Erosion, Sediments Transport and Riverbank Stability: A Review

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Abstract. This paper is a review of the basic theoretical information needed to understand the riverbank stability, failure mechanism, and its causes. The first part describes the basic principles of river systems involving river hydraulics, sediment load, and channel morphology. This is pursued by a brief discussion concerning riverbank erosion that involves theoretical equations and numerical methods to quantify erosion. Finally, an in-depth discussion concerning riverbank stability that involves the types of failure mechanism, tension cracks, and riverbank settlement is conducted. Also, the paper reviews some previous studies on riverbank stability.

Keywords: Erosion, River, Riverbanks, Sediments, Hydraulic of flow.

1. Introduction

Rivers are the lifeline for hundreds of millions of peoples around the world. The sediment transport along the river section affecting the water quality and the storage capacity as well as the navigation of the river. Most of these tons of the sediments are coming from the collapsibility of the riverbanks particularly during the cyclic of flood-scarcity season. Physical and numerical modeling of rivers include the study of hydraulic system, sediment transport, and riverbank stability, however, these elements have not been studied in one model, where most of the models provide developed resolutions on hydraulic of flow and sediment transport, but they cannot analyze riverbank stability, so, more numerical studies are needed to evaluate and control the models [1]. This paper reviews the basic theoretical information needed to understand the riverbank stability, failure mechanism, and its causes. The first part describes the basic principles of river systems involving river hydraulics, sediment load, and channel morphology. This is pursued by a brief discussion concerning riverbank erosion that involves theoretical equations and numerical methods to quantify erosion. Finally, in-depth discussion concerning with riverbank stability that involves types of failure mechanism, tension cracks, and riverbank settlement. Also, the paper reviews some previous studies on riverbank stability.

A numerical study is conducted to investigate the effect of seasonal variation of the river and the rise of groundwater level on the slope stability, the slope was designed over a period of 97 days with the most effective periods affecting the stability which is the decreasing of river level and the increase of groundwater level, the results showed that the factor of safety decreased by 13% to 17% at the end of the period [2].

A field study is conducted to describe the riverbank stability of a part of the Hilla river in Babylon province, the fieldwork included measuring the dimensions of the riverbank, identifying the erosional and sedimentation riverbank, and preparing a map in this regard [3]. The results of the study showed that the types of failures in the area of study are the alcove-shape failure, the slap-shape failure, and the toppling-shape failure, and found that the most important parameters which harm the stability of
riverbank are the bank height, the bank slope, and the intensity of river meander. A study is carried out to investigate the effect of soil properties on the stability of the Shatt AL-Arab riverbank, where four study areas were selected [4]. After the laboratory tests were conducted to determine the soil properties of each area, cohesion, internal friction angle, and the weight density of soil, and for different depths, the Prokon software was used for slope stability analysis of the selected areas, the results of their study showed that all the slopes are stable but it is consistent in the degree of stability, and cohesion has a major role in conjunction with the bank height in determining the degree of stability, in addition to the effect of water flow level and groundwater level, from their study they obtained predictive equations that can be used to determine the slope stability in different conditions.

Principles of physical modeling are followed to investigate the stability of overhanging riverbanks using a transparent tank that has dimensions of 200 cm in length, 100 cm width, and 100 cm height [5]. The main purpose of their study was to compare the cantilever failure mechanism, where two types of material were used with three different densities. The results of their study showed that the mechanism of toppling failure is more likely to happen than the mechanism of shear failure. (A. Samadi et al. 2012) and performed numerical modeling using SIGMA/W software to simulate the stress-strain attitude in the bank of the model, the numerical results showed a good agreement between experimental and numerical data, however, experimental failures observed in a high-density cohesive soil were not repeated in simulations. An erosion measurement device is designed and built containing an acrylic flume with a length of 243 cm in length, 10 cm wide, and 5 cm height [6]. The purpose of the device was to measure the function of erosion (which referred to the relationship between the hydraulic shear stress and the rate of erosion) for a specific soil specimen, and water used from the red river in Winnipeg, Manitoba. Jianfar, 2014 [6] conducted a numerical modeling using Geo-Studio software to study the slope stability and seepage applying two scenarios one in the normal state of flow and the other in a state of flooding, based on previously available information on flow velocity and shear stress conducted by KGS group using Flow-3D software, Jianfar’s results showed that the operation of floodgate has no effect on the stability of riverbank in the upstream as the factor of safety has approximated value in both of the two scenarios.

