Erosion resistance test of soil cement application for surface erosion protection

Sokline Pheng	extsuperscript{i}, Kinuko Hibi	extsuperscript{ii}, Toshikazu Hori	extsuperscript{iii} and Yuji Kohgo	extsuperscript{iv}

i) Ph.D Student, Department of Agricultural and Environmental Engineering, Tokyo University of Agricultural and Technology, 183-8509, 3-5-8, Saiwai Cho, Fuchu, Tokyo, Japan
ii) Graduate Student, Graduate School of Agriculture, Tokyo University of Agricultural and Technology, 183-8509, 3-5-8, Saiwai Cho, Fuchu, Tokyo, Japan
iii) Team leader, National Agriculture and Food Research Organization, 305-8609, 2-1-6 Kannondai, Tsukuba, Ibaraki, Japan
iv) Professor, Graduate School of Agriculture, Tokyo University of Agricultural and Technology, 183-8509, 3-5-8, Saiwai Cho, Fuchu, Tokyo, Japan

ABSTRACT

In this study, soil cement, as a method to enhance soil strength, was used as surface erosion protection. A series of erosion resistance tests were conducted to evaluate the resistance of soil cement to erosion due to rainfalls. In the experiments, two materials: DL clay (artificial silt) and normal Portland cement were used. The erosion model tests consisted of two layers of soils: 10 cm thick top layers treated with cement and 20 cm thick DL foundation layers. Three cases with different cement contents: C\textsubscript{c} = 0, 3 and 5% in dry weight ratio were conducted under rainfall intensity 50 mm/h. The slope models were compacted in dry density: \( \rho_d = 1.3 \text{ g/cm}^3 \), the water content: w = 17 % and degree of compaction: D = 86%. The soil cement layers were cured for 7 days. The results of experiments show that in the case with C\textsubscript{c} = 0%, the erosion developed from the lower to the middle part of the slope, and it was recognized as rill erosion. In the case with C\textsubscript{c} = 3%, little erosion occurred and several spot splits, whose diameters were approximately 5 cm, were found on the surface. In the case with C\textsubscript{c} = 5%, some small holes were only seen on the surface after the test. The bond due to cement hydration was sufficiently so strong that it prevented the surface layer treated with cement from strong detachment. The hydration of cement, DL clay and water formed the intra-aggregate pores inside the treated soil, which lead to increase the permeability and enhanced the infiltration of water into the soil. It reduced amounts of runoffs and soil loss. The overall results suggest clearly that the cemented DL clay layer effectively protects soil surface from erosion.

Keywords: soil cement, surface erosion, rainfall erosion resistance tests

1 INTRODUCTION

Surface erosion, one type of erosion involving the detachment of surface soil particles by water flowing on the surface, adversely affects the function of earthen structures. Poor soil property is one of the most urgent issues affecting the quality of earthen irrigation structures, such as embankments and channels (Indraratna et al., 2013). Embankments without effective surface protections are highly susceptible to surface erosion. As surface erosion continually develops, the embankment will be eventually dysfunctional and collapse (Powledge et al., 1989). Understanding the process of surface erosion remains vital to evaluate possible protection methods and to reduce the risk of erosion for the earthen irrigation structures. The process of surface soil erosion by water starts from falling raindrops creating compression and shear stress to detach soil particles (Al-Durrah and Bradford, 1982). While some water infiltrates into the soil, the excess of water contributes to surface runoff (i.e., overland flow). The detached soil particles are then transported by overland flow. The detachment of soil particles by raindrop strikes depends on several factors such as the inter-granular shear, the viscosity of pore fluid, the kinematic energy of raindrops, and the mechanical bonds (Cruse and Larson, 1977). The raindrop strikes and overland flow are the two principal erosive agents for the surface soil erosion (Morgan, 2005). Many studies have shown that adding a small percentage of cement to the soil can increase soil strength (e.g., Kawamura and Diamon, 1975; Lade and Overton, 1989; Abdulla and Kiousis, 1997; Sasanian and Newson, 2014). Recognizing cement as a low cost material, soil cement has been successfully used to increase stability for various earthen structures such as road, foundation of irrigation structure, and brick or block materials for houses (Ola and Mbata, 1990; Mubee, 2005; Sariosseiri et al., 2011; Agrela et al.,

https://doi.org/10.3208/jgssp.v07.077 488
2012; Mehenni et al., 2016). However, use of soil cement as a control against surface erosion for earthen irrigation structures has not been fully studied. The objective of this study is, therefore, to evaluate the resistance of soil cement against surface erosion. The resistance soil cement against erosion was evaluated experimentally using a rainfall simulator.

