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RESEARCH ARTICLE

Calculation of The Initiation of Sediment Motion in Open Earthen Channels

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Abstract

This article analyzes the conditions under which sediment movement begins in open channels with earthen channels. The relationship between tangential stress and critical stress, as well as the main factors influencing the movement of sediment particles, are considered. Based on the Shylds parameter and its determination methods, the start threshold of particle motion is estimated. The influence of the canal's hydraulic parameters on sediment dynamics is also highlighted. The research results are of great importance in the design and effective operation of open canals.

KEYWORDS

Open channel, flow velocity, sediments, bottom sediments, suspended sediments; turbidity, tangential stress, shear force, bank.

INTRODUCTION

Water flow in a channel continuously tends to erode its boundaries. Fine sediments (silt), gravel, or even larger boulders are first detached from the bed or banks and then transported downstream by the flow. The detachment of sediments from the bed or banks and their subsequent movement along the flow is referred to as sediment transport, a phenomenon of significant economic importance [2, 4, 7, 8].

Sediment discharge:

The amount of solid particles (sediments) entering the channel is called sediment discharge. It is one of the key factors determining the stable shape and cross-sectional form of the channel [1–5, 9].

Sediments moving within a fluid can conventionally be divided into two categories:

1. Bed load:

This refers to the movement of bed material in the lowermost layer of the flow. Due to hydrodynamic conditions, particles in this layer do not become suspended. Bed load particles are not supported by the flow; instead, they move along the channel bed by rolling, sliding, and saltation. The weight of bed load particles is supported by the stationary particles of the bed. These particles are in continuous motion, regularly exchanging positions with the immobile particles of the channel bed. 2. Suspended load:

Due to hydrodynamic conditions, sediments in this layer can exist in suspension. Unlike bed load, particles are not in continuous contact with the bed; instead, they are carried within the flow. However, near the bed, particles may still intermittently interact with the surface through rolling, sliding, and saltation.

As the flow velocity increases, finer particles are lifted into suspension under the influence of the upward components of turbulent flow. At the same time, particles continuously tend to settle under the action of gravity. The flowing water, through turbulent mixing, generates upward-directed motions that counteract this settling process.

As a result of turbulent exchange, water continuously moves between different horizontal layers over a certain distance. The upward-moving water originates from lower layers with higher sediment concentration, while the downward-moving water comes from upper layers with lower sediment concentration.

During this turbulent exchange process, a resultant upward-directed force is formed. This force supports the upward movement of sediment particles and counterbalances their tendency to settle under gravity, thereby maintaining a dynamic equilibrium.

Suspended sediments also contribute to additional hydrostatic pressure within the channel bed.

Thus, the upward-moving flow carries sediments from high-concentration lower layers, while the downward-moving flow brings clearer water from upper layers. The net effect of turbulence is the presence of an excess upward force, which maintains particles in suspension and balances the gravitational settling effect. Suspended load also produces additional hydrostatic pressure on the channel bed [1, 3, 7, 9, 10].

Theory of tractive force:

In studying the process of sediment transport, it is commonly assumed that bed material particles are non-cohesive, since most riverbeds consist of sand and gravel. The primary mechanism governing sediment motion is the tractive force exerted by the flowing water on the channel bed in the direction of flow. This force is also referred to as shear force or tangential force. It represents the force applied by the flow to the wetted perimeter of the channel, acting along the bed surface [1, 11, 12].

Let us consider a channel of length L and cross-sectional area ω.

The volume of water within the channel is equal to ωL. If γ is the specific weight of water, then the total weight of water in this length of the channel is $\gamma\omega L$.

The weight of water acting in the vertical direction is $\gamma\omega L$. The horizontal component of this weight is $\gamma\omega L\sin\theta$, where θ is the bed slope angle of the channel. Thus, the horizontal component of the weight is: $\gamma\omega LI$

This horizontal force generated by the water is considered the **tractive force (shear force)**. If the average tractive force acting per unit wetted surface is denoted by τ, then:

$$\tau = \frac{\gamma\omega LI}{\chi L} = \frac{\gamma\omega I}{\chi} = \gamma IR \qquad (1)$$

Thus, the average unit tractive force (also called shear stress) is expressed as: $\tau = \gamma IR$

For wide channels, the hydraulic radius is approximately equal to the flow depth.

Therefore, the tractive force can also be written as:

$$\tau = \gamma Ih \quad (2)$$

If the tractive force exceeds the frictional resistance between particles, the particles begin to move. The resistance to sediment motion is proportional to the particle diameter and to the submerged (apparent) weight of the sediment in water.

The value of the critical tractive force is expressed as follows:

$$\tau_c = C\left(\rho_s - 1\right)d \qquad (3)$$

where **C** is a constant (later found to be variable); ρ_s is the specific weight of solid sediment particles.