An experimental rectangular flume is made of Plexiglas wall that has dimensions of 10m x0.3cm x0.2m, to inspect the cantilever mechanism of the failure of cohesive riverbank’s models and the fluvial erosion [7]. The slope was set to be 1/500, three types of soil were used which were classified according to the silt-clay content, their results showed that the initial stage of cantilever failure starts when the upper part of the river bank undermined due to the fluvial erosion at the lower part, followed by the appearance of cracks on the surface of the bank, then the cantilever failure occurs. Patsinghasanee et al. 2015 [7] applied a numerical model of their study consist of three grids, 1D grid for flow modeling in the lateral direction, a 1D grid for sediment transfer and representation of deformation in the lateral direction, and 2D grid for modeling the cantilever failure in the vertical and lateral direction, the experimental and simulated results showed a good coincidence. A study is conducted on the Tigris riverbank erosion in the city of Nu’amania using a two-dimensional hydraulic mathematical RMA2 model, in addition to the use of static BSTEM software [8]. The purpose of their study was to find out the cause of riverbank erosion in the area to determine the best ways to address the problem of riverbank erosion that meets the hydraulic requirements at the lowest cost possible, where three types of treatments were compared which is the riprap, gabion, and vegetation. The result of their study showed that the treatment using riprap is the best solution due to the low cost, in addition to it reduces the flow velocity at the riverbank.

A horizontal flume has 1.7m length, 0.5m wide, and 0.6m deep is used, which was divided into two parts, one for the river, and the other for the bank, to investigate the tension cracks development due to change of water level and how these cracks effect on the riverbanks’ stability. [9]. Their study investigated three elements, decline of river levels, primary water elevation, and the slope angle of the riverbank. Two experimental formulas were used to estimate the location of tension cracks and the angle of failure plane to verify the accuracy of the model used, where the model gave a good prediction in riverbank stability analysis.

An experimental test using 0.75m long, 0.25m wide and 0.25m deep slopping flume is used, with a rainfall simulator, and a strip laser device, to conduct an experimental erosion test, to investigate how
the changes in the soil surface topography forms effect on the erosion practicability were estimated by the strip laser device [10]. Six slopes inclination of the flume were applied (5°, 10°, 15°, 20°, 25°, and 30°) and the rainfall simulator produced a 30-min with a rate of an equivalent kinetic energy 80 mm/hr. The variance between a digital elevation model of the different periods was used to gain the eroded soil volume and the conformable rating of the loss in the soil mass. The consequence was that the volume of eroded soil and sediment crops related to the slope and rainfall period. A flume made of acrylic material is manufactured, and consists of two segments, inflow segment of 50 cm long, and main channel segment of 150 cm long, 10 cm wide, and 15 cm high [11]. To study the factors affecting sediment connectivity of landslide materials, where they applied different angles for flow and channel gradient, and using different types of sediment with changing the water content for each one from (0 to 100, up to 20%), the results showed that all landslides occurred when the water content was greater than or less than saturation and that the largest landslides were with the largest angle of flow and angle of the gradient.

2. River Systems
The primary explanation behind the complication of river engineering is that river flow has no fixed boundaries and geometry compared with, state, pipe flow, or open-channel flow. Also, the complication resulting from the change in roughness of the boundary due to the transfer of the sediment [12]. The main purpose that the rivers are serving is the transportation of water and sediment. The characteristics of flow and sediment load depend on two factors, climate, and geology of the region [13]. The discharge of the river depends on the climate in the region, where the composition of the river bed and banks depend on the geology of the region. River morphology is related to channel composition and geometry, and with the longitudinal profile, it is time-dependent and changes with discharge, sediment properties, and with the material of the bank [12]. River morphology is mainly based on climate and geology of the region, which in turn affect discharge and sediment load as shown in Fig 1, [14].

![Figure 1. Variables affecting river morphology [13]](image)

The operations that modify the morphology involve erosion or entrainment, conveyance of sediment load, and deposition [15].

