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RESEARCH ARTICLE

COMPARATIVE ANALYSIS OF THE EFFICIENCY OF PARABOLIC AND TRAPEZOIDAL SECTIONS IN IRRIGATION CANALS

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Abstract. *One of the current scientific directions in hydraulic engineering is to give irrigation canals a hydraulically and statically stable cross-sectional shape in the form of the most advantageous parabolic profile. This approach allows maximizing the sediment transport capacity of the flow and significantly reducing the time and costs of construction and maintenance works, using optimization criteria for next-generation machinery and mechanisms. The significance of this research lies in developing a new concept for designing, constructing, and operating irrigation canals in hydraulic engineering systems with cross-sectional shapes that are both hydraulically and statically stable. These shapes aim to maximize sediment transport capacity, ensure ecological sustainability of natural-technical basin systems, and contribute to national food security. The objects of study are hydraulic engineering structures, specifically the inter-farm canals of irrigation systems within the Syr Darya river basin in the southern region of the Republic of Kazakhstan. For the study, methods were used including stability analysis of earth slopes using circular-cylindrical sliding surfaces, methods based on analogy between shear curves and slopes, and methods based on the theory of limit equilibrium. Calculations have demonstrated the advantages, including increased resistance to cross-section deformation, reduced earthwork volumes during irrigation canal construction and cleaning by 20-25%, decreased materials and work volume for possible lining by 13-18%, narrower canal top width and land acquisition zones by 11-17%, lower labor costs by 13-16%, reduced construction costs by 14-18%, and decreased specific adjusted costs by 15-18%.*

Keywords: *irrigation canals, hydraulic structures, slopes, Plaxis 3D.*

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ҒЫЛЫМИ МАҚАЛА

СУАРУ КАНАЛДАРЫНЫҢ ПАРАБОЛАЛЫҚ ЖӘНЕ ТРАПЕЦИЯ ТӘРІЗДІ ҚИМАЛАРЫНЫҢ ТИІМДІЛІГІН САЛЫСТЫРМАЛЫ ТАЛДАУ

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Аңдатпа. *Гидротехникадағы қазіргі ғылыми бағыттардың бірі суару каналдарына ең тиімді параболалық профиль түрінде гидравликалық және статикалық тұрақты көлденең қима пішінін беру болып табылады. Бұл тәсіл ағынның шөгінділерді тасымалдау қабілетін барынша арттыруға және жаңа буын машиналары мен механизмдерін оңтайландыру критерийлерін қолдана отырып, құрылыс және техникалық қызмет көрсету жұмыстарының уақыты мен шығындарын едәуір қысқартуға мүмкіндік береді. Бұл зерттеудің маңыздылығы гидравликалық және статикалық тұрақты көлденең қимасы бар гидромелиоративтік жүйелердегі суару каналдарын жобалау, салу және пайдалану бойынша жаңа тұжырымдаманы әзірлеуде жатыр. Бұл нысандар шөгінділерді тасымалдау қабілетін барынша арттыруға, табиғи-техникалық бассейн жүйелерінің экологиялық тұрақтылығын қамтамасыз етуге және ұлттық азық-түлік қауіпсіздігіне үлес қосуға бағытталған. Зерттеу объектілері - гидротехникалық құрылымдар, атап айтқанда Қазақстан Республикасының оңтүстік аймағындағы Сырдария өзені бассейніндегі суару жүйелерінің шаруашылықаралық каналдары болып табылады. Зерттеу үшін дөңгелек цилиндрлік жылжымалы беттерді қолдана отырып, жер беткейлерінің тұрақтылығын талдауды, ығысу қисықтары мен беткейлері арасындағы ұқсастыққа негізделген әдістерді және шекті тепе-теңдік теориясына негізделген әдістерді қамтитын әдістер қолданылды. Есептеулер нәтижесі артықшылықтарды көрсетті, соның ішінде көлденең қиманың деформациясына төзімділіктің жоғарылауы, суару арналарын салу және тазалау кезінде жер жұмыстары көлемінің 20-25%-ға қысқаруы, ықтимал жабын материалдары мен жұмыс көлемінің 13-18% - ға қысқаруы, каналдың жоғарғы беті ені мен жерді алу аймақтарының кішіреюі 11-17% - ға, еңбек шығындарының 13-16% - ға азаюы, құрылыс шығындарының 14-18% - ға азаюы және нақты түзетілген шығындардың 15-18% - ға төмендеуі.*

Түйін сөздер: *суару каналдары, гидротехникалық құрылымдар, беткейлер, Plaxis 3D.*

