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Calculation of effective hydraulic parameters of concrete irrigation canals

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Abstract: When taking water from pre-mountain rivers, for transferring of large amounts of river sediments, rich in mineral fertilizers, along with water to crop fields through irrigation networks requires high sediment transport capacity and deformation resistance from irrigation networks. The projecting and construction of irrigation canals with these features in the foothills requires concreting the canal. The high content of river sediments in the Sokh River (5 kg·m^{-3}) and the low efficiency of the Right Bank Irrigation Reservoir (10–15%) require high hydraulic efficiency of water intake canals from this system. The main challenge is to reduce costs in concreted canals and ultimately ensure technical superiority. In the research were used generally accepted research methods in hydraulics, in particular field research and consequently, mathematical analysis. Kokandsay, Kartan and Bachkir irrigation canals were accepted as the object of research, the canals were designed on the basis of the best hydraulic section, the canal side slope was taken as a variable parameter and the technical and economic efficiency was checked using computer software. As a result, it was found that the consumption of concrete raw material for 1 running meter can save 0.2–0.3 m^3, depending on the adoption of the canal side slope, the acceptance of the slope of the canal wall at values 1–1.5 will increase up to sedimentation 10%.

Keywords: canal bottom relative width, concrete canal, irrigation canal, sediment transport capacity, sedimentation tank, the best hydraulic section, trapezoidal shape

INTRODUCTION

When taking water from foothills, a large amount of sediment, rich in mineral fertilizers, also moves in irrigation canals along with water. However, due to the low efficiency of hydraulic and reclamation facilities which built for the management of river sediments, regulation of water volume and their use in obtaining water from foothills, river sediments are regularly transferred to irrigation canals [Eaton *et al.* 2004; Samiyev *et al.* 2020]. As a result, the process of deposition in irrigation canals, which are the arteries of agriculture of Uzbekistan, is accelerating. Similar problems can be observed in large irrigation canals such as Big Fergana, Big Andijan, Bozsuv, Tashkent, Parkent, South Mirzachul, Dustlik, Amu Bukhara, Karshi, Karakum and Shovot, which receive water from major rivers in Central Asia, such as Syr Darya, Amu Darya and Zarafshan [Khalimbetov *et al.* 2020; Yunusov *et al.* 2020].

About 88% of the canals built in the Republic of Uzbekistan are earthen canals, and due to the amount of filtration and the high level of runoff in these canals, about 40% of water is wasted in the network, and the required amount of water does not reach crops. According to research on the hydraulic efficiency of irrigation canals, if the total water losses in the system are assumed to be 100%, 70–75% will account for filtration, 3–5% for evaporation and the remaining 20–25% will technical [Chow 1959; Fatxulloyev *et al.* 2020b]. As a result, irrigation works are delayed and yields are significantly reduced. To prevent such problems, in the country has developed state programs for the reconstruction of irrigation networks and working to cover the canals with concrete [Mirziyoyev 2020]. Covering ground canals with concrete pavements is a complex process and requires a large amount of investment.

Scientists have conducted scientific research at various times to substantiate and construct hydraulic parameters in the design of earthen canals. The aim of these scientists was to increase the hydraulic efficiency of soil canals, and the studies did not specify the conditions of hydraulic efficiency of the concrete canal [Choi *et al.* 2004; Ibrahim *et al.* 2021; Karaushev 1977; Raveendra 2017].

The sediment transport of flow in the canals i.e. the assessment of the sediment movement many scientists conducted scientific research and gave their practical recommendations. These studies did not take into account the effect of river sediments on the flow of concrete canals [Arifjanov, Fatxulloyev 2020; Carling 1988; Kovalenko, Mikhaylov 2008; Mirchkhulava 1967].

Research has been conducted by Grishkan [1961] to ensure the hydraulic stability of the trapezoidal canal section, to justify the width of the canal bottom, and a number of practical results have been achieved. However, based on these results, the project and construction of self-concreting canals leads to an increase in costs. Because, according to the projection results, canal bottom relative width is β = 2–5, which leads to an increase in the amount of raw materials used for concreting [Cheng *et al.* 2019; Koç 2012].