2.1. Hydraulic of Flow
Corrosion of the bed and banks of a channel is the consequence of the shear stress that affects the cross-section of the channel. Shear stress depends on the fluid viscosity and velocity gradient as shown in Eq. 1 [16]. An increment in the velocity gradient leads to an increment in the shear stress.
\[
\tau = \nu \frac{dv}{dy}
\]

Where \(\tau\) is the shear stress, \(\nu\) is the fluid viscosity, \(dv/dy\) is the velocity gradient. The velocity distribution in the open channel flow section is not uniformly due to the existence of the free surface and to the friction of the bed and banks of the channel. Other factors are also dominant, the velocity distribution such as the channel section shape, and the existence of the bends. The maximum velocity predominantly found at the free surface, where at the bed of the channel the velocity diminution to zero due to the frictional forces [17]. The utmost amount of erosion results from the highest shear stress at the bed and the toe bank region of the channel which causes the maximum velocity gradient. The effect of the inertial force and the fluid viscosity specify the attitude of open channel flow where the flow may be laminar or turbulent, in laminar flow the particles of water seem to move in definite streamlines and thin layers of fluid slip over neighboring layers, whereas in turbulent flow the particles of water stir in chaotic paths which causes great erosion [17]. Fig. 2 shows the velocity distribution in cases of laminar and turbulent flow.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{velocity_distribution.png}
\caption{Velocity distribution in laminar and turbulent flow conditions [17]}
\end{figure}

To specify whether the flow is laminar or turbulent, the Reynold number should be calculated as expressed in Eq. 2, which represents the proportion of viscous and inertial forces [18]. The flow is laminar when the Reynold number is less than 500 and turbulent when it is greater than 2500.

\[
Re = \frac{\rho VL}{\mu}
\]

Where \(Re\) is the Reynold number, \(\rho\) is the density of water, \(V\) is the flow velocity, \(L\) is the characteristics length which represent by the hydraulic depth or the hydraulic radius in free-surface flows, \(\mu\) is the dynamic viscosity. In laboratory flume, the disturbance that occurs at the entrance of the channel which is unavoidable causes arising in the water level in one side resulting in a spiral motion on this site only, but after a distance from the entrance, there will be a spiral motion on both sides of the channel, in this stage the spiral motion could be ignored for practical purposes in the straight channels because the shear stress on both sides will be in equilibrium in this state [17].

In the distribution of the mean velocity, the lines of equal velocity (isovels) are nearer at the boundaries as shown in Fig.3. In the center of the channel, the velocity is the highest due to the lack of friction as far from the boundaries [17]. The shear stress is greatest where the isovels are closer together, so in a wide shallow section, the shear stress is the highest at the bed, wherein narrow deep-section the shear stress is greatest at the banks [17].
2.2. Sediment Load
Sediment transport typically due to a combination between gravity acting on the sediment, and/or the movement of the fluid in which the sediment is entrained. The resisting force of the grains forming the boundary in alluvial streams controlled by the cohesion and angle of friction between the grains, when the driving force that caused by fluid motion, overcome the resisting force, the grains will be brought into motion. If the shear stress at a certain point is larger than the critical shear stress, the grains will be detached from its location, and the region is said to be scoured. There are two mechanisms of sediment transport, bedload and suspended load, in bed load sediment transportation, the ratio of relative tractive force $\frac{\tau}{\tau_c}$ at a point, is slightly greater than 1 [18]. In bed load transportation, the large grains of sediment (coarse sand and gravel) with size larger than 0.06 mm in diameter slide and roll on the bed, where could not be transported with flow due to its heavyweight [16]. Reciprocally, when the relative tractive force is much large, fine grains will be carried by the fluid in suspension and move downstream by turbulence [18].

The suspended load which is composed of fine particles (silt and clay), requires little or no energy to be transported with the flow, which results in raising the efficiency of the river by decreasing the frictional losses of energy due to inner turbulence reduction [16]. The bedform affected by several parameters which are the flow velocity and the flow depth, slope of the bed, size of sediment particles, and the fall velocity of the particles, sediment particles will begin to move increasing the flow velocity [20]. When the mean velocity is greater than the critical velocity, the sediment particles will entrain and transport with fluid, and when the critical velocity is greater than the mean value, the sediment will drop out of suspension [16].

Hjulstrom curve expresses the relationship between the size of sediment particles and flow velocity for entrainment, transportation, and deposition as shown in Fig. 4, the upper line shows the erosional velocity or critical erosion velocity that needed to initiate sediment erosion, the lower line shows the fall or settling velocity, between the two lines there is the region of sediment transportation. Hjulstrom curve shows that noncohesive sediment such as sand needs low velocity to entrain from the bed, however, silt and clay need higher velocity to be entrained due to cohesive nature of clay particle that makes strong bonds among particles called electrochemical bonds, but once clay particles are entrained from the bed, they are easily maintained in suspension at a lower velocity than the velocity that needs to entrained the particles [15]. Hjulstrom curve also shows erosion which is the picking up of sediment and requires high velocity than transportation. In contrast, the deposition region of the diagram for coarse particles of sediment, where deposition happens if the velocity drawdown below the erosional velocity.
2.3. Channel Morphology