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НАУЧНАЯ СТАТЬЯ

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ЭФФЕКТИВНОСТИ ПАРАБОЛИЧЕСКИХ И ТРАПЕЦЕИДАЛЬНЫХ СЕЧЕНИЙ ОРОСИТЕЛЬНЫХ КАНАЛОВ

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Аннотация. *Одним из современных научных направлений в гидротехнике является придание оросительным каналам гидравлически и статически устойчивой формы поперечного сечения в виде наивыгоднейшего параболического профиля. Такой подход позволяет максимально увеличить пропускную способность потока для транспортировки наносов и значительно сократить время и затраты на строительные и ремонтные работы, используя критерии оптимизации для машин и механизмов нового поколения. Значимость этого исследования заключается в разработке новой концепции проектирования, строительства и эксплуатации оросительных каналов гидромелиоративных систем с формами поперечного сечения, которые являются как гидравлически, так и статически устойчивыми. Параболические формы направлены на то, чтобы максимально увеличить пропускную способность каналов, обеспечить экологическую устойчивость природно-технических систем бассейнов и способствовать национальной продовольственной безопасности. Объектами исследования являются гидротехнические сооружения, в частности, межхозяйственные каналы гидромелиоративных систем в бассейне реки Сырдарья в южном регионе Республики Казахстан. Для исследования были использованы методы, включающие анализ устойчивости земляных откосов с использованием кругло-цилиндрических поверхностей скольжения, методы, основанные на аналогии между кривыми сдвига и откосами, и методы, основанные на теории предельного равновесия. Расчеты продемонстрировали преимущества, в том числе повышенную устойчивость к деформации поперечного сечения, сокращение объемов земляных работ при строительстве и очистке оросительных каналов на 20-25%, уменьшение объема материалов и работ для возможной облицовки на 13-18%, уменьшение ширины верхнего края канала и зон отвода земли на 11-17%, снижение затрат на рабочую силу на 13-16%, снижение затрат на затраты на строительство снизились на 14-18%, а удельные скорректированные затраты - на 15-18%.*

Ключевые слова: *оросительные каналы, гидротехнические сооружения, откосы, Plaxis 3D.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

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КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

1 INTRODUCTION

Over the past 50 years, the world has produced more industrial and agricultural products than in all previous human history, naturally leading to intensive exploitation of water resources. In the past century, global water consumption has increased more than twelvefold, doubling approximately every 20 years (**Li et al., 2022**).

Sustainable water use is achieved through optimal satisfaction of the water needs of economic sectors and the population. Effective justification of water resource utilization in river basins is based on integrated ecological and economic criteria. Addressing this complex task involves numerous risks: natural and anthropogenic factors, continuous and unjustified growth in water consumption, and pollution of water sources (**Li et al., 2022**).

For most of Kazakhstan's irrigation systems, water is abstracted from mountain and foothill rivers that transport significant sediment loads, leading to canal deformations and reduced canal capacity. Over the last 20 years, the operational reliability of many hydraulic structures has declined, posing ecological and social threats (**Moldamuratov et al., 2014**).

According to the Water Management Committee of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan, during the peak of irrigated agriculture development, annual sediment removal volumes amounted to about 50 million m³; currently, this volume is projected to be around 25-27 million m³ (**Moldamuratov et al., 2021**).

Restoring the hydraulic components of Kazakhstan's agro-industrial complex is directly linked to the need for reconstruction and construction of hydraulic structures - the main elements of the irrigation network (**Moldamuratov et al., 2021**).

Studying the operational experience of irrigation canals, their kinematic structure, and conditions for forming stable canals to address deficits in water resources due to siltation and reduced capacity is extremely relevant (**Moldamuratov et al., 2022**).

The complexity of river and canal formation processes, addressing the pressing issue of canal formation, must be considered in conjunction with sediment transport capacity issues. This approach will enable forecasting of potential changes in morphodynamic canal types, their cross-sectional characteristics, erosion rates of banks and bed, and sediment ingress into irrigation canals (**Ikramov et al., 2023**).

Analysis of existing technological processes for constructing and maintaining Kazakhstan's hydraulic reclamation system canals indicates the need to reduce sediment removal volumes, lower their associated costs, and enhance the quality of operational measures for irrigation canals.

The increasing volumes of construction and repair-restoration works, the need to reduce their execution times, and enhance labor productivity necessitate advancements in the processes for constructing and maintaining hydraulic reclamation system canals in a reliable condition, alongside other technical progress directions (**Abdrazakov et al., 2023**).