In the Fergana valley, more than a dozen irrigation canals, which receive water from the foothills such as Naryn, Karadarya and Sokh, serves supply water to the existing 500 thous. ha irrigated areas and other sectors of the economy [Samiyev *et al.* 2020]. The depletion of water resources due to global climate change today requires a sharp increase in the efficiency of irrigation systems [Turral *et al.* 2011]. This requires the reconstruction of existing irrigation networks and the consideration of these factors in the construction of new ones. Substantiation of hydraulic parameters is important in the project of concrete canals. This is because, in addition to substantiating hydraulic parameters, it is possible to project and build dynamically robust and cost-effective sections [Code 1923; Fatxulloyev *et al.* 2020a; Han, Easa 2016].

The aim of this study is to develop the calculation of irrigation canal parameters based on the best hydraulic section conditions in the construction and reconstruction of irrigation networks. The use of concreting canals in the best hydraulic section conditions allows reducing the cost of canal construction and increasing the sediment transport capacity of the canal.

STUDY MATERIALS AND METHODS

STUDY MATERIALS

Starting from the northern slopes of the Alay and Turkestan mountain ranges, glaciers at an altitude of 5550 m a.s.l., there is a high technical demand for irrigation canals through the Kokand hydrocomplex built on the Sokh River, which supplies water to irrigated areas in several districts of the Fergana valley.

The Sokh is a river in Kyrgyzstan and Uzbekistan (40.6553° N 70.7340° E). It takes its rise at the joint of the north slopes of Alay Mountains and Turkestan Range and ends in Ferghana Valley. The Sokh River is a combination of the Dalbek, Shudmon and Khojaochkan rivers near the village of Zardoli, with a total length of 124 km, a catchment area of 3,510 km^2 and an average elevation of 3480 m a.s.l. In the upper part it flows through a very deep and narrow gorge (4–10 m wide). Upon reaching the hillside zone, the river valley widens to 500 m. 71% of the annual rainfall in the river basin is snow and 29% is rain, so it is a river saturated with ice and snow. The average yearly discharge of 42.1 m^3·s^{-1}, and the water turbidity is 0.99 g·dm^{-3} [Foziljonov 2020; O'zbekiston … 2012].

Due to the high amount of river sediments (5 kg·m^{-3}) in the Sokh River during the irrigation period, an irrigation reservoir is used to draw water from the river into the irrigation canals. The "Right Bank" sediment settling tank, which receives water from the Kokand hydrocomplex to the right canal, was built in 1958 to trap sediment particles in the Sokh River and reduce its impact on the lower reaches, with a flow capacity of 110 m^3·s^{-1} (Fig. 1). This irrigation reservoir is built at the head of the right canal of the Kokand hydrocomplex, through which more than 40% of the river water is taken into the canal (Tab. 1).

Fig. 1. Spatial image of the Kokand hydrocomplex; source: own elaboration

Table 1. Distribution of water from Kokand hydrocomplex to irrigation canals

Main water intake canal	Water discharge (m^3·s^{-1})	Total length (km)	Useful work coefficient (%)
Dasturkhan	6	10	88
Left canal	40	3.4	90
Naymansoy	100	41.9	85
Right canal	110	3.34	90

Source: own elaboration.

Currently, the sediment reservoir serves to transfer water partially purified from river sediments to irrigation canals that supply water to crop fields in Uchkuprik, Buvayda, Baghdad districts. However, studies in the Right Bank irrigation sediment reservoir have shown that there is a large range between seasonal changes in the amount of river sediment in the outlet of the sediment (0.7–5.0 kg·m^{-3}) and therefore the efficiency of the sedimentation process is 10–15% (Fig. 2).

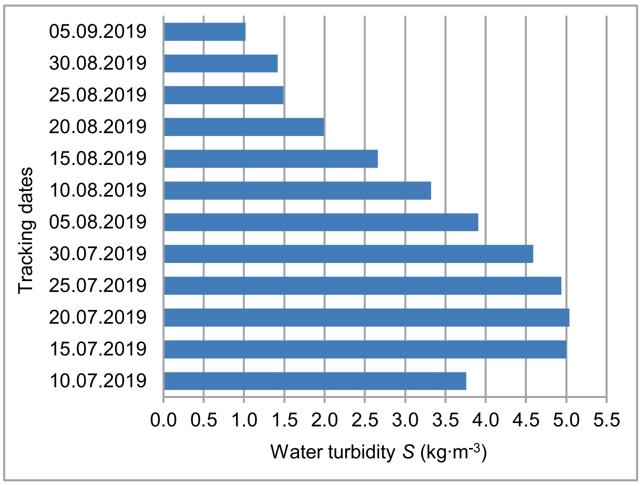

Fig. 2. Change in the amount of river sediment leaving the sedimentation tank; source: own study