Channel morphology related to channel composition and geometry; it is time-dependent, changes with longitudinal profile, sediment amount and characteristics, discharge, and bank material properties [12]. Climate and geology of the region are secondary factors that influence the discharge and sediment type [13]. The precipitation amount and hence the discharge are specified by the hydrology, whereas the properties of the channel bed and banks and hence the sediment type are specified by the geology of the region. The channel form related to the processes that occur in the river which are erosion, sediment load transportation, and deposition [15]. For example, the flow velocity increases due to the discharge increase as a result of heavy rainfall, the channel restraint for this increase by extending the cross-sectional area to be able to carry the flow.

The cross-section degradation of the river depends on the response of different types of sediment to erosion [15]. Sediments that respond easily to erosion such as sand, produce wide and shallow channels, whereas clay and silt sediments produce steep and narrow channels [15]. When the discharge increases too quickly, the flow surpasses riverbank and the flooding occurs. Flow velocity decreases on the land surface and the deposit of the sediment, which are composed of the bed and banks of the floodplain. The coarse sediments deposited near the channel edge, while the finer and lighter sediments move away [21]. River flow starts from high regions towards lower and planer regions and then pours into the ocean [13]. The cross-section of the river and the sediment load differs from one region to another according to the difference of the topography of the earth. The amount and size of the sediment carried by flow have a significant impact on the river morphology when the concentration of sediments increases, deposition occurs on the bed due to the inability of discharge to carry the sediment load as a result of decreasing in river efficiency [13].

2.4. Equilibrium

Rivers are a system in dynamic equilibrium which means neither erosion nor deposition occurs, balancing of water flow and sediment transport. When river channels are altered under naturally dynamic hydrologic conditions, the river readjusts itself concerning morphology to reach its former balance or equilibrium. Some researchers have suggested the term of dynamic equilibrium or changing balance, where the river changes in some parts to reach an equilibrium state [15]. The state of the equilibrium of rivers can be achieved by the deposition of the soil particles and the erosion process. Many parameters affect directly of the riverbank’s erosion such as the channel size, channel discharge, and the strength of the flow. Moreover, even of the river flow is stable, for a long period of flow, the sedimentation and the erosion of the riverbanks is an ongoing natural process [22].

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Figure 4. Hjulstrom curve for erosion, transportation, and deposition as a function of particle size and river velocity [19].
3. Erosion

The removal process of soil particles from the bed and banks of the river, known as the erosion process [15]. Erosion concerns to many factors that could be categorized under three types, geometric factors that include the geometry of the channel, geomorphic factors that include the soil characteristics of the channel bed and banks, and hydraulic factors that include the flow characteristics. To determine the amount of eroded soil from the channel bed and banks, three variables should be known, which are the fluid shear stress, critical shear stress, and erosion rate. Previous researchers have presented several methods to calculate these variables; the following section will present some of these methods.

3.1. Fluid Shear Stress

Fluid shear stress is one of the most important factors desired to calculate the amount of erosion. It is known as the force per unit area in the flow direction [23]. Fig 5 illustrates the distribution of shear stress in the two-dimensional uniform flow in a channel, the direction of flow within x-axis, z-axis perpendicular to the flow. The stresses and forces implicate the horizontal component of the fluid weight $W_x$, shear stress $\tau$ on BC, and the hydrostatic forces on AB and CD. All forces implement in the x-direction. The hydrostatic forces are equal and opposite when the flow is uniform and $W_x$ must be equiponderant by the shear force.

![Figure 5. Schematic of forces acting on a unit volume of flow [21]](image)

Fenton, 2005 presented the tractive force or drag force method, the tractive force resulting from the shear stress that is exerted by water flow on the channel bed and banks, occurs in straight channels with uniform flow. It is the most dependable method in channels that are exposed to erosion or scours in the boundary, where the erosion occurs as the forces that cause particle movement are larger than the resisting forces, this concept was reintroduced by [18]. The distribution of the tractive force or the shear stress on the channel bed and banks approximately considered to be equal to as shown in Eq. 3 and 4 respectively [24].

$$\tau_o = \gamma RS$$  \hspace{1cm} (3)

$$\tau_o = 0.76 \gamma RS$$  \hspace{1cm} (4)