A significant portion of operational activities for maintaining hydraulic reclamation systems in working order involves canal desilting. The maximum annual volume of desilting works carried out in recent years solely on the hydraulic reclamation systems in southern Kazakhstan exceeds 25 million cubic meters.

According to the Water Management Committee of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan, the total length of hydraulic reclamation system canals in the country has now reached 60,000 kilometers, with nearly 88% of them passing through earth canals. The length of canals of inter-farm significance exceeds 12,000 kilometers. The primary workload in operating Kazakhstan's hydraulic reclamation systems falls on irrigation and collector-drainage canals (**Moldamuratov et al., 2023**).

The aim of this study is to enhance the technology of canal construction, enabling improvement in sediment transport capacity and ensuring hydraulic and static stability of their cross-sectional shape over extended periods of operation (**Arifjanov et al., 2020**).

To achieve the stated goal, the following tasks need to be addressed:

- Investigate the impact of operational factors on the sediment transport capacity of earth canals in canals.
- Systematize the structural features and statistical parameters of irrigation canals in the southern region of the Republic of Kazakhstan and their influence on the selection criteria for machinery and mechanisms.
- Study the stability of slopes of parabolic-profile irrigation canals.
- Develop methodological approaches to formulating the most advantageous cross-sectional profile for canals.
- Design a methodology and principles for selecting earthmoving equipment for construction and maintenance of hydraulic reclamation system canals.
- Develop technical solutions to ensure operational reliability in the functioning of hydraulic reclamation system canals.

2 LITERATURE REVIEW

When designing canals, the dimensions of their canals and hydraulic characteristics must meet specific requirements based on their intended use. For irrigation canals designed in soil, these requirements boil down to ensuring that the cross-sectional shape remains resistant to erosion, free from siltation, and maintains overall canal stability. The reliability of a canal's operation, free from siltation and erosion, largely depends on establishing a stable, deformation-resistant cross-sectional shape and corresponding hydraulic characteristics (**Kosichenko et al., 2020**).

Analysis of the canal regime of canals constructed in soil or formed through self-cleansing has shown that their canals, much like river canals, are susceptible to free deformations that manifest in the self-formation of stable shapes and sizes (**Namaee et al., 2013**).

The process of forming a stable canal follows a general developmental scheme akin to natural river canal processes but occurs under the influence of relatively constant flow over time. It actively progresses until the canal dimensions and shape establish a flow velocity structure that achieves a state of equilibrium conducive to the canal bed's soil (**Moghazi et al., 1997**).

Field observations have established that trapezoidal cross-sectional shapes are unstable: the slopes of such canals deform, angular spaces silt up and become overgrown, ultimately altering the initial canal shape completely. The canal may take on irregular contours in the upper part and curvilinear shapes in the lower part over time (**Swamee et al., 2005**).

This understanding underscores the importance of designing irrigation canals with stable cross-sectional profiles that can resist deformation and maintain their hydraulic efficiency over extended periods of operation, thus ensuring effective water flow and minimal maintenance needs (**Vatankhah et al., 2011**).

K. Roushangar notes: "In straight sections within homogeneous soils, a symmetric, parabolic canal is formed. In cohesive soils, the banks have steeper slopes, and the cross-sectional shape approaches an elliptical curve" (**Roushangar, K. et al., 2021**)

M.N. Sennikov points out that cross-sectional profiles of rivers on straight planar sections often take the form of a semi-ellipse or higher-degree parabola (from second to twelfth). These profiles are commonly found in mountainous and plain river sections where the bed consists of erodible materials and the banks are composed of less erodible soils (**Sennikov et al., 2014**).

Research by C.R. Suribabu indicates that in alluvial soils, river canal sections exhibit shapes defined by parabolas of various orders, ranging from second to twelfth (**Suribabu et al., 2010**).

The materials from research conducted under the guidance of O.A. Baev **(Baev, 2023)** on a canal to study its resistance to erosion and silting showed that a parabolic section (described by a fifth-order parabola) best fits the actual canal section (**Table 1**).

