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Experimental Study of Subsurface Erosion in River Banks

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***Abstract*—**Subsurface erosion in river banks and its details, in spite of its occurrence in various parts of the world has rarely been paid attention by researchers. In this paper, quantitative concept of the subsurface bank erosion has been investigated for vertical banks. Vertical banks were simulated experimentally by considering a sandy erodible layer overlaid by clayey one under uniformly distributed constant overhead pressure. Results of the experiments are indicated that rate of sandy layer erosion is decreased by an increase in overburden; likewise, substituting 20% of coarse (3.5 mm) sand layer bed material by fine material (1.4 mm) may lead to a decrease in erosion rate by one-third. This signifies the importance of the bed material composition effect on sandy layers erosion due to subsurface erosion in river banks.

***Keywords*—**Subsurface Erosion, Vertical Banks, Bed Material Size

I. Introduction

EROSION of streambanks is a combination of: (1) lateral erosion of the bank toe by fluvial entrainment of in-situ bank materials, often tented fluvial erosion; and (2) mass failure of the upper part of the bank due to gravity.

In one hand, streambank failure occurs when gravitational forces that tend to move soil down slope exceed the forces of friction and cohesion that resist movement. The risk of failure is usually expressed by a factor of safety (FS) representing the ratio of resisting-to-driving forces or moments. Banks may fail by four distinct types of failure mechanisms [1]: (1) planar failures, (2) rotational failures, (3) cantilever failures and (4) piping and sapping failures (Figure 1). Steep banks commonly fail along planar failure surfaces, with the failure block sliding downward and outward into the channel [2]. High, mildly sloped stream banks (bank angle less than 60°) usually fail along cursed surfaces. Cantilevered or overhanging banks are generated when erosion of an erodible layer in a stratified bank leads to undermining of overlying, erosion-resistant layers [3]. Streambanks may also fail by exfiltrating seepage and internal erosion known as piping and sapping [4].On the other hand, streambank erosion can occur at times and in places not consistent with common theories of tractive force erosion.

Banks and shorelines may fail long after periods of high stage and in locations where deposition would be anticipated (e.g., on the convex or bar side of bends).

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A major cause of such unanticipated erosion may be outflow of seepage, with attendant removal of soil particles in the exfiltration zone, and consequent instability of underlying strata located above the zone of soil loss. Figure 1-d shows a site where seepage flow out of a sandy layer carried sand out of the streambank, and the overlying more cohesive upper bank layer was undermined and collapsed [5]. According to figure 2, collapse of undercut soil layers may partially or totally obscure the exfiltration zone where the internal erosion was initiated [6]. Quite often, internal erosion of sandy soil creates approximately cylindrical conduits, or "pipes". Consequently, this form of erosion has been called "piping", defined by Mears in 1968 as "… subterranean erosion initiated by percolating waters which remove solid particles … to produce tubular underground conduits". Figure 3 shows an area of streambank in which multiple cavities were created by seepage outflow and where soil loss was extensive [7].

The detrimental effects of concentrated seepage outflow in cohesionless soils have long been recognized.

Instability in soil embankments caused by seepage-related internal erosion was described by Casagrande and the importance of this erosion mechanism to the safety of dams has been demonstrated repeatedly by Terzaghi [4]. However, the significance of piping / sapping in bank and shoreline erosion has not been widely recognized [8]-[9].The important influence of antecedent moisture on the erodibility of soils has long been understood as has the role of pore-water pressure in slope stability [10].