Where $\tau_o$ is the shear stress, $\gamma$ is the specific weight of water, R is the hydraulic radius, S is the channel bed slope. Anderson, 1970 presented the same concept of the different of the shear stress in trapezoidal channels between the channel bed and banks, where the maximum shear stress occurs at the channel bed, and the minimum shear stress occurs at the top of the channel banks, as shown in Fig. 6 [25]. For this specific cross-section of side slope 2:1, the maximum shear stress on the bed and banks are 1.37$\gamma$RS, and 1.08$\gamma$RS, respectively.
3.2. Critical Shear Stress

Soil particles begin to move when the force that causing movement is larger than the resisting forces. The resisting forces of soil particles depend on the soil properties, for example, in the non-cohesive soils like sand and gravel, the amount of particles resistance to erosion is the amount of gravity force to its submerged weight [15]. The amount of critical shear stress for non-cohesive soils can be determined from the Shields curve as shown in Fig. 8 which represents the relationship between soil particle diameters ranging from 0.1 mm to 10000 mm and the amount of critical shear stress ranging from 0.1 Pa to 10 Pa, this relationship based on several experiments conducted on a set of flat layers of sand. Shields curve has been developed by many researchers to include a larger range of particle diameters, but it nevertheless provides critical shear stress only on the channel bed [13].

Figure 6. Shear stress distribution in the boundary of the trapezoidal channel [21]

The shear stress coefficient on the bed and banks of the channel was adjusted by [21], as a function of the ratio of the bed width to the water depth, Fig.7 (a and b) illustrates these coefficients for different side slopes.

Figure 7. Maximum shear stress coefficient on the channel boundary with different side slope; (a) on the bed, and (b) on banks [21]

Figure 8. Shields curve [15]
The critical shear stress in the channel sides is different from that on the channel bed, where the particles in the channel sides slip down due to the effect of the weight component along the side slope, while the particles on the channel bed are exposed to the drag force in the direction of flow. To calculate the critical shear stress at the channel sides, the critical shear stress at the channel bed is multiplied by the factor $K$, which represents the drag force required to initiate movement on the channel sides relative to the tractive force required to initiate movement on the channel bed, Eq. 5 is used to determine the value of $K$ factor, [26].

$$K = \sqrt{1 - \frac{\sin^2\theta}{\sin^2\phi}}$$  \hspace{1cm} (5)

Where, $\theta$ is the side slope angle, and $\phi$ is the friction angle of soil. Critical shear stress for cohesive soils cannot be calculated from the Shields curve because the gravity force that causes the particles to slide down the side slope is much smaller than the cohesive force between these particles, so it is neglected. The resisting force for cohesive soil depends on the physical and chemical properties such as the chemical bonding between particles, interaction with pore, and eroding fluid [27].

A study was presented by [27] to develop a quantitative method to predict the critical shear stress and the rate of erosion for natural soil, 42 soil samples were collected from different stream-bank sites, half of the samples were taken from stable sites where no erosion was occurring, the other half were taken from sites where significant erosion was causing a problem with bank stability. Preliminary tests were conducted on all the 42 soil samples, and then based upon the preliminary test results, 30 samples were selected for detailed analysis which consists of flume erosion test, rotating cylinder erosion test, and some of the other preliminary tests. The results of the study showed that as the salt concentration of the eroding fluid decreased, the critical shear stress of the soil decreased and the amount of change of the erosion rate increased. From Fig. 9 that developed by [28] and revised by [9], the critical shear stress of soil can be calculated as a function of sodium adsorption ratio SAR, electrical conductivity, and soil salt concentration [27].

![Figure 9](image)

**Figure 9.** Critical shear stress as a function of SAR for different value of electrical conductivity and different soil salt concentration [27]

Sodium adsorption ratio is an indicator of soil salinity, which determines the ratio of sodium (Na) relative to calcium (Ca) and magnesium (Mg), as shown in Eq. 6 to determine the soil flocculation which improved water absorption. Calcium and magnesium are good soil flocculation while sodium is not. The term double-layer diffusion propagates on the surface of soil particles that are negatively charged, and which attract positively charged particles [30].
\[ SAR = \frac{Na^+}{\sqrt{Ca^{++}+Mg^{++}}} \]  

Another method for measuring critical shear stress was introduced by [31], using Erosion Functional Apparatus (EFA), where the soil sample is pumped using Shelby tube then flow is poured on it and at certain limits of velocity, after that, the time required to erode the soil is calculated and under the effect of a certain velocity, and the shear stress is determined using Eq. 7.

\[ \tau = \frac{1}{8} f \rho v^2 \]  