Table 1

Comparison Table of Actual Canal Section Parameters with Calculated Parabolic, Elliptical, and Semi-Circular Sections (author's material)

Section profiles	Relative width of the canal by water level, β	Specific wetted perimeter, χ_0	Canal width by water level, B, m	Canal filling depth, h, m	The area of the living section, ω, m^2	Wetted perimeter, *X, m*	Hydraulic radius, R, m	Flow rate, ϑ, m/s
The actual	7,18	10,8	10,8	1,25	8,76	9,71	0,9	0,473
Parabolic %	7,2	10,3	8,9	1,23	9,1	9,65	0,94	0,488
of discrepancies	+0,279	-4,63	-0,892	-1,6	+3,88	-0,62	+4,44	+3,16
Elliptical %	6,75	10,4	8,8	1,31	9,12	9,74	0,94	0,487
of discrepancies	-5,98	-3,7	-2	+4,6	4,11	+0,31	+4,44	+2,96
Semicircular %	4,75	8,54	7,8	1,64	8,7	8,6	1,01	0,512
of discrepancies	-33,8	-20,9	-13,15	+31,2	-0,685	+11,45	+12,2	+8,28

It is important to note the significance of correctly choosing the slope alignment in irrigation canal construction. Z. Ma asserts that proper slope alignment of irrigation canals is crucial. Steep slopes lead to erosion and siltation, clogging the canal, while shallow slopes increase earthwork volumes and reduce the area available for easements (**Ma et al., 2019**).

The cross-sectional profile of a canal, influenced by the physical-mechanical properties of soil, groundwater conditions, flow erosion, and other factors, tends towards a more stable curved shape. This shape often aligns closely with a parabolic or semi-elliptical form.

Lopez-Medina T. highlights that trapezoidal-sectioned canals without reinforcement can only be constructed in dry or cohesive soils that resist rapid saturation (such as peat, structurally intact clay, or non-podzolized coarse loam). Even in uniformly homogeneous soils, polygonal profiles are more advantageous. In such cases, steeper slopes are applied to the upper layer of the slope, and gentler slopes to the lower layers. Polygonal-sectioned canals can easily adopt semi-elliptical or parabolic outlines without compromising their stability (**Lopez-Medina et al., 2021**).

V.V. Nalimov research has identified stable slope forms using actual geotechnical parameters of slope soils. Field studies have shown that canal slope profiles stabilize over time, often resembling a parabolic shape (**Ejidike et al., 2023**).

Research by I.S. Lapidovskaya has established that the main threat to the stability of an open canal is the development of soil upheaval zones within its boundaries. For trapezoidal canal profiles designed in projects, stable slope alignment that prevents upheaval from the canal boundaries often results in significant loss of useful area. A more economical polygonal section is recommended, where upheaval zones are eliminated by transitioning to a gentler slope at a critical depth (**Moldamuratov et al., 2023**).

Research by Ibadi-Zade on canal stability demonstrated that during operation, the construction profile of a canal deforms and adopts a stable curved shape. For instance, the K-18 canal in southern Kazakhstan, after one year of operation, deformed and assumed a curved shape, with a reduction in depth by 31.5%. Ibadi-Zade proposed a method for calculating the stable cross-sectional profile of a parabolic canal, aligning with the profile of a natural canal (**Moldamuratov et al., 2023**).

3 MATERIALS AND METHODS

To conduct the research, the following methods were used:

1. Method for calculating the stability of slopes of earth structures using circular-cylindrical sliding surfaces.
2. Method based on analogy between shear curves and slopes.
3. Method based on the theory of limit equilibrium.

Modeling was performed using the PLAXIS 3D software suite.

For the calculation of irrigation canal designs, the following initial data are adopted: the canals have construction depths of 1.5, 2, and 3 meters respectively; hydraulic parameters of the canals such as discharge, roughness coefficient, and slope are uniform; the canals are designed in half-cut and half-fill with a bedding height equal to half the canal depth; soils include medium loam and light loam; the canal profile is a quadratic parabola.

In Tables 2, 3 and **4** the main parameters for calculation and modeling are provided. **Figures 1** and **2** show the dependencies of additional parameters on the channel depth for trapezoidal and parabolic profiles.

Table 2

Technological parameters of irrigation network canals (author's material)

Type of profile section	Canal Parameters							
	Flow rate (m^3/s) Q	Canal depth (m) h_k	Filling depth (m) h	Bottom width (m) b	Laying of slopes (parabola parameter) m	Width at the top B_k	The perimeter of the section (m^2) χ_k	Cross-sectional area S_k
Trapezoidal	1,65	1,5	1,2	0,8	1:1,25	4,55	5,6	4,01
Parabolic	1,62	1,5	1,2	-	P=1,02	3,5	4,85	3,5
Trapezoidal	4,16	2,0	1,7	1,0	1:1,5	7	8,2	8
Parabolic	4,18	2,0	1,7	-	P=1,66	5,16	6,84	6,88
Trapezoidal	14,26	3,0	2,7	2,0	1:1,75	12,7	14,1	21,75
Parabolic	14,13	3,0	2,7	-	P=4,16	10	12	20