According to the laboratory analysis of the samples taken at the outlet of the reservoir, 87% of the fractional composition of river sediments in the water is sand (large: 0.63–1.25 mm, medium: 0.315–0.630 mm, fine: 0.140–0.315 mm). It was found that 13% is gravel (fine: 1.25–2.5 mm) – Figure 3 – and their average diameter is large diameter (d_{avg} = 0.74 mm) sand, calculated by generally accepted methods in hydraulics below.

$$d_{\text{avg}} = \frac{\sum d_i PCT_i}{100} \quad (1)$$

where: d_{avg} = average diameter of sediment; d_i = diameter of sediment i; PCT_i = percent of sediment i.

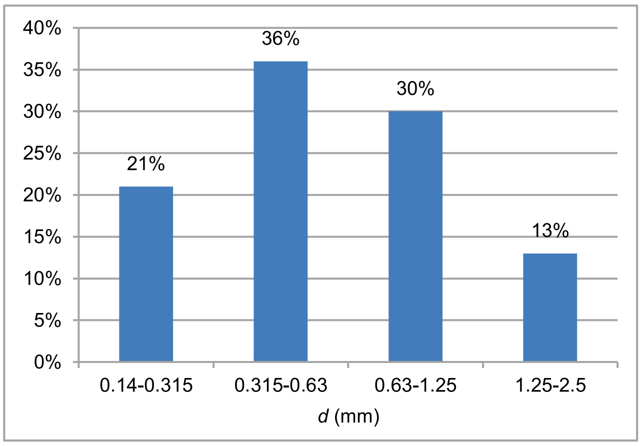

Fig. 3. Fractional composition of river sediments from the reservoir, d = diameter of sediment; source: own study

The Kokonsay, Kartan and Bachkir concrete canals were selected as the object of the study based on the low efficiency of the Right Bank reservoir and therefore the high amount of river sediments flowing into the lower canals (Tab. 2).

Despite the fact that the Kokandsay, Kartan and Bachkir canals are covered with concrete, the deformation processes in the canals can be observed in these canals due to the high level of turbulence of the flow. The design parameters of these canals do not take into account the amount of solid flows causing the canal to erode, the parapets protecting the coastline from waves caused by high flow turbulence, which leads to frequent accidents along the canal route (Photo 1).

Photo 1. The current condition of the research object (phot.: *D. Allayorov*)

Particular attention should be paid to the kinematic and dynamic characteristics of the flow in order to achieve the hydraulic efficiency of the canal when concreting the existing irrigation canals. It is desirable that the canals receiving water from the foothills of the rivers provide its priority by concreting the riverbed, as well as forming a high permeability feature.

STUDY METHODS

Canals receiving water from foothills should have high volumetric flow rate. Canals that conduct water at maximum velocity from the existing surface unit are called canals with the highest water permeability or hydraulically the best cross-section canals [Abdulrahman 2007; Han *et al.* 2017; Monadjemi 1994; Parviz 1994]. Based on this condition, it is expedient to project concrete canals, which will drastically reduce the material consumption for the construction of canals and have a high sediment transport capacity due to the high velocity [Fatxulloyev *et al.* 2020a].

Table 2. Currently indicators of canals which takes water from Kokand hydrocomplex

Water intake main canals	Water intake first order canals	Water discharge ($m^3 \cdot s^{-1}$)	Total length (km)	The width of the canal bottom (m)	Side slope	Canal depth (m)	Canal slope
Right canal	Kokandsay	25	17.1	2	1.5	2.1	0.002
	Kartan	20	10.3	2	1.5	1.9	0.002
	Bachqir	18	11.0	2	1.5	1.7	0.0025

Source: own elaboration.

Currently, the section of the canals is built mainly in the form of a trapezoid. Based on the hydraulic elements of trapezoidal canals (Fig. 4), the water permeability of the canal is often determined using the Chezy formula (Eq. 2) based on the design (or existing) parameters of the canals [ShNQ 2.06.03-12 2012].

$$v = C\sqrt{R_h S} \quad (2)$$

where: v = flow velocity, C = Chezy's coefficient; R_h = hydraulic radius; S = canal slope.

$$v = \frac{S}{n} R_h {}^{2}\!/3 \quad (3)$$

where: n = Manning's roughness coefficient.

