scale although the space dependence of $\tau_{c,f}$ has been well recognized [6], [7], [8], [9]. In addition, temporal variability of $\tau_{c,f}$ is also exist due to temporal effect of several processes [6], [8]. Therefore, applying a single $\tau_{c,f}$ value in modelling streambank erosion will lead to inaccurate bank retreat prediction.

The goal of this study is to investigate the influence of space and time dependent soil physical properties, more specifically the bulk density, age, and water content, to the erosional strength of streambank soils. Thirty soil samples were cut and excavated from the streambank of Clear Creek in Iowa City, Iowa. From those extracted samples, six (6) samples were tested in the standard soil laboratory for obtaining their bulk density and particle size distribution, six (6) samples were tested their bulk density and heterogeneity using Gamma radiation scanning, and eighteen (18) samples were tested their erosional strength, $\tau_{c,f}$, using conduit flume technique [10], [11].

In addition, six (6) pure Kaolinite-clay samples were constructed with various water content and age or degree of consolidation for measuring their $\tau_{c,f}$ values using conduit flume technique. Kaolinite is a clay mineral that consists of one silica sheet and one alumina sheet bounded together by strong hydrogen bonding as well as van der Waals attraction [12], [13]. These strong bonds make kaolinite the most stable clay mineral with its layers tend not to separate. Due to this attribute, the results obtained from this kaolinite experiment should be well-defined and repeatable.

The state of the art of this study was the use of gamma radiation technique for assessing the bulk density heterogeneity of streambank soil samples. This technique could show the spatial discrepancy of bulk density within centimeter scale. Also, the use of pure Kaolinite-clay, in investigating the nature of erosional strength for cohesive soils, is unique. In addition, the erosional strength data obtained from this experiment is repeatable and comparable with similar investigation in the future. More importantly, the results of this study would highlight the influence of time and space dependent variable, e.g. bulk density, age, and water content on the magnitude of $\tau_{c,f}$. Such that the $\tau_{c,f}$ value is also space and time dependent. Therefore, it is important to account for not only spatial but also temporal variability of $\tau_{c,f}$ in modeling streambank erosion, applying a single $\tau_{c,f}$ value would lead to inaccurate bank retreat prediction.

2. Methodology

2.1. Soil sample extraction

Thirty (30) soil samples were cut and excavated from the left and right banks of Clear Creek in Iowa City, Iowa. Samples were extracted at the crest, midbank, and toe of the bank for measuring key soil index properties and more importantly for investigating the effects of soil bulk density and heterogeneity on the erosional strength of the streambank soils. Initially, six (6) “undisturbed” soil samples were extracted from the bank using Shelby tubes with the size of 40 cm long and 7.62 cm in diameter (figure 1a). These soils were tested for obtaining their composition and bulk density. From the same location, twenty four (24) soil blocks were extracted using wire saw and spatula (figure 1b). Six (6) out of 24 soil blocks were chosen for measuring the degree of consolidation and heterogeneity of the bank soils using a gamma radiation technique. The remaining eighteen (18) samples were tested using a conduit flume technique for measuring their erosional strength $\tau_{c,f}$.

The extraction procedure was consistent for each soil block. Two spatulas and a wire saw were used to cut and extract each soil block with a size of 35 cm x 20 cm x 15 cm (figure 1b). To minimize dehydration and maintain soil intact, the extracted soil blocks were carefully enclosed in cheese cloth, plastered with wax, and placed within plastic boxes. Then, the samples were transported to the laboratory and stored in a room at a constant temperature of 20°C before being tested.

2.2. Soil index properties

The six (6) Shelby-tube soil samples were tested to obtain their particle size and distribution and bulk density. The sieving and hydrometer procedures (ASTM D422-63) were used to obtain particle
size distribution, while the bulk density was determined by the ratio of soil mass to its volume (ASTM 4254-91).

2.3. Bulk density heterogeneity
Six (6) soil samples from the crest, midbank and toe of the left and right banks were scanned using automated gamma scanning system to obtain their bulk density heterogeneity. The samples were cut in half length wise (figure 2a) so they could fit within the space between gamma source and detector set-up (figure 2b). The gamma radiation scanning system has two main components, a radiation source and a detector (figure 2b). The detector was equipped with a photomultiplier for detecting the attenuated radiation. A similar system was used in Papanicolaou and Maxwell study [13].

