Settling and non-settling velocities in irrigation canals, Hamidieh and Ghods irrigation network, South of Iran

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Sedimentation in irrigation canals is one of the important problems in the exploitation of any irrigation project. This problem has many direct and indirect effects on the hydraulic characteristics and economical considerations of canals. The main objectives of the present study were: (1) to study the influence of the transmitted sediments on the hydraulic capacity of the canals, (2) to examine the various existing theories and relationships for determining the settling and non-settling velocities in the irrigation canals, and (3) to recommend the best possible and economical solutions to avoid sedimentation process in irrigation canals. The results of the study show that the limiting concentration theory and the Kennedy method had the best agreement with the measured values, respectively. Thus, these methods can be used in the design of irrigation canals to avoid sedimentation process. Also, by regulating the water surface elevation in the canals and monitoring the concentration of the sediments in the entering water, it would be possible to create the non-settling velocity conditions in irrigation canals.

Key words: Non-settling velocity, irrigation canal, regime theory, limiting concentration theory.

INTRODUCTION

One of the most important factors in designing irrigation canals is to establish special conditions to avoid settling of suspended particles on the beds of such canals. It means that the transport capacity of an irrigation canal for suspended particles must be equal to or greater than the amount of the incoming suspended particles (Moazed et al., 2004).

Theories and methods regarding sedimentation problem in irrigation canals include:

Methods based on the Regime Theory

This theory was originally developed by Kennedy and Lindley in India (Lindley, 1919; Chang, 1985). Based on this theory, the regime condition is one in which there is no erosion/sedimentation on the canal walls and bed (Lawrence and Atkinson, 1998; Garde and Ranga, 2000; Vanoni, 2006). Kennedy and Lindley concluded that for a specific depth of flow, there is a velocity that provides the regime condition in an irrigation canal.

Methods based on the minimum non-settling velocity

If the flow velocity in the canal reaches a value at which all the suspended materials with a specific diameter do not settle, this velocity is referred to as the minimum non-settling velocity (Novak and Nalluri, 1975; Nalluri and Mayerli, 1989; Nestor, 1998; Herman and Nestor, 2002). Zamarin, Girshkan, Levy, and Pavolowski studied the non-settling velocity in different irrigation canals and presented various relationships in this regard (Arora et
Table 1. Values of the $m$ coefficient for use in the Kennedy equation.

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>$m$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-grained sandy soils of the rivers in the north of India</td>
<td>1.0</td>
</tr>
<tr>
<td>Coarse-grained sandy soils and residual of the dense and heavy-textured soils</td>
<td>1.1</td>
</tr>
<tr>
<td>Sandy soils, loamy silt soils</td>
<td>1.2</td>
</tr>
<tr>
<td>Coarse-grained silty soils, residual of the dense and heavy-textured soils</td>
<td>1.3</td>
</tr>
<tr>
<td>River silt</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Limiting concentration method in lined canals

The settling process of the suspended materials in lined canals has been studied since 1970. Although the flow velocity has been considered as one of the effective factors in preventing the settling of the suspended materials, however, to obtain better results, all other factors effective in the settling and transport of suspended materials have been considered, as well. One of the important factors in this regard is the transport capacity of the suspended materials of the canal. Thus, the limiting concentration theory was presented for lined canals. The limiting concentration theory describes the potential of transporting suspended materials under various conditions (Nalluri and Mayerli, 1989; Lawrence and Atkinson, 1998). Pollaiah described the ultimate concentration as a function of dimensionless parameters (Paul and Sakuja, 1990). Arora et al. (1984) completed the studies of the Pollaiah and performed a number of experiments considering the limiting concentration and assessed the transport of suspended materials in suspension. Arora et al. (1984) found that the ultimate concentration ($C_s$) of the suspended materials in the canals with different sections and under various conditions is a function various parameters.

The main objectives of the present study were: (1) to study the influence of the transmitted sediments on the hydraulic capacity of the canals, (2) to examine the various existing theories and relationships for determining the settling and non-settling velocities in the irrigation canals, and (3) to recommend the best possible and economical solutions to avoid sedimentation process in irrigation canals.