Where \( \tau \) is the shear stress, \( f \) is the friction factor obtained from the Moody chart, \( \rho \) is the water density, \( v \) is the flow velocity in the flume. The results introduced by [31] showed that the critical shear stress for fine-grained soil ranging from 0 to 5 Pa. In flume studies, the critical shear stress is measured visually or graphically, visually, by measuring the shear stress at failure, as mentioned by [32] showed that the critical shear stress occurs when “pitting of the surface” occur, while [33] stated that the critical shear stress occur when “the water became cloudy”, and when “general movement of the soil composing the channel bed was observed” as mentioned by [34]. To avoid inaccuracies in visual calculations of critical shear stress, the graphical representation can be used by plotting the shear stress versus the erosion rate with a best-fit line, the shear stress value that intersects with the point where no erosion occurs, represent the critical shear stress value [35]. Eq. 8 related between the critical shear stress for cohesive soil and the clay percent by weight, was presented by [34] through an experimental flume study conducted on 11 soil samples.

\[ \tau_c = 0.493 \times 10^{0.0182 P_c} \]  

Where, \( \tau_c \) is the critical shear stress (Pa), \( P_c \) is the percent clay by weight.

### 3.3. Erosion Rate

Erosion rate is the amount of soil that lost over a while, once the applied shear stress on the soil overcomes the critical shear stress. The determination of the erosion rate can be useful in back-calculated to predict the bank retreat. Eq. 9 used to estimate the erosion rate depending on the excess shear stress, for fine-grained soil where the erosion occurs due to soil scour or overland flow [35], [36].

\[ \varepsilon = K_d (\tau_a - \tau_c)^a \]  

Where, \( \varepsilon \) is the erosion rate (m/s), \( \tau_a \) is the applied shear stress (Pa), \( \tau_c \) is the critical shear stress (Pa), \( a \) is a component commonly assumed equal to 1, \( K_d \) is the erodibility coefficient (m^3/(N.s)) calculated from Eq. 10 as a function of critical shear stress [39].

\[ K_d = 0.2 \tau_c^{-0.5} \]  

The average applied shear stress can be calculated using Eq. 11.

\[ \tau_a = \rho g d S \]  

Where \( \rho \) is the density of water (kg/m^3), \( g \) is the gravity acceleration (m/s^2), \( d \) is the height of water above the midpoint of the section (m), \( S \) is the channel slope. Lane, 1955 Calculated the erosion rate using Eq. 12 which depending on the eroded sample height represented by (h), and the time desired to erode the soil (t), where the criterion height of the soil sample is 1 mm from the flume bottom [23].

\[ z = \frac{h}{t} \]  

A relationship between the excess shear stress and actual erosion rate was developed by [38], as illustrated in Eq.13 and 14. This relationship based on the test results of [29].
\[ dB = \frac{223 \times 10^{-4} \tau_c e^{-0.13 \tau_c}}{\gamma_s} \]  

(13)

Where, \( dB \) is the initial erosion rate (m/min per unit area), \( \tau_c \) is the critical shear stress (dynes/cm\(^2\)), \( \gamma_s \) is the unit weight of soil (kN/m\(^3\)). The actual rate of erosion was then determined by applying the excess shear stress, as shown in Eq. 14.

\[ dw = dB \frac{(\tau - \tau_c)}{\tau} \]  

(14)

Where, \( dw \) is the actual erosion rate (m/min), \( \tau \) is the fluid shear stress (dynes/cm\(^2\)).

4. Conclusions

The paper presents the basic principles for the study of riverbank stability and failure, in terms of the failure mechanism and its causes. The conclusions are:

- Several factors contribute to the destabilization of the riverbank, which include hydraulic factors, geomorphic factors, and geometric factors.
- The climate and geology that differs from one region to another, play a major role in the degree of riverbank failure, where the climate controls the precipitation hence the discharge of the river, in addition to water level variation between summer and winter, also the effect of humidity, drought, ice, and melting. However, the geology controls the sediment load.
- The erosion rate of the riverbank is considered an important cause of riverbank failure, erosion rate depends on the fluid shear stress, and the critical shear stress. Previous researchers developed experimental and theoretical methods to calculate the critical shear stress which mainly depends on the material properties.
- The importance of the study of riverbank stability is to understand the reasons that led to failure, and thus to identify the necessary treatment that is compatible with the hydraulic requirements to prevent the recurrence of failure, also that to design stable slopes, one needs to know the changes that occur in the soil properties within the slope overtime under the effect of different factors that lead to failure.

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