![Figure 1](image1.png)

**Figure 1.** Streambank soil extraction. (a) A soil extraction plan for the left and right banks. (b) A soil block was cut from the right bank. Inset: the sample was carefully covered in a cheese cloth for maintaining its original intact and structure before being tested in a conduit flume.

![Figure 2](image2.png)

**Figure 2.** Gamma radiation scanning. (a) Soil samples, from the crest, midbank, and toe, were cut into half before being scanned with gamma radiation. (b) The source emitted gamma radioactivity on the soil surface. The radioactive signal penetrated through the sample and would be detected by the detector at the other side of the sample. The signal was attenuated as it travelled through the sample. The signal intensity received by the detector was dictated by the bulk density and degree of consolidation of the soil sample.
The source and detector can make a vertical and horizontal movement as they were installed to a stepper motor which was controlled by a QuickBASIC program. The measurement points were arranged such that they make a grid pattern over the scanned area. The vertical and horizontal distances between neighbouring grid points was 1 cm. Initially, a calibration procedure was conducted with the gamma system to obtain an equation that relates the gamma count rate and bulk density. The calibration was performed using soils of known concentration or bulk density. The calibration equation can be written as in equation (1):

\[ \rho_{bulk} = -189.4 + 1422e^{-1.098 \times 10^{-3} I} \]  

where \( \rho_{bulk} \) is soil bulk density (g/l), \( e \) is natural number 2.71826, and \( I \) is gamma count rate (counts per second).

2.4. Kaolin sample preparation

Six (6) Kaolinite-clay samples were constructed with various water content and degree of consolidation or age (see table 1) before being measured their erosional strength, \( \tau_{c.f} \). To investigate the effect of age on the \( \tau_{c.f} \), the first group of three (3) samples (PK1, PK2, and PK3) were constructed with similar water content (170\%) and various age or consolidation time (e.g., 1, 8, and 21 days). On the other hand, the second group of three (3) samples (PK4, PK5, and PK6) were made with similar age (0.1 days) but various water content (50, 80, and 120\%) to study the influence of water content to the \( \tau_{c.f} \).

| Group | Soil ID | W (%) | % Sand | % Silt | % Clay (Kaolin) | Sediment Age (days) |
|-------|---------|-------|--------|--------|----------------|---------------------|
| Group I | PK1 | 170 | 0 | 0 | 100 | 1 |
| PK2 | 170 | 0 | 0 | 100 | 8 |
| PK3 | 170 | 0 | 0 | 100 | 21 |
| Group II | PK4 | 50 | 0 | 0 | 100 | 0.1 |
| PK5 | 80 | 0 | 0 | 100 | 0.1 |
| PK6 | 120 | 0 | 0 | 100 | 0.1 |
Figure 3. Kaolin sample preparation. (a) Apparatus for preparing kaolin samples. (b) Kaolin and water were mixed using mixer. (c) Sample was put in the tray. (d) Sample was wrapped with plastic sheet to minimize evaporation.

Each sample was made of a 300 gram dry Kaolin mixed with a certain amount of water, depend on the predetermined water content (figure 3a and b). After being well mixed in the mixer for 5 minutes, the sample was poured into a tray and spread evenly using spatula (figure 3c). The sample and the tray were wrapped with a plastic sheet to minimize evaporation during the settling period. Each sample was allowed to settle for a certain time, depend on predetermined consolidation time or age (figure 3d).

2.5. Fluvial erosional strength

Eighteen (18) soil samples from the left and right banks as well as the six (6) constructed Kaolinite-clay samples were tested in a straight conduit flume for obtaining their erosional strength, $T_{c.f}$. A detail information on the $T_{c.f}$ measurement procedure using conduit flume can be found in [10], [11], [14], and [15].

3. Results and discussions

3.1. Bank soil index properties

The composition of the streambank soils were (52.50 ± 12.50) % sand, (39.19 ± 10.73) % silt, and (7.44 ± 2.98) % clay (see table 2, column 1-3). More specifically, the crest and toe soils were dominated by sand portion (figure 4a). By plotting the soil composition into USDA triangular chart (figure 4b), the crest and toe soils fell in sandy loam category, while the midbank soils can be classified as silt loam.