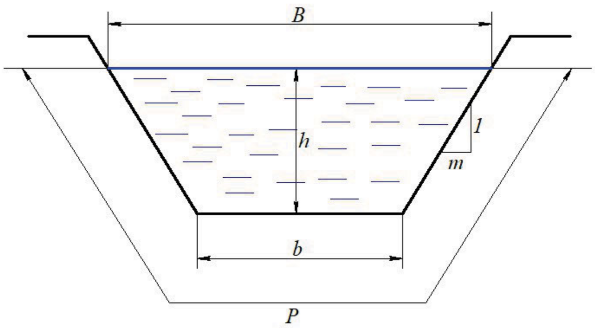

Fig. 4. Cross section of trapezoidal canal; b = the width of the bottom, B = the width of the water surface, h = the canal depth, m = side slope, P = wetted perimeter; source: own elaboration

We use the following mathematical analysis of the Chezy and Manning formula (Eq. 3) to substantiate the best hydraulic section elements of the irrigation canal.

$$v_{\max}\begin{cases} S = \text{const} \\ n = \text{const} \end{cases} R_{h\,\max} \quad (4)$$

$$R_h = \frac{A}{P}\begin{cases} A = \text{const} \\ P \neq \text{const} \end{cases} R_{h\,\max} = \frac{A}{P_{\min}} \quad (5)$$

where: A = area of cross-section of a canal, P = wetted perimeter.

According to this analysis, in order to be hydraulically best of irrigation canal, the perimeter of wetting should be kept to a minimum without changing the canal surface unit. This, in turn, allows to minimize the amount of concrete used in construction and increase the sediment transport capacity of the canal. The minimum condition of the wetting perimeter (for trapezoidal canal) is given below:

$$P = b + 2h\sqrt{1+m^2} \quad (6)$$

where: P = wetted perimeter; b = width of the bottom; h = canal depth; m = side slope.

In order to reduce the variables, we use the constant of the surface unit:

$$P = \frac{A}{h} - mh + 2h\sqrt{1+m^2} \quad (7)$$

where: A = area of cross-section of a canal.

To reach the minimum value of Equation (7), we obtain the first-order derivation from the equation on the variable (h) and set it to zero:

$$\frac{dP}{dh} = 0 \quad (7.1)$$

$$\frac{d\left(\frac{A}{h} - mh + 2h\sqrt{1+m^2}\right)}{dh} = 0 \quad (7.2)$$

$$-\frac{A}{h^2} - m + 2\sqrt{1+m^2} = 0 \quad (7.3)$$

$$\frac{bh + mh^2}{h^2} - m + 2\sqrt{1+m^2} = 0 \quad (7.4)$$

as a result we obtain the following equation for the minimum condition of the wetting perimeter for the canal cross-section variables:

$$\frac{b}{h} = 2\left(\sqrt{1+m^2} - m\right) \quad (8)$$

The cross section of trapezoidal canals can be projected and constructed in several arbitrary dimensions. In the hydraulic calculation, the concept of the canal bottom relative width (the ratio of the bottom width to the depth of water in it) is used and is written as follows:

$$\beta = \frac{b}{h} \rightarrow \beta = 2\left(\sqrt{1+m^2} - m\right) \quad (8.1)$$

where: β = canal bottom relative width.

Based on Eq. 8 above, the width of the bottom (b) of the best hydraulic section irrigation canal is determined as follows:

$$b = 2h\left(\sqrt{1+m^2} - m\right) \quad (8.2)$$

Based on Eq. 8.1, the water discharge equation of the concreted irrigation canal will look like this:

$$Q = 0.63\frac{\sqrt{S}}{n}(\beta + m)h^{8/3} \quad (9)$$

where: n = Manning's roughness coefficient, n = 0.012–0.015.

Concreting of canals on the basis of the above equation leads to inconveniences in construction works. Because in this case the ratio of the bottom width to the depth is β = 0.4–1.0 and its value is irrational. In this case, it is advisable to use the coefficient of convenience in construction.

$$b_c = kb \quad (10)$$

where: b_c = convenient width of the bottom for construction, k = coefficient of convenience in construction and it can be taken from 1.2 since 2.