E. V. Leyn proposed the following equation for determining the critical tractive force τ_c:

$\tau_c = 0,078d$ (кг/м² да), bu yerda д d mm da o'lchanadi.

where d is the particle diameter, measured in millimeters (mm), and τ_c is expressed in kg/m².

For different soil types, the values of the critical tractive force (in kg/m²) are presented in Table 1.

Table 1

Soil type	Value of τ_a (kg/sm²) (tractive force)
Medium sand	0.17
Sandy soil (loamy sand)	0.20
Alluvial silty sand, coarse sand, etc.	0.25
Fine gravel	0.37
Coarse gravel	1.47
Hard (consolidated) layers	3.18

Let us consider the influence of side slopes. The stability of a horizontal channel bed is determined by equations (1) or (2). However, on the bank slopes, an additional driving force acts, namely the component of the particle weight.

Let us consider a particle at rest on the bank slope with weight G. The following forces act on this particle:

$$\tau = \gamma IR; \quad (4)$$

- the component of the particle weight acting **along the bank slope**: $w \sin\theta$;
- the component of the particle weight acting **normal to the bank slope**: $R \tan\theta$;

where: θ - the angle of the bank slope relative to the horizontal; φ - the angle of natural repose.

Figure 1 illustrates the different forces acting on the particle and their force diagram.

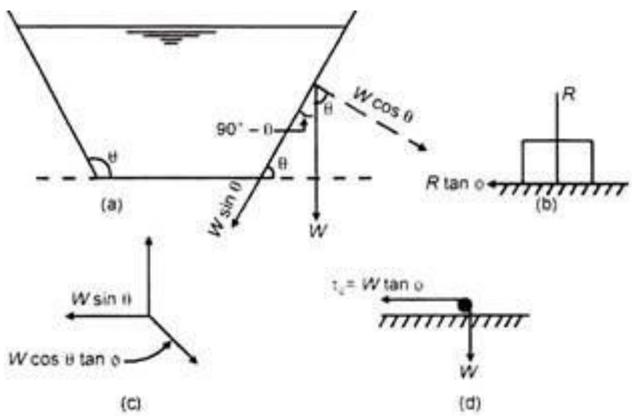

Figure 1. Forces acting on channel side slopes.

$$\tau_c = w\mu = w\tan\varphi \qquad (5)$$

Here, τ_c is the critical shear stress required to move a similar particle along a horizontal bed.

Let us consider the force diagram of the forces acting on the particle.

$$(\tau_0)^2 + (\omega \sin\theta)^2 = (\tau_c \cos\theta)^2 = (W \tan\phi \cos\theta)^2$$

$$(\tau_0)^2 + \left(\frac{\tau_c}{\tan\phi}\sin\theta\right)^2 = \left(\frac{\tau_c}{\tan\phi}\cos\theta\tan\phi\right)^2$$

$$(\tau_0)^2 + \frac{\tau_c^2}{\tan^2\phi}\sin^2\theta = \tau_c^2\cos^2\theta$$

$$\tau_0^2 = \tau_c^2\left[\cos^2\theta - \frac{\sin^2\theta}{\tan^2\phi}\right]$$

$$\frac{(\tau_0)^2}{(\tau_c)^2} = \cos^2\theta - \frac{\sin^2\theta}{\tan^2\phi} = \cos^2\theta\left[1 - \frac{\tan^2\theta}{\tan^2\phi}\right]$$

$$\left(\frac{\tau_0}{\tau_c}\right) = \left[\cos^2\theta + \sin^2\theta - \sin^2\theta - \frac{\sin^2\theta}{\tan^2\phi}\right]$$

$$= \left[1 - \sin^2\theta - \frac{\sin^2\theta}{\tan^2\phi}\right]$$

$$= \left[1 - \sin^2\theta\left(1 + \frac{1}{\tan^2\phi}\right)\right]$$

$$= \left[1 - \sin^2\theta\left(\frac{1+\tan^2\phi}{\tan^2\phi}\right)\right]$$

$$= \left[1 - \sin^2\theta\frac{\sec^2\phi}{\tan^2\phi}\right]$$

$$= 1 - \frac{\sin^2\theta}{\sin^2\phi} \qquad (7)$$

$$\left(\frac{\tau_0}{\tau_c}\right) = 1 - \frac{\sin^2\theta}{\sin^2\phi} \qquad (8)$$