2 MATERIALS AND EXPERIMENTAL TEST

2.1 Materials and equipment

DL clay is an artificial soil material made from silica, kaolin and pyrophyllite, from Showa KDE Co., Ltd. It is classified as non-plastic silt (ML in Japanese unified soil classification system) with 0.1 % sand, 90.4 % silt and 9.5 % clay contents. The characteristics and grain size distribution curve are shown in Table 1.

To stabilize with DL clay, ordinary Portland cement (Type 1) from Sumitomo Osaka Cement Co., Ltd was used in this experiment. The cement contents tested in this study were 0, 3, and 5% by dry weight ratio.

A slope adjustable soil box, which has a dimension of 200 cm in length, 50 cm in height and 48 cm in width, shown in Fig. 1 was used for the rain erosion resistance test. A constant slope angle 20 degrees (about 36% slope) was used in this study. A rainfall simulator, which simulates rainfall intensity 50 mm/h, was mounted over the top of the soil box. Two circle cone spray nozzles were used to supply uniformly water droplets as artificial rainfall to the soil box. A wire mesh sheet with 1 cm thickness was placed in the bottom of the soil box to reinforce the compacted soil. A gabion filled with 2 mm gravels was placed at the toe of the slope to prevent the slope from sliding, when one side of the box was lifted to create the desired 20 degree slope. Pore water pressure transducers (tensiometers with 100kPa air entry value ceramic filter) were also installed into the model to monitor the presence of water inside the soil slope.

Table 1. Physical properties of DL clay

| Property                      | Value   |
|-------------------------------|---------|
| Sand                          | 0.1     |
| Silt                          | 90.4    |
| Clay                          | 9.5     |
| Soil particle density \( \rho_s \) (g/cm\(^3\)) | 2.65    |
| Maximum dry density \( \rho_{dry} \) (g/cm\(^3\)) | 1.55    |
| Air entry value               | 10      |
| Optimum water content \( w \) (%) | 19.1    |
| Saturated coefficient of permeability \( k_s \) (cm/s) | \( 6.7 \times 10^{-5} \) |

At first, DL clay foundation layer (Base layer), which mimicked embankment surface, was compacted into a soil box of slope equipment. The thickness was 20 cm and the dry density and the water content were 1.30 g/cm\(^3\) and 17%, respectively. The degree of compaction is about 86% for both layers. The soil cement was compacted on the base layer in 10 cm thickness. During the compaction, thickness of spread layer was 5 cm. After the compaction, the surface elevations were checked whether an acceptable error of less than 2 mm was achieved. In case of the soil mixed with 3 and 5% of cement content, the soil box was covered with a plastic sheet for 7 days for curing. After curing, the one end of the soil box was lifted to achieve a 20-degree slope. The 50 mm/h of rainfall was then
applied. The duration of rainfall applied for the all three cases was about 4 hours.

### 2.3 Data collection
Surface displacements were determined by using a grid method. The soil surface was divided into $5 \times 5$ cm square grids. A depth sampler was used to measure the changes in elevation at all grid nodes. For each grid node, four initial ($h_1$ to $h_4$ in Figure 3) and final ($h'_1$ to $h'_4$) heights were measured at four nodes. The surface eroded volume $\Delta V_i$ per grid was calculated with the following equation:

$$\Delta V_i = L \left[ \frac{(h_1 - h'_1) + (h_2 - h'_2) + (h_3 - h'_3) + (h_4 - h'_4)}{4} \right]$$  \hspace{1cm} (1)

where $L$ is the size of the grid. Surface eroded volume of each grid was summed up to compute the total volume of the top layer $\Delta V$ with the following equation:

$$\Delta V = \sum_{i=1}^{n} \Delta V_i$$  \hspace{1cm} (2)

where $n$ is the number of grids.

![Initial and Final Surface Conditions](image.png)

Fig. 3. The conceptual of surface eroded volume calculation

Changes in pore water pressures (PWP) within the soil slope were measured continuously during the test. Amount of surface runoff, which included eroded soils, and infiltrated rain waters were collected in every 15 minutes. The eroded soils collected were then oven dried.