MATERIALS AND METHODS

The Kennedy and Lindley (1985) relationship is as follows (Chang, 1985):

$$V = 0.546my^{0.64}$$  \[2\]

Where, $V =$ flow velocity for the regime condition, $Y =$ depth of the flow, and $m =$ a coefficient dependent on the materials of the walls and bed of the canals (Table 1).

The Lacy equation is as follows:

$$V = 0.834(fR)^{1/2}$$  \[3\]

Where, $V =$ non-settling flow velocity (m), $R =$ hydraulic radius (m) and $f =$ a parameter which depends on the diameter of the bed materials of the canal and is obtained from the following relationship:

$$f = 1.587\sqrt{D_{50}}$$  \[4\]

In which $D_{50}$ is the mean diameter (mm) of the 50 percent of the settled particles and can be obtained from the grain-size distribution curve of the bed materials.

The United States Bureau of Reclamation (USBR) relationships are the most common equations that are used by the USBR in determining the minimum permissible velocity in irrigation canals. These equations are very similar to the Kennedy equation with a little change in the $m$ coefficient. The USBR relationships in the SI system of units are as follows:

$$V = 0.652Cy^{0.64}$$  \[5.a\]

$$V = 0.652Cy^{0.54}$$  \[5.b\]

Where, $C$ is a coefficient, which varies with the material of the canal bed and varies from 0.84 to 1.09. Equations 5.a and 5.b are used for waters with high and low concentrations of suspended particles, respectively.

The Levy relationship is:

$$V = 0.01\frac{w}{\sqrt{D_{av}}}\sqrt{R\left(\frac{0.0225}{n}\right)}$$  \[6\]

Where, $D_{av}$ and $W$ are the mean diameter of the suspended particles (mm) and the settling velocity (mm/s), respectively. The Girshkan equation is as follows:

$$V = AQ^{0.2}$$  \[7\]

Where, $V =$ the minimum permissible velocity (m/s), $Q =$ the canal discharge ($m^3/s$), and $A =$ a coefficient dependent on the settling...
velocity of the particles and is determined according to the following conditions:

\[ W < 1.5 \text{ mm/s}, \quad A = 0.33 \]
\[ 1.5 < W < 3.5 \text{ mm/s}, \quad A = 0.44 \]
\[ W > 3.5 \text{ mm/s}, \quad A = 0.55 \]

The Zamarin equation is as follows:

\[ V = \left( \frac{m}{350} \right)^{1/3} \times \left( \frac{W}{R} \right)^{1/2} \]  \[ (8.a) \]
\[ V = \left( \frac{m}{700} \right)^{1/3} \times \frac{W}{(Ri)^{1/2}} \]  \[ (8.b) \]

Where, \( m = \) the concentration of the suspended materials (kg m\(^{-3}\)), \( V = \) the minimum non-settling velocity (m s\(^{-1}\)), \( W = \) the settling velocity (mm s\(^{-1}\)), \( i = \) the slope of the energy line (longitudinal slope of the canal bed, m m\(^{-1}\)), \( R = \) the hydraulic radius (m), and \( n = \) the Manning’s roughness coefficient.

The Pavolowski equation is:

\[ V = 0.25(n^2) - 0.75(n^2 - 0.1)R^2 \]  \[ (9) \]

Where, \( n = \) the Manning’s roughness coefficient (dimensionless), \( R = \) hydraulic radius of the canal (m) and \( V = \) the minimum non-settling velocity (m/s).

Pollahia relationship is as follows:

\[ C_s = f\left( q \frac{S}{V} \Delta S_f / S_f, f_b, \frac{w.d}{v}, D^* \right) \]  \[ (10) \]
\[ \Delta S_f = S_f - S_c \]  \[ (11) \]
\[ f_b = \frac{8gR_s}{v^2} = \frac{8g}{R^2} \]  \[ (12) \]

Where, \( C_s = \) the ultimate concentration of the suspended materials (ppm), \( q = \) discharge per unit width of the water surface, \( S_c = \) specific gravity of the suspended materials, \( f_b = \) friction coefficient of the canal bed, \( d = \) diameter of the settling particle, \( y_0 = \) mean flow depth, \( S = \) longitudinal slope of the canal bed, \( v = \) kinematic viscosity of the fluid, \( w = \) falling velocity of the settling particle in pure water and \( D^* = \) hydraulic velocity.