Figure 4. (a) Six (6) oven-dried bank soil samples. (b) Bank soil samples classification based on USDA triangular chart.
3.2. Bulk density heterogeneity of bank soils

The streambank soil bulk density tends to increase from the crest to the toe of the bank as shown in Table 2 (column 5). Concerning to the left bank soils, the average bulk density were 1553 kg/m$^3$ for the crest soils, 1794 kg/m$^3$ for the midbank soils, and 2014 kg/m$^3$ for the toe soils, respectively. Regarding to the right bank soils, the average bulk density were 1299 kg/m$^3$ for the crest soils, 1618 kg/m$^3$ for the midbank soils, and 1880 kg/m$^3$ for the toe soils, respectively. By this means, the crest soil has lower degree of consolidation when compared to the midbank and toe soils. This finding indicates that the streambank soils were heterogeneous.

Figure 5 shows the bulk density profiles for the crest, midbank, and toe soils of the right bank measured with gamma radiation technique. The average bulk density values for the crest, midbank, and toe soils were 1273 kg/m$^3$, 1594 kg/m$^3$, and 1863 kg/m$^3$, respectively. These values were closer to the results of standard bulk density measurement shown in table 2 (column 5). Similarly, the result of gamma radiation technique demonstrates an increasing trend of bulk density from the crest to the toe of the bank.

Table 2. Streambank soil index properties.

| Sampling Location | Sand % | Silt % | Clay % | D$_{50}$ (mm) | $\rho_\text{bulk}$ (kg/m$^3$) |
|-------------------|--------|--------|--------|--------------|-----------------|
| CC 1, left bank   | Crest  | 65.00  | 30.54  | 4.46         | 0.130, 1553     |
|                   | Midbank| 40.00  | 49.59  | 10.41        | 0.056, 1794     |
|                   | Toe    | 65.00  | 28.46  | 6.54         | 0.100, 2014     |
| CC 1, right bank  | Crest  | 43.00  | 49.91  | 7.09         | 0.040, 1299     |
|                   | Midbank| 45.00  | 47.17  | 7.83         | 0.058, 1618     |
|                   | Toe    | 58.74  | 30.95  | 10.31        | 0.100, 1880     |

One of the advantages of using gamma radiation scanning is the ability of revealing the variability in bulk density within a tested soil sample, thereby giving a sense of heterogeneity on the scanned sample. The density profile graphs in figure 5 shows more scattered data points for soil samples from the crest and midbank. In contrast, for toe soil, the data points tend to collapse into a constant value. This means that soils from the crest and midbank have higher bulk density heterogeneity comparatively to toe soil. This can be attributed to the fact that the crest and midbank soils were originated from deposited and transported sediment during the flood season, these materials had only short consolidation time and thus low degree of consolidation. On the other hand, the toe soil was fairly well consolidated.
Figure 5. Bulk density profile for the right bank soils obtained from gamma radiation scanning. The “height” is the distance from the top of soil sample to the measurement point, while the “width” is the distance from the side of soil sample to the measurement point.

3.3. Fluvial erosional strength

Table 3 shows a summary of the $T_{c.f}$ values obtained from conduit flume test for all 18 soil samples from the left and right banks. The $T_{c.f}$ values (table 3 columns 2 and 9) demonstrate a growing tendency in magnitude of $T_{c.f}$ from the crest to the toe of the bank. The $T_{c.f}$ values were 1.57, 1.53, and 1.92 Pa for the crest, midbank, and toe soils from the left bank. In similar order, the $T_{c.f}$ values were 1.46, 1.47, and 1.83 Pa for the soils from the right bank. An analogous trend was revealed previously for the bulk density (table 2). This resemblance indicates a positive interrelation between $T_{c.f}$ and bulk density.