### 3 RESULTS AND DISCUSSION

#### 3.1 Surface displacement
Three cases tests were conducted. Cases 1, 2, and 3 had cement content $C_c = 0$, 3, and 5%, respectively. Table 2 summarizes the experimental conditions of each case. The rainfall durations were different for the three cases. They were adjusted by the surface conditions. Figure 4 shows the surface displacement conditions after the tests. Pictures of surface conditions are shown in each left side and each right figure shows distributions of surface displacements. The unit = mm.

The surface condition in Case 1 was distinctly different from other two cases because of the soil characteristics.

#### 3.2 Surface eroded volume changes
The total surface eroded volume of the top layer was computed by the result of surface elevation changes as described in section 2.3. As expected, the total surface eroded volume of each three cases was exponentially decreased with an increase in cement content as shown in Figure 5. Total surface volume changes were 8,213 cm$^3$ in Case 1, 1,031 cm$^3$ in Case 2 and 147 cm$^3$ in Case 3, respectively.

| Case No | $C_c$ (%) | Rainfall duration (min) | Curing time (day) | Rainfall intensity |
|---------|-----------|------------------------|-------------------|-------------------|
| Case 1  | 0         | 210                    | 0                 | 50 mm/hr          |
| Case 2  | 3         | 240                    | 7                 |                   |
| Case 3  | 5         | 255                    |                   |                   |

According to the study of Wishmerier and Mannering (1968), soils, which contain high amount of silts, are the most erodible materials. As the soil sample used in this test consisted of 90.1 % of silt, it could be easily eroded by surface runoff. Erosion developed from lower to middle part of the slope, and it was recognized as rill erosion. In Case 2, several spot splits, whose diameters were approximately 5 cm, were found on the surface. At the lowest part of the slope, small soil aggregates were deposited because these aggregates were small enough to be transported. In Case 3, only small surface crusts were observed on the surface. The deepest erosion was found in Case 1, about 10 cm, which was considered as serious surface erosion comparing to soil cement cases. There was no serious erosion found in Cases 2 and 3. Liu et al. (2006) reported that the soil crusts were consequently formed when soil cements were exposed to rainfalls. It was due to the hydration process, which was a reaction of cement with water and gradually bonded soil particles together that resulted in hardening the soil cement.

![Surface Conditions](image.png)

Fig. 4. Surface conditions of soil slope after testing. Pictures of surface conditions shown in each left side and each right figure shows distributions of surface displacements. (unit = mm)
also affects the infiltration capacity. When raindrops fall on a dry surface, much of the raindrops are absorbed by the soil pores (Poesen, 1981). The rainfall water therefore might infiltrate into the cemented DL clay layer faster than DL clay layer only did. Hence, this is another reason why cemented soil layer may make the surface erosion reduce.

3.4 Runoff and soil losses

The amounts of accumulated runoff water for different cement contents are shown in Figure 7. Runoff amounts in all the cases continued to increase with time. The amount in Case 1 was larger than those in Cases 2 and 3. This figure also indicates that the cemented DL clay layer possibly may store more water inside than the DL clay layer only does. At the end of the test, accumulated runoff water became almost the same in all the cases. It was also found that the water storage capacity of the cemented DL clay layer might increase. As mentioned above, the cemented layer might create larger pores and as the result the cemented layer might hold more water inside.

Rahardjo et al. (2018) mentioned that there is a significant increase in surface runoff when soil mixture has lower water storage. It was found that the runoff amount of the cemented layer became relatively small because of the performances of faster infiltration and higher water storage.

The relationship between sediment losses and cement contents is shown in Fig. 8. The sediments collected from the runoffs were measured from 120 minutes when the layers were almost saturated for 100 minutes. The amount of sediment losses in Case 1 was much higher than those in Cases 2 and 3. Such observation has also found in some studies where small amount of soil losses and detachment associated with an increase in soil strength (Poesen, 1981; Brunori et al., 1989; Reddi et al, 2000). The cemented soil improved the soil strength which soils can have a higher resistance to erosion processes.
4 CONCLUSION

In this study, soil cement was used for surface erosion protection for embankments. A series of resistance of soil cement application tests were conducted under rainfall simulator at 50 mm/h. The results indicated that small changes in the cemented DL clay layers mainly due to some little crusts formed. Improving the soil shear strength possibly reduces the detachment and transport process of erosion on the cemented layers. Due to the hardened surface of the cemented soil, it helps preventing soil detachment. The hydration of cemented DL clay increased the permeability and enhanced the infiltration of water into the soil. They reduced amounts of runoffs and soil loss. The overall results suggest clearly that the cemented DL clay layer effectively protects soil surface from erosion due to not only an increase in shear strength but also an increase in permeability.