Projecting high-efficiency irrigation canal based on the best hydraulic section requires the selection of optimal values of the canal side slope, and this value significantly affects the sediment transport capacity of the canal. The results of scientific research on the assessment of sediment flow rate in open streams show that the sediment transport capacity is directly proportional to the flow velocity [CARLING 1988; DEPEWEG, MENDEZ 2002; KARAUSHEV 1977; SAMIYEV *et al.* 2019]. The Equation (11) proposed by Prof. A. Arifjanov for the assessment of sediment flow rate (Q_s) in open streams has been presented as a comparative evaluator of the scientific research of many scientists [FATXULLOYEV *et al.* 2020b; HANDAYANI *et al.* 2021; JURÍK *et al.* 2018]. This equation was used to evaluate the sediment transport capacity of the flow on the computer software (DGU 13170) used in the article. In contrast to the existing methods of Equation (11), α is a variable quantity in the equation, the value of which varies depending on the mode of motion and energy state of the particles in the stream.

$$Q_s = \alpha \frac{v^3}{gR_h w_s} \tag{11}$$

where: v = flow velocity, R_h = hydraulic radius, w_s = sink velocity of sediment, g = gravitational acceleration, α = coefficient depending on the hydromechanical properties of the sediment.

RESULTS AND DISCUSSION

The hydraulic parameters of the concrete canals are fully compatible with the best hydraulic section conditions of the hydraulics. The best hydraulic section – it allows to transfer the maximum water discharge in the existing cross section. As a result, water from the source reaches the crop fields through canals in a short period of time and leads to a high sediment transport capacity of the canal.

Using the above calculation equations, the technical and economic efficiency of the Kokandsay, Kartan and Bakhkir irrigation canals, which receive water from the Kokand hydrostation through the Right Canal, was checked using computer software DGU 13170 [ALLAYOROV *et al.* 2021]. The main variables of Equation (8) in the process are the volume of concrete (V_{RMT}) used for 1 running meter (RMT) of the canal the amount of concrete used to concrete the canal route (V_{sum}), and the volume of concrete used for concreting the canal route, and the sediment flow rate (Q_s) of the canal was taken into account (Tab. 3).

According of the obtained results, the concrete consumed for 1 RMT in the design of canals on the basis of the best hydraulic section conditions there are savings of 0.2–0.3 m^3 depending on the adoption of the raw material canal side slope (Fig. 5).

The possibility of transporting river sediments in the flow of irrigation networks, designed on the basis of the most favorable hydraulic section of the canals, indicates the existence of a critical situation. In the canals concreted with using the recommended method, found that the acceptance of the canal side slope at values of 1–1.5 significantly increases the sediment transport capacity (Fig. 6).

Based on the analysis of the results obtained on the basis of this research method, the effective hydraulic parameters of the Kokandsay, Kartan and Bachkir irrigation canals receiving water from the Kokand hydrostation through the Right Canal were calculated (Tab. 4). Compared to the current situation, there is a difference between these recommended hydraulic parameters (b, h, m) and the efficiency of the proposed method is high.

Table 3. Results of process verification using computer software

Side slope *m*	Feasibility indicators	Irrigation canals		
		Kokandsay	Kartan	Bachkir
2.00	V_{RMT}	1.3	1.2	1.1
	V_{sum}	22,135.7	12,459.1	12,470.3
	Q_s	7.9	7.3	9.4
1.75	V_{RMT}	1.2	1.1	1.1
	V_{sum}	20,936.1	11,779.4	11,785.3
	Q_s	8.1	7.4	9.5
1.50	V_{RMT}	1.2	1.1	1.0
	V_{sum}	19,808.5	11,140.8	11,142.1
	Q_s	8.1	7.5	9.6
1.25	V_{RMT}	1.1	1.0	1.0
	V_{sum}	18,797.7	10,568.6	10,566.0
	Q_s	8.1	7.5	9.6
1.00	V_{RMT}	1.1	1.0	0.9
	V_{sum}	17,973.1	10,102.0	10,096.5
	Q_s	8.0	7.4	9.5
0.75	V_{RMT}	1.0	1.0	0.9
	V_{sum}	17,439.7	9,800.3	9,793.0
	Q_s	7.8	7.2	9.3
0.50	V_{RMT}	1.0	0.9	0.9
	V_{sum}	17,344.2	9,746.3	9,738.7
	Q_s	7.4	6.8	8.8

Explanations: V_{RMT} = volume of concrete used for RMT of the canal (m^3), V_{sum} = the amount of concrete used to concrete the canal route (m^3), Q_s = sediment flow rate (kg·m^{-3}).
Source: own results.