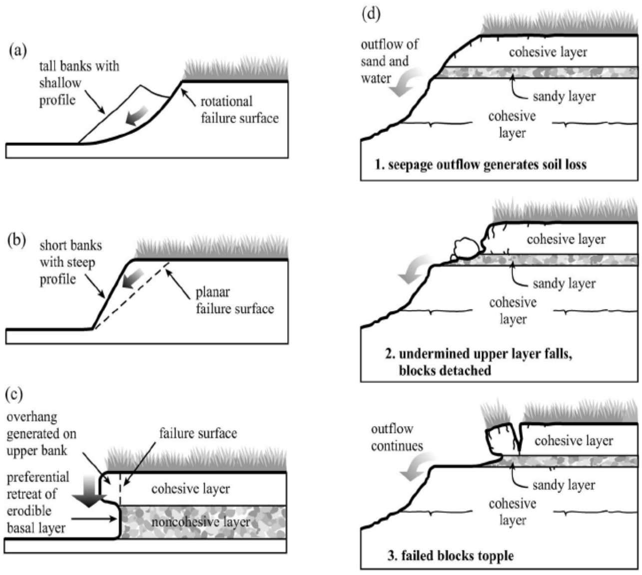

Fig. 1 Bank failure mechanism: (a) Rotational; (b) Planar; (c) Cantilever and (d) Piping or sapping [5]

II. Significance Of Piping / Sapping

Fig. 2 Collapse of layer undercut by piping / sapping [6]

Piping and sapping are significant erosion mechanisms because of their role in the initiation of drainage patterns. Recognition that through flow may be important in rill formation is relatively new, especially in the context of experimental demonstration. Piping and sapping are important also because of their widespread geographic occurrence; erosion by seepage outflow has been noted in many different geological settings (alluvial banks, glacial terrain, and residual and colluvial soils), as well as in many different localities. Finally, piping / sapping is important because of the way this mechanism interacts with other bank and shore processes to influence sediment transport.

Fig. 3 Cavities of typical piping / sapping erosion [6]

A. Formation of Drainage Patterns

Infiltrating precipitation commonly passes through soil zones of decreasing hydraulic conductivity between the soil surface and the pedological parent material; such layers of lower relative permeability tend to retard vertical flow and promote lateral flow. If this lateral flow emerges at an exfiltration face where the surface elevation is lower, a rill or gully may be initiated. Piping has long been recognized as an important factor in gully formation, but the mechanism was considered more important in arid climates than in humid zones. Other and more research has shown that piping is significant in the initiation of a total drainage pattern [4].Much of the emphasis on piping as an initiator of regional drainage has been prompted by the demonstration that through-flow is a very important component in the hydrologic system in a watershed [4], [8]. Some investigators have even speculated that seepage is the dominant factor in the formation of regional drainage systems [4], [8]. Piping is considered a major factor in the formation of submarine canyons and has been shown to be the cause of both very large erosional features and minute features in drainage ditches [2], [4], [8].

B. Geographic Distribution

While piping has been shown to be important in the formation of drainage patterns, it also has been shown to be an erosion mechanism operating on streambanks and shorelines throughout the world. Piping / sapping erosion has been documented in almost anywhere in the world e.g. Australia, Canada, China, Northern Ireland, Iran, Poland, Sudan and United States [2], [4]-[6].

C. Geologic Distribution

The most commonly noted occurrence of piping in streambanks has been in alluvial soil deposits where the natural layering associated with alluvium favors concentration of flow in more pervious strata, and more cohesive layers tend to bridge over cavities, allowing conduits to form [4]. However, piping and sapping have been noted in glacial terrain where the heterogeneity of the soil deposits may concentrate flow and where secondary features such as joints in precompressed deposits also may lead to localized flow and exfiltration.

Frozen soil zones can retard and concentrate flow to produce sapping, and the piping / sapping mechanism may act in concert with freeze-thaw mechanisms to cause destruction of soil structure and loss of soil from a bank or shoreline. Numerous instances of piping / sapping operating with other mechanisms have been seen in lakeshore bluffs. Piping occurred even in lacustrine deposits consisting of interbedded silts and varved clays when the lakebed deposits were exposed by excavation below the water table [4]-[5].