ACKNOWLEDGEMENTS

The authors would like to thank staffs in Agricultural Research Institute Rural Engineering for facilitating and supporting this research.

REFERENCES

1) Abdulla, A. A. and Kiousis, P.D. (1997): Behavior of cemented sands—I. Testing. Int. Numerical and Analytical Methods in Geomechanics, 21, 533–547.
2) Al-Durrah, M.M. and Bradford, J.M. (1982): The Mechanism of Raindrop Splash on Soil Surfaces 1. Soil Science Society of America Journal, 46(5), 1086-1090.
3) Agrela, F., Barbudó, A., Ramírez, A., Ayuso, J., Carvajal, M.D., Jiménez, J.R. (2012): Construction of road sections using mixed recycled aggregates treated with cement in Malaga, Spain. Resource Conservation and Recycle, 58, 98–106.
4) Bellezza, I. and Fratalocchi, E. (2006): Effectiveness of cement on hydraulic conductivity of compacted soil–cement mixtures. Proceedings of the Institution of Civil Engineers-Ground Improvement, 10(2), 77-90.
5) Brunori, F., Penzo, M.C., Torri, D., 1989. Soil shear strength: Its measurement and soil detachability. Catena, 16, 59–71.
6) Cruse, R. and Larson, W. (1977): Effect of soil shear strength on soil detachment due to raindrop impact. Soil Science Society of America Journal, 41, 777–781.
7) Hueso-González, P., Ruiz-Sinoga, J.D., Martínez-Murillo, J.F. and Lavee, H. (2015): Overland flow generation mechanisms affected by topsoil treatment: Application to soil conservation. Geomorphology, 228, 796–804.
8) Indraratna, B., Athukorala, R. and Vinod, J. (2013): Estimating the rate of erosion of a silty sand treated with lignosulfonate, Journal of Geotechnical and Geoenvironmental Engineering, 139, 701–714.
9) Kawamura, M., Diamond, S. (1975): Stabilization of clay soils against erosion loss.
10) Lade, P.V. and Overton, D.D. (1989): Cementation effects in frictional materials. Journal of Geotechnical Engineering, 115, 1373-1387.
11) Liu, Y.W., Yen, T., Hsu, T.H. and Liou, J.C. (2006): Erosive resistibility of low cement high performance concrete. Construction Building Materials, 20, 128–133.
12) Mehenni, A., Cuisinier, O. and Marsouri, F. (2016): Impact of Lime, Cement, and Clay Treatments on the Internal Erosion of Compacted Soils. Journal of Materials in Civil Engineering, 4016071.
13) Morgan, R.P.C. (2005): Soil erosion and conservation, third ed. Blackwell publishing, Australia.
14) Mubeen, M.M. (2005): Stabilization of soft clay in irrigation projects. Irrigation and Drainage, 54, 175–187.
15) Nimmo, J.R. (2013): Porosity and pore size distribution, Reference Module in Earth Systems and Environmental Sciences. Published by Elsevier Inc.
16) Ola, S.A. and Mbata, A. (1990): Durability of soil-cement for building purposes rain erosion resistance test. Construction Building Materials, 4, 182-187.
17) Poesen, J. (1981): Rainwash experiments on the erodibility of loose sediments. Earth Surf. Process. Landforms, 6, 285–307.
18) Powledge, B.G.R., Ralston, D.C., Miller, P., Chen, Y.H., Clopper, P.E. and Temple, D.M. (1989): Mechanics of overflow erosion on embankments. II: hydraulic and Design Consideration, 115, 1056–1075.
19) Rahardjo, H. et al., (2018): Effect of concrete waste particles on infiltration characteristics of soil. Environmental Earth Science, 77:347.
20) Reddi, L. N., Lee, I-M., Bonala, M.V.S., 2000. Comparison of internal and surface erosion using flow pump tests on a sand-kaolinite mixture. Geotechnic Testing Journal, 23, 116-122.
21) Sasanian, S. and Newson, T.A. (2014): Basic parameters governing the behaviour of cement-treated clays. Soils and Foundation, 54, 209–224.
22) Sariosseiri, F., Razavi, M., Carlson, K. and Ghazvinian, B. (2011): Stabilization of soils with portland cement and CKD and application of CKD on slope erosion control. In Geo-Frontiers 2011: Advances in Geotechnical Engineering, 78-787.
23) Wischmeier, W.H. and Mannering, J.V. (1969): Relation of soil properties to its erodibility 1. Soil Science Society of America Journal, 33, 131-137.