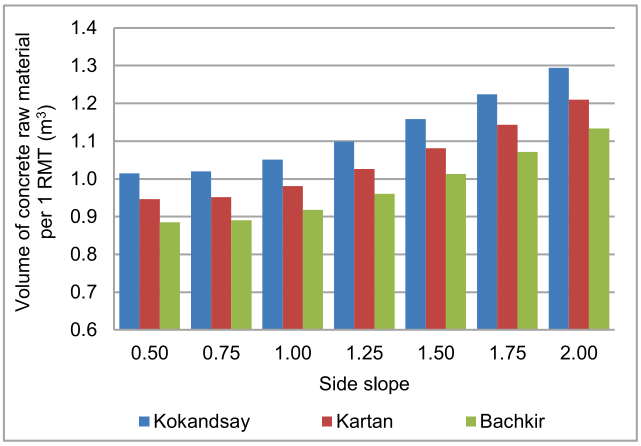

Fig. 5. Relationship between volume of concrete raw material per 1 RMT of the canal and side slope; source: own results

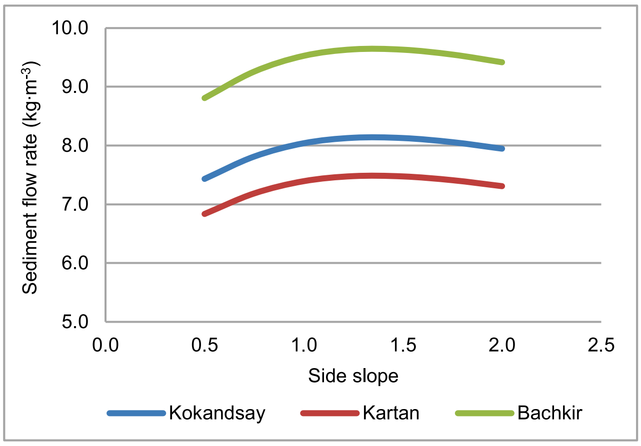

Fig. 6. Relationship between sediment flow rate and side slope; source: own results

Table 4. Redesign indicators of canals which takes water from Kokand hydrocomplex

Water intake main canal	Water intake first order canals	Water discharge ($m^3 \cdot s^{-1}$)	Width of the canal bottom (m)	Side slope	Canal depth (m)	Canal slope
Right Canal	Kokandsay	25	1.5	1.25	2.4	0.0020
	Kartan	20	1.4	1.25	2.2	0.0020
	Bachkir	18	1.3	1.25	2.0	0.0025

Source: own results.

CONCLUSIONS AND RECOMMENDATIONS

Due to population and economic growth, and their demand for water is increasing year by year, water resources are increasingly shortening. The largest consumer of fresh water in the Republic of Uzbekistan is agriculture, the efficiency of irrigation networks supplying it is 60%. According to studies on the hydraulic efficiency of irrigation canals, 70–75% of the total water losses in the system are relation to filtration process. So the biggest problem we have to deal with is filtration. The solution is concreting the canal. It is more effective to cover the riverbeds with concrete pavements than to use water-saving technologies in the irrigation areas served by these canals. Reducing the cost of concreting canals and at the same time increasing the hydraulic efficiency of the canal is an urgent issue for the water economy industry. Today commonly method in the design of concretelined irrigation canals in the territory of the Republic is hydraulic calculation methods used in the design of earthen canals. However, this method dramatically increases the cost of canal construction. The research method is an innovative approach to the design and construction of concreting irrigation canals from the best hydraulic section of the canal. Reducing the amount of concrete raw material in the projected canal requires optimizing the wetted perimeter. The result of the mathematical analysis performed on the basis of the most favourable cutting condition of the hydraulics shows that the canal bottom relative width depends on the side slope.

In general conclusion, the use of this research method in the design of concrete canals minimizes the cost of concrete for canal construction, and the adoption of a canal side slope of 1.25 increases the efficiency of irrigation canal.

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