| Sampling location | Left Bank | Right Bank |
|-------------------|-----------|------------|
| Sample ID | $T_{c.f}$ (Pa) | $T_{c.f}$ (Pa) | Std. Dev. (%) | Avg Dev. (%) | Sample ID | $T_{c.f}$ (Pa) | $T_{c.f}$ (Pa) | Std. Dev. (%) | Avg Dev. (%) |
| Crest  | CC-L-C1 | 1.67 | 1.67 | 6.29 | 6.29 | CC-R-C1 | 1.30 | 1.30 | 11.19 | 11.19 |
|         | CC-L-C2 | 1.47 | 1.51 | 0.14 | 6.39 | CC-R-C4 | 1.28 | 1.28 | 0.30 | 12.26 |
|         | CC-L-C3 | NA | NA | NA | NA | CC-R-C5 | 1.80 | 1.80 | 23.45 | 23.45 |
| Midbank | CC-L-M1 | 1.73 | 1.73 | 14.17 | 14.17 | CC-R-M1 | 1.49 | 1.49 | 1.40 | 1.40 |
|         | CC-L-M2 | 1.31 | 1.31 | 0.31 | 14.17 | CC-R-M2 | 1.59 | 1.59 | 0.13 | 8.13 |
|         | CC-L-M3 | NA | NA | NA | NA | CC-R-M3 | 1.33 | 1.33 | 9.53 | 9.53 |
| Toe     | CC-L-T1 | 1.75 | 1.75 | 8.38 | 8.38 | CC-R-T1 | 1.60 | 1.60 | 12.25 | 12.25 |
|         | CC-L-T2 | 1.90 | 1.90 | 0.18 | 1.24 | CC-R-T2 | 2.37 | 2.37 | 0.48 | 29.88 |
|         | CC-L-T4 | 2.12 | 2.12 | 10.10 | 10.10 | CC-R-T5 | 1.50 | 1.50 | 17.62 | 17.62 |

Note: Sample was disrupted when it was cut for sliced in the ray.

This trend in bulk density of streambank soils indicates a presence of spatial variability in $T_{c.f}$ value for streambank soils, the crest soil tend to be more erodible than the toe soil. This finding suggests that applying a single $T_{c.f}$ value in a streambank erosion modelling will give inaccurate results. This finding also support the nonlinearity of cohesive soil erosion rate discussed in previous studies [16], [17], [18].

Table 4 presents a summary of the $T_{c.f}$ values obtained from conduit flume test for six (6) Kaolinite-clay samples. Based on the test results for samples in Group I, it can be revealed that the sample with more age or degree of consolidation would have higher $T_{c.f}$. On the other hand, the
results for samples in Group II shows that the sample with larger water content would have lower $\tau_{c,f}$.

This finding imply that the $\tau_{c,f}$ for a streambank soil is not a constant value, there should be a temporal variability in $\tau_{c,f}$ value as the streambank soil age and water content may change in time [16], [17], [18] due to the sediment erosion and deposition process occurred on the streambank, rain, groundwater table, stream flood, etc.

Table 4. Summary of fluvial erosional strength values for Kaolinite-clay samples.

| Group      | Soil ID | W (%) | Sediment Age (days) | Measured $\tau_{c,f}$ (Pa) |
|------------|---------|-------|---------------------|-----------------------------|
| Group I    | PK1     | 170%  | 1 day               | 0.39                        |
|            | PK2     | 170%  | 8 days              | 1.35                        |
|            | PK3     | 170%  | 21 days             | 1.82                        |
| Group II   | PK4     | 50%   | 0.1 day             | 0.87                        |
|            | PK5     | 80%   | 0.1 day             | 0.62                        |
|            | PK6     | 120%  | 0.1 day             | 0.33                        |

4. Conclusions

The $\tau_{c,f}$ measurements over the samples from the crest, midbank and toe of the bank, using conduit flume technique, revealed that the $\tau_{c,f}$ value grows from the crest to the toe of the bank. A similar tendency was obtained for the bulk density based on the Gamma radiation scanning and standard laboratory bulk density test. This resemblance indicates a positive interrelation between $\tau_{c,f}$ and bulk density. Also, this trend in bulk density of streambank soils indicates a presence of spatial variability in $\tau_{c,f}$ value for streambank soils. The crest soil tends to be more erodible than the toe soil. This finding suggests that applying a single $\tau_{c,f}$ value in a streambank erosion modelling will give inaccurate results.

The results of Kaolinite-clay sample experiments demonstrated that samples with higher degree of consolidation or more age would have higher $\tau_{c,f}$. In addition, the Kaolinite-clay samples with higher water content would have lower $\tau_{c,f}$. This finding imply that the $\tau_{c,f}$ for a streambank soil is not a constant value, there should be a temporal variability in $\tau_{c,f}$ value as the streambank soil age and water content may change in time due to the erosion and deposition processes occurred on the streambank, rain, groundwater table, stream flood, etc.

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