D. Influence on Sediment Transport

Piping / sapping removes soil grains from exfiltration faces and transports those grains away from the exfiltration zone. If the piping occurs in a streambank or shoreline, the displaced material is particularly susceptible to further transport and working by currents, waves, and other bank / shore phenomena [4]. The structure of the in situ soil mass is disrupted, and the displaced soil grains tend to be loose and erodible. Furthermore, formation of cavities in a seepage outflow zone commonly undermines strata located at higher elevations. Tension and shear stresses are created in the undercut layers, cracks form parallel to the face of the bank or bluff, and blocks or slabs fall from the face. The fallen blocks and slabs are disrupted and weakened, and thus are more erodible. Moreover, the presence of blocks or slabs that have fallen onto the lower bank causes significant interference with flow when the bank is inundated during subsequent periods of high stage.

Turbulent flow around the displaced soil masses will be more effective in eroding those masses than would have been the flow over the bank prior to the piping / sapping and consequent collapse of upper strata. Wave action will be more effective in breaking down fallen slabs and blocks than would have been the waves breaking on the shore before the piping / sapping and collapse. Soil loss from a site will be accelerated greatly if piping / sapping is severe there. Piping and sapping also will occur wherever concentrated seepage outflow is sufficiently intense to cause removal of soil grains; piping / sapping is not related by necessity to planform considerations in a stream or to proximity to a body of water (other than the source of the seepage outflow).

Piping can be caused by infiltrating precipitation, by lateral flow from a surface impoundment, or by leakage from a pipeline or tank; thus, piping can occur and may even be more likely when the stream itself is relatively inactive. Piping and subsequent collapse of undercut strata can occur at elevations far above the stream or lake level and during periods of low discharge and / or low stage. When the stream floods, or when winds drive waves onto the shore, an irregular configuration of erodible materials may await the onslaught of currents or waves because of the operation of piping and sapping in prior times. Whether or not the erodible failed material is present will depend upon whether or not all conditions necessary for piping / sapping to occur were met [4]-[6].

III. Experimental Study Design

As mentioned above, subsurface erosion most occurs in non-cohesive soils. Also existence of layers of soil with different hydraulic conductivity in river bank is necessary for gathering seepage flow. This experimental study was done for modeling subsurface erosion in a sandy layer in a river bank with vertical slope.

A. *Flume Experiments*

According to figure 4, flume experiments were carried out in a 60 cm long, 40 cm high and 6 cm wide of a metal box. One of the walls was made off Plexiglas which helps to observe the present phenomenon and erosion's process easily. At the bottom of it there is a tank made off plastic pipe with 5 cm diameter. Next to the Plexiglas wall you can see ruler for measuring erosion level. Water enters from top of plastic tank and provides the required water height to make selected hydraulic gradient. For making fixed the height of water, there are some holes in selected heights. Water comes up till the selected height and extra water goes down from holes and doesn’t let it go up. The bottom of tank and end of experiment box connect to each other by a rectangular hole with size of 4*4 cm. Water enters sandy layer through this hole. Each of Clay and sandy layers with 4 cm thickness was poured inside of experiment box. In order to impose overhead pressure to the soil layers, a rigid plate with the size of 4.5 *5.5*60 cm was put on clay layer.

TABLE I
CHARACTERISTICS OF TESTS AND THEIR RESULTS

Test No.	Single Load (kg)	Grain-size Distribution Type	D_{50} (mm)	Water Level H (cm)	Critical Water Level H_c (cm)	Erosion Rate (cm/min)
1	10	1	1.6	60	30	10
2	20	1	1.6	60	35	6.67
3	30	1	1.6	60	50	1.92
4	10	2	1.1	45	35	4.76
5	20	2	1.1	45	40	2.17
6	30	2	1.1	60	50	0.95
7	20	2	1.1	60	40	10.5
8	20	3	1.4	60	59.9	6.8
9	20	4	3.5	60	58	2.29

The overhead pressure was supplied by exerting a single load to the mid-point of the plate and therefore exerted to the soil layers' surface uniformly.

Fig. 4 Side view of experimental flume

B. *Soil Conditions*

The experiment was carried out for two layers, sandy layer at the bottom and clay one at top. Clay layer has high cohesion and trivial infiltration. In this experiment the role of this layer is to prevent water infiltration from walls and to distribute overhead pressure to lower layers more uniformly. The soil properties which were used in this study could be classified according to table I.