Tables 3
Changes in parameters of irrigation network canals [author's material]

Changes			Change in the total cross-sectional area of the structure (m^2/%)
Width at the top (m/%)	**Perimeter (m/%)**	**Cross-sectional areas (m^2/%)**	
$\Delta B_к$	$\Delta \chi_k$	$\Delta S_к$	$\sum \Delta S$
1,06/13,4	0,75/13,3	0,51/12,7	- 1,35/12,3
- 1,84/26,2	1,36/16,6	1,12/14	- 2,96/15,17
- 2,5/20	2,1/14,9	1,75/8,04	- 4,25/8,78

Table 4
Values of parameters of irrigation canals of parabolic (χ^2=2ρy) and trapezoidal cross-section profiles (author's material)

Canal depth, m	Laying of slopes	Parabola parameter p for canals along the bottom:							
		0,4 m	**0,6 m**	**0,8 m**	**1,0 m**	**1,5 m**	**2,0 m**	**2,5 m**	**3 m**
1,5	1:1	0,56	0,7	0,83	1,02	-	-	-	-
	1:1,25	0,7	0,85	1,02	1,17	-	-	-	-
	1:1,5	0,75	0,88	1,1	1,26	-	-	-	
2,0	1:1,25	-	-	1,13	1,35	1,75	2,17	-	-
	1:1,5	-	-	1,38	1,66	2,03	2,56	-	-
	1:1,75	-	-	1,56	1,85	2,25	2,8	-	-
	1:2	-	-	1,75	2,03	2,45	3,02	-	-
3,0	1:1,5	-	-	-	-	2,66	3,37	3,92	4,5
	1:1,75	-	-	-	-	3,01	3,8	4,5	5,13
	1:2	-	-	-	-	3,48	4,16	4,95	5,56

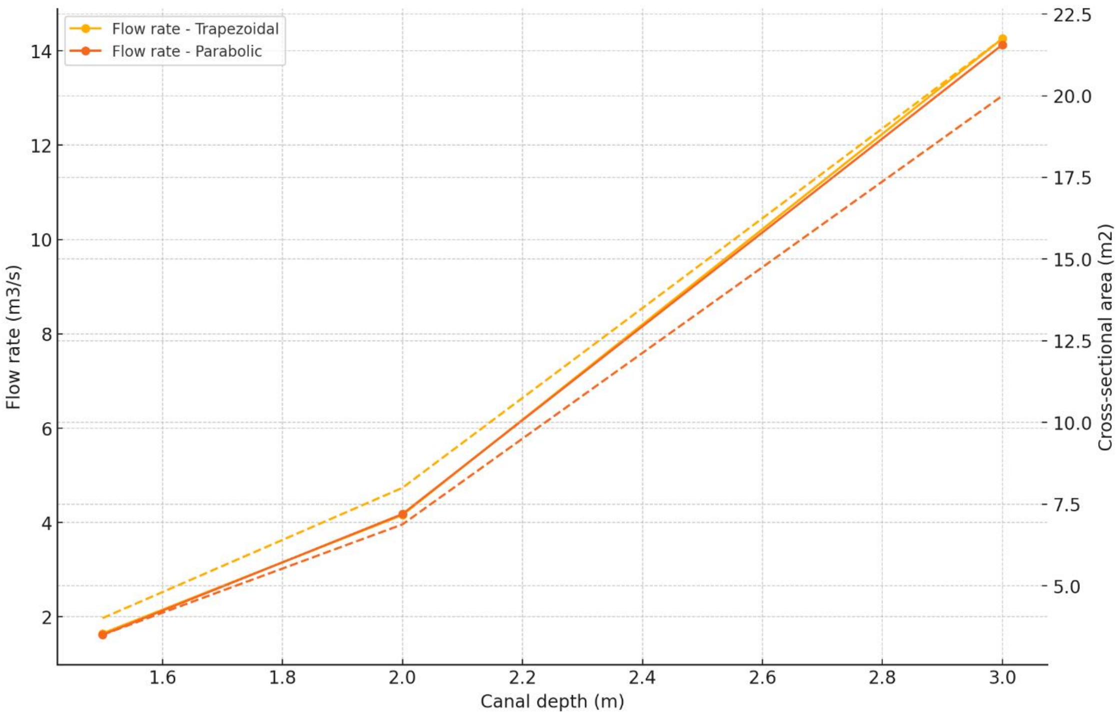

Figure 1 – Graph of the dependence of water flow rate and cross-sectional area on canal depth for trapezoidal and parabolic profiles [author's material]