The Arora relationship is:

\[ C_s = f\left( qS_{2.5}^2 \frac{y}{f_b}, \frac{y}{D^*}, \frac{w.d}{v}, d^{-0.6} \right) \]  \[ (13) \]

In which \( S_c = \) the slope parameter and is obtained from the following relationship:

\[ S_c = \frac{S}{\Delta S_f / S_f} \]  \[ (14) \]

With the assumption of \( S = 1 \), the \( S_c \) becomes:
the suspended particles was determined by the centrifuge method, sieve analysis and the hydrometric method. The concentration of suspended materials were taken every month for a period of six months. The samples from the bed materials were collected for determining the settling and non-settling sections were chosen. The settling sections chosen for the study were Voseyle1, Voseyle2, Voseyle3, Ghods2, Ghods3, Ghods4, ML1, ML2, MR1, MR2 and MR3 the non-settling sections selected were Ghods1, ML3, ML4, and MR4.

The main parameters measured were the geometric and the hydraulic characteristics of the canals required for determining flow at the chosen sections. The geometric characteristics of the selected canals included cross sectional area and bed slope and the hydraulic characteristics of the canals were flow velocity and flow rate, respectively. The cross sectional area and bed slope of the canals were obtained from surveying. The flow velocity was considered to be one of the transport parameters required in determining the settling and non-settling conditions in the canals and was measure by a micromullinet (model A. OTT, Germany). The flow rate for each canal was computed by multiplying the cross sectional area and the flow velocity. Samples for determining the suspended materials were taken every month for a period of six months. The samples from the bed materials were collected for analysis as well.

The grain-size distribution of the suspended particles was prepared by the assistance of a Mastersizer (Malvern, 35344-783, UK) apparatus. Grading of the bed materials was done by both sieve analysis and the hydromethod. The concentration of the suspended particles was determined by the centrifuge method.

RESULTS AND DISCUSSION

To evaluate the different theories and methods used in determining the non-settling velocity in the canals and comparing them with the measured ones, the sections were divided into three categories based on their settling potential of suspended materials as follows: - Sections that were sediment yielding in character and had dredging problems, - Sections that reached regime conditions (non-settling and non-eroding in character), and - Sections with minimum settling of suspended materials.

The canal sections at the Ghods1, ML3, ML4, and MR4 stations were non-settling. All other sections were settling in character, and regime condition was not observed, especially in the earth canals. Therefore, in evaluating the theories for determining the non-settling velocity, the 21 flow velocities measured at the Ghods1, ML3, ML4, and MR4 stations were non-settling, and others were settling. To select the best method for predicting flow velocity, the flow velocities calculated by the various methods were compared with the measured ones. In comparison, if a calculated velocity was greater than the measured one, the measured velocity was considered settling, otherwise, it was considered non-settling. Also, if both the measured and calculated velocities were settling, the answer was considered correct, otherwise, it was considered incorrect. The results obtained in this regard are shown in Table 2. In the following, each method is discussed first, and then by comparing the different methods, the best one is introduced.

The calculated flow velocities by the Kennedy method (Equation 2, and m = 0.7 for river silt from Table 1) consisted of five non-settling velocities which were not in agreement with the measured values and thus, were considered as incorrect answers. The remaining calculated settling and non-settling ones were in agreement with the measured ones and were considered as correct answers. This method with 46 correct and five incorrect answers and with a mean velocity of 0.39 m/s best fitted the measured values. The calculated velocities by this method along with the standard line obtained are shown in Figure 2.