C. *Experiment Procedure*

The main steps of this experimental study can be summarized as follows; At first the selected sand was poured in box and was distributed uniformly with 4 cm thickness, then clay layer just like the previous layer and the same thickness was poured over it .After that the rigid plate was settled on it. The slope of frontal part of soil is unstable and it will collapse with a little shake. For solving this problem during the pouring the soil inside the box, a plastic plate was located in front of it and after pouring soil and before exerting the overhead pressure, at first the water was entered into the box slowly. Water with infiltration in sandy layer was rise and attracted into the upper clay layer. After about 30 minute, the water humidifies the whole upper layer. Now by removing the plastic plate and because of high cohesion of clay layer, the vertical slope is stable. In all steps, it was tried to keep safe the soil against the effect of external forces like stroke and severe shake which affect soil's compaction. Then, overhead pressure was exerted for all experiments for 18 hours and after that water enters to the box slowly. A selective photograph of the experiment was shown in figure 5.

Water level by opening the tap in a controlled manner goes up. The holes in selected height make it possible to keep the water level stable in that height. In lower water level, none erosion was observed but through the raising of water level and passing the critical level, erosion starts. The erosion of sandy layer starts from forward side and develops into the backward. In order to compare the erosion process in different experiments, the measurements was monitored for a 10 cm band. It is important to remind that the proportionate level of water for beginning the erosion was recorded as a critical water level.

In this study 9 sets of experiment were tested. Characteristics of these tests and their results were summarized as table I.

IV. Results and Conclusion

According to above mentioned subsurface erosion in river banks and its details, in spite of its occurrence in various parts

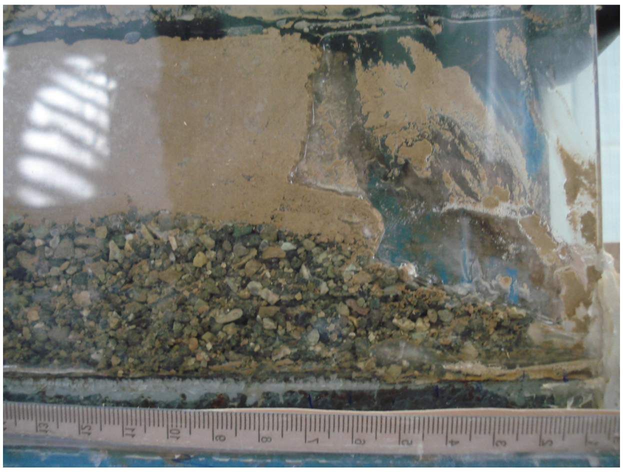

Fig. 5 A sample view of the experiment

of the world has rarely been paid attention by researchers. In this paper, an experimental study has been planned to investigate the subsurface erosion in river vertical banks.

This study aimed to find out the: (a) variation of erosion rate due to overhead pressure changes, (b) variation of critical water level for beginning of erosion due to overhead pressure changes, and (c) variation of erosion rate due to different effective particle size. According to the results the above mentioned goals were investigated accordingly; Figures 6 shows the variation of erosion rate due to overburden changes for D_{50}=1.6 mm and H=60 cm. In the same way, figure 7 shows the variation of erosion rate due to overburden changes for D_{50}=1.1 mm and H=45 cm.

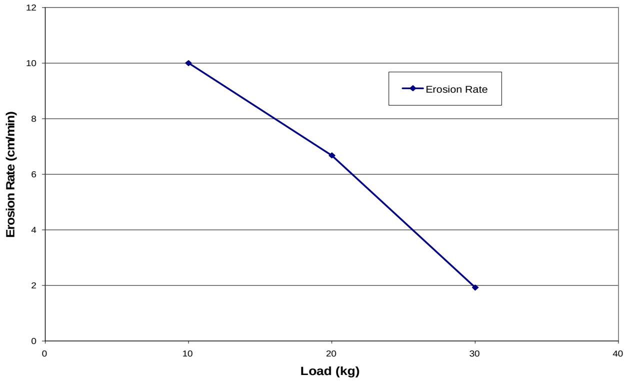

Fig. 6 Variation of erosion rate due to overburden changes for D_{50}=1.6 mm and H=60 cm