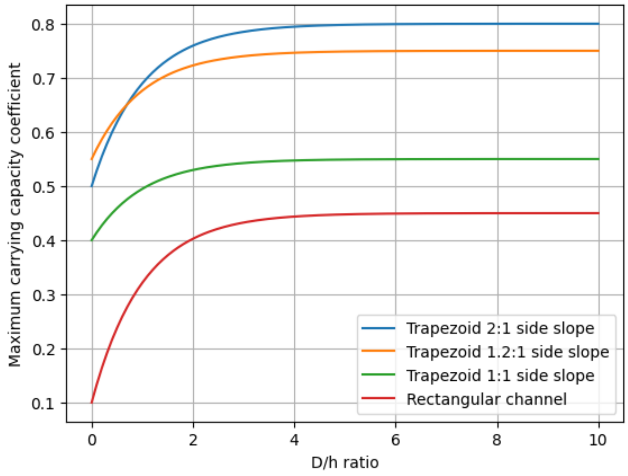

Figure 2. For the side slope

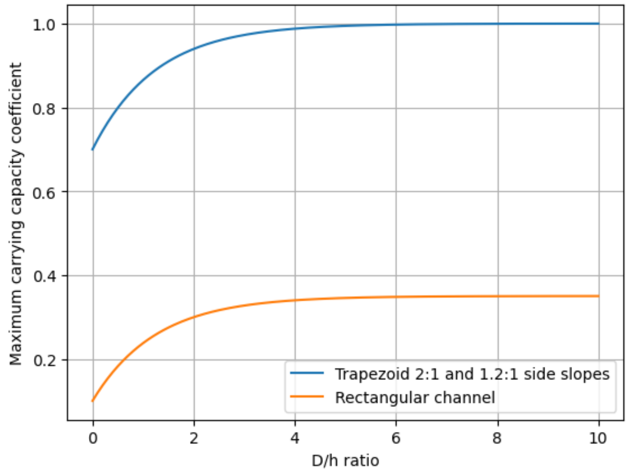

Figure 3. For the bed

This equation $\tau_c > \tau_0$ shows that the required shear stress on a slope is smaller. This means that the frictional force, or shear stress, required to move a particle along an inclined surface is less than that required to move the same particle along a horizontal bed.

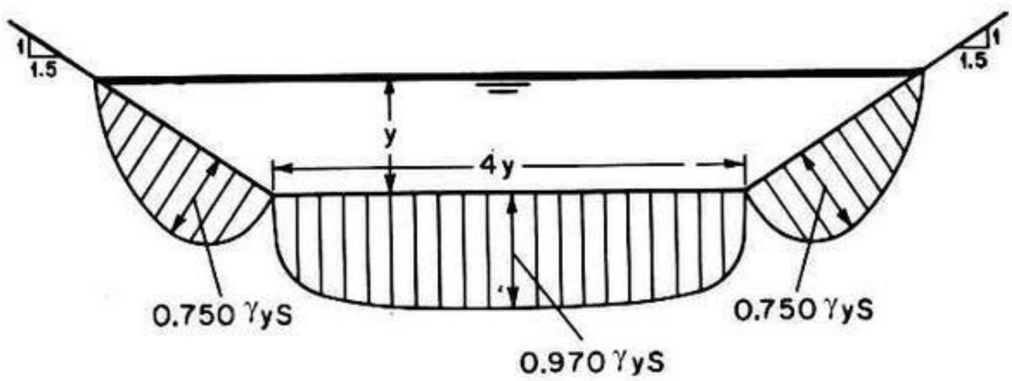

Figure 4. Typical distribution of tractive force

The average shear stress (tractive force) generated by water flowing in a horizontal channel is determined by the formula:

$$\tau_0 = \gamma IR$$

On slopes (side walls), its value is reduced and is expressed as: $\tau_c = 0,75\tau_0 = 0,75\gamma IR$

The distribution of shear stress (tractive force) is shown in Figure 4.

As illustrated in Figure 4 the distribution of unit tractive force (shear stress) is rectangular over the channel bed and parabolic along the side slopes. The magnitude of the unit tractive force (shear stress) also depends on the curvature of the channel.

The permissible tractive force for curved and straight channels is given as follows:

Degree of curvature	Relative critical tractive force (%)

Straight channel	100%
Slightly curved channels	90%
Moderately curved channels	75%
Sharply curved channels	60%

Channels formed in coarse alluvium are designed based on the **Shields criterion for the initiation of sediment motion**. This method is explained as follows:

According to this approach, the motion of a particle at the bed depends on the following variables:

- the bed shear stress (tractive force per unit area) τ_0 ;
- the density of the sediment particle ρ_s ;
- the density of the fluid ρ_f ;
- the particle diameter d ;
- the dynamic viscosity of the fluid μ .

Among all these variables, the **shear stress** τ_0 is the most important factor, since it represents the flow's capacity to initiate sediment motion. This parameter depends on the flow velocity υ .

To study the motion of particles at the channel bed, the method of **dimensional analysis** is applied.