The non-settling velocity was calculated by the Lacy method using Equation 3 with the f coefficient obtained from Equation 4 and on the basis of D50 of the bed materials. With 21 incorrect answers, all the calculated velocities were settling, and the mean of the calculated velocities was 0.58 m/s.

To calculate the non-settling velocity by the USBR method, Equation (5.b) was used due to the low concentration of the suspended materials in the incoming water, and with a C coefficient value equal to 1.09. All the calculated velocities were determined to be settling (Figure 3) with a mean value of 1.12 m/s which is relatively a high value.

Although in the Levy method (Equation 6), more parameters are used to calculate the minimum non-settling velocity in comparison to other methods; however, in this study its accuracy was low and all the calculated velocities were determined to be non-settling. The mean calculated velocity was 0.006 m/s which showed that this method was not an accurate one. By applying a suitable coefficient of 100, the values were modified so that, 36 of the answers were correct and 15 were incorrect; the mean velocity obtained was 0.62 m/s.

Since the calculated settling velocities for the suspended materials by the Girshkan method (Equation 7) at all areas were less than 1.5 m/s, the value of parameter A was selected as 0.33. In general, 42 calculated velocities were correct, nine were incorrect, and the mean velocity was determined to be 0.41 m/s. Therefore, the values obtained by this method were relatively in good agreement with the measured ones. In the Zamarin method (Equation 8), the concentration parameter is an effective parameter in determining the non-settling velocity. As a result, some scattering was observed in the calculated velocities. On the other words, there existed a wide range for the calculated velocities, and accordingly,
To calculate the minimum non-settling velocity by the Pavolowski method, Equation 9 was used. This equation is a function of the Manning’s roughness and the hydraulic radius. In applying this equation, the calculated or recommended roughness coefficients were considered. All the calculated velocities by this method were settling, and the mean value was 0.65 m/s.

As mentioned earlier, the limiting concentration method was presented to be used in lined canals only; there were a large number of incorrect answers as well.

Table 2. Evaluation of calculated velocities with different methods.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Regime theory</th>
<th>Minimum non-settling velocity</th>
<th>Limiting concentration theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling</td>
<td>35</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>Regime</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Non-settling</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Correct answers</td>
<td>46</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Incorrect answers</td>
<td>5</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Percent incorrect</td>
<td>10</td>
<td>41</td>
<td>41</td>
</tr>
</tbody>
</table>
accordingly, it was used in this study to examine the settling conditions in the lined sections of the canals. Since in the Arora function (Equation 13), the ultimate concentration of the suspended materials, \( C_s \), is a function of a series of parameters such as hydraulic parameters, sediment characteristics, etc., it was considered to be the most reliable method in determining the non-settling conditions in lined canals like the Hamidieh and Ghods Irrigation Network. Based on this method, it would be possible to present an algorithm for designing canals in order to control the settling conditions. Therefore, at first the \( (X) \) parameter could be determined using Fig. 1 for a specific value of concentration and particle size distribution of the incoming sediments from the following equation:

\[
X = \left[ q \cdot S \cdot C \cdot \frac{(D_0)^2}{f_{w}} \cdot \frac{(w_0 \cdot d)}{v} \right]^{0.6}
\]  

Then, from Equation 16, the depth or non-settling velocity could be determined keeping other parameters constant. In this study, at first the \( (X) \) parameter was calculated, and then the settling or non-settling condition of the flow velocity was determined for various suspended material concentrations using Figure 1. Based on the results shown in Table 2, 18 settling and nine non-settling velocities calculated by this method were correct answers, whereas six measured settling velocities were calculated (assuming no change in the bed level during a six-month period) by this method as non-settling and thus, were considered as incorrect answers. The incorrect answers calculated by this method were those that occurred at the times of rainfall, when the concentration of the suspended materials in the incoming water was high.

**Conclusion**

The following conclusions could be drawn from the results obtained in this study:

1) In lined irrigation canals, the limiting concentration method showed the best agreement with the measured values in determining the settling and non-settling velocities, and

2) In unlined irrigation canals, the Kennedy Method and the Girshkan Method showed the best agreement with the measured values respectively.

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