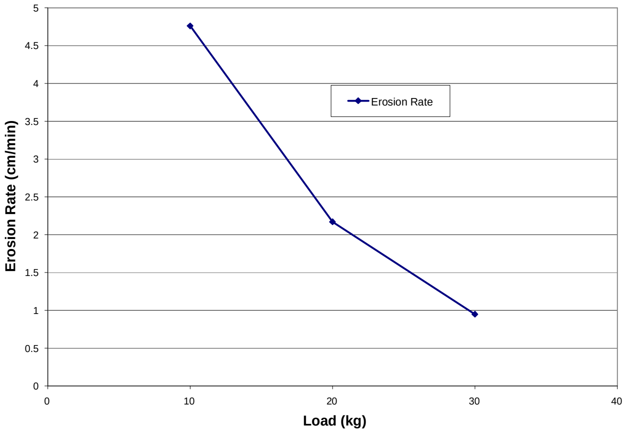

Fig. 7 Variation of erosion rate due to overburden changes for D_{50}=1.1 mm and H=45 cm

Figure 8 shows the variation of critical water level for beginning of erosion due to overburden changes for D_{50}=1.1 mm and D_{50}=1.6 mm.

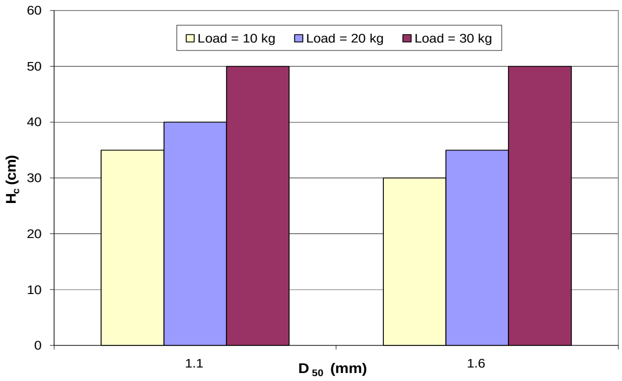

Fig. 8 Variation of critical water level for beginning of erosion due to overburden changes for D_{50}=1.1 mm and D_{50}=1.6 mm)

Figure 9 shows the variation of erosion rate due to different effective particle size (D_{50}) for load=20 kg and H=60 cm.

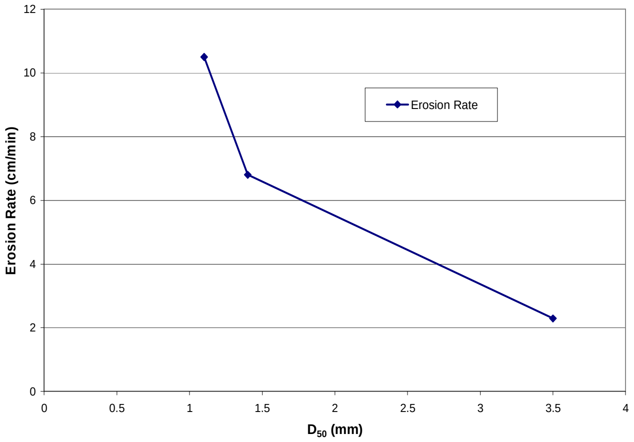

Fig. 9 Variation of erosion rate due to different effective particle size (D_{50}) for load=20 kg and H=60 cm

Results of the experiments are indicated that rate of sandy layer erosion is decreased by an increase in overburden; likewise, the rate of critical water level for beginning of erosion due to overburden changes erosion is increased by an increase in overburden; and finally, substituting 20% of coarse (3.5 mm) sand layer bed material by fine material (1.4 mm) may lead to a decrease in erosion rate by one-third. This signifies the importance of the bed material composition effect on sandy layers erosion due to subsurface erosion in river banks.

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