By grouping the six variables listed above, three **dimensionless parameters** can be obtained. These parameters are as follows:

$$\frac{\tau_0}{P_f g d}, \frac{P_s}{P_f}, \frac{d\sqrt{P_f \tau_0}}{\mu}. \qquad (9)$$

Although the velocity term is not strictly required, it is convenient to introduce a parameter with the dimension of velocity. Therefore, we introduce a new term called the **shear (friction) velocity**, denoted by υ' .

$$\upsilon' = \sqrt{\frac{\tau_0}{P_f}}$$

or

$$\tau_0 = (\upsilon')^2 P_f .$$

The first dimensionless parameter is equal to $\frac{\tau_0}{P_f g d}$.

$$\frac{\upsilon'^2 P_f}{P_f g d} = \frac{\upsilon'^2}{gd}$$

The three dimensionless parameters are as follows:

$$\frac{\upsilon'^2}{gd} \qquad (10)$$

$$\frac{P_s}{P_f} \qquad (11)$$

$$\frac{\sqrt{P_f \tau_0}}{\mu} = \frac{\sqrt[d]{P_f (\upsilon')^2 P_f}}{\mu} = \frac{d\upsilon' P_f}{\mu} = \frac{d\upsilon'}{\frac{\mu}{P_f}} = \frac{d\upsilon'}{\upsilon} \quad (12)$$

By combining the dimensionless parameters (10) and (11), another dimensionless parameter of the form $\upsilon_2' / gd(S_s - 1)$ can be obtained.

This expression can be further simplified as follows:

$$\omega = 1 \qquad \tau_0 = \omega RS \qquad \frac{\upsilon'^2}{gd(S_s-1)} = \frac{\tau_0}{\frac{P_f}{gd(S_s-1)}} = \frac{\tau_0}{P_f gd(S_s-1)} = \frac{\tau_0}{\omega d(S_s-1)}; \quad (13)$$

where $P_f g = \gamma$ - the specific weight of water, and S_s - is the specific weight of the sediment particle.

This dimensionless number is called the Shields parameter and is denoted by F_c.

The third dimensionless parameter, expressed as $d\upsilon' / \upsilon$ is called the Reynolds number (Re) where υ is the kinematic viscosity.

Thus, the motion of a particle can be described as a function of these two parameters, namely. The relationship between F_c and Re can be represented graphically, as shown in Figure 5. The resulting curve serves as a fundamental tool for the design of channels requiring prevention or minimization of bed deformation.

When the Reynolds number exceeds 400, its value becomes practically constant, which significantly simplifies the analysis. In this case, the critical Shields parameter approaches a constant value of approximately 0.056.

It is observed that when the particle diameter exceeds 6 mm, the particle Reynolds number is typically greater than 400.

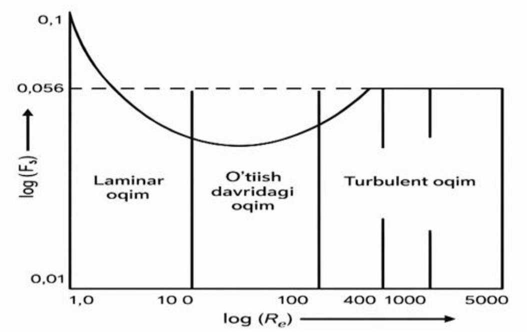

Figure 5. Relationship between F_S and R_C

Therefore, for channels composed of coarse alluvium (with particle size greater than 6 mm),

$$\frac{\tau_0}{wd(S_s-1)} = 0,056$$

For water $\gamma = 1;$ $\tau_0 = \gamma RI;$

$$\frac{\gamma RI}{\gamma d(S_s - 1)} = 0,056\$$$

$$\frac{RI}{d(2,65-1)} = 0,056.$$

In solution, $d = 11RS.$

This equation defines the **maximum particle size** that remains at rest in a channel with known values of R and I. If the particle diameter d is smaller than this value, the particle will be set in motion.

Over time, finer particles are washed away from surfaces covered with coarse stones. Therefore, in practice, the selected particle size should be somewhat larger than the value calculated using this equation.

$$d = 11RI$$

CONCLUSION

The initiation of sediment motion in open earth channels is directly governed by the hydraulic characteristics of the flow and the physical properties of the sediment particles. When the shear stress of the flow reaches a certain critical value, particles begin to move, thereby initiating deformation processes at the channel bed.

Accurate assessment and calculation of this process are essential for the proper design of channels, their efficient operation, and the prevention of adverse phenomena such as bed erosion or sediment deposition. Both theoretical and practical studies indicate that the use of scientifically grounded methods for determining sediment motion ensures the reliability and stability of hydraulic structures.

Therefore, a comprehensive understanding and proper consideration of the interaction between flow and sediment in open channels is a key factor in improving the efficiency of water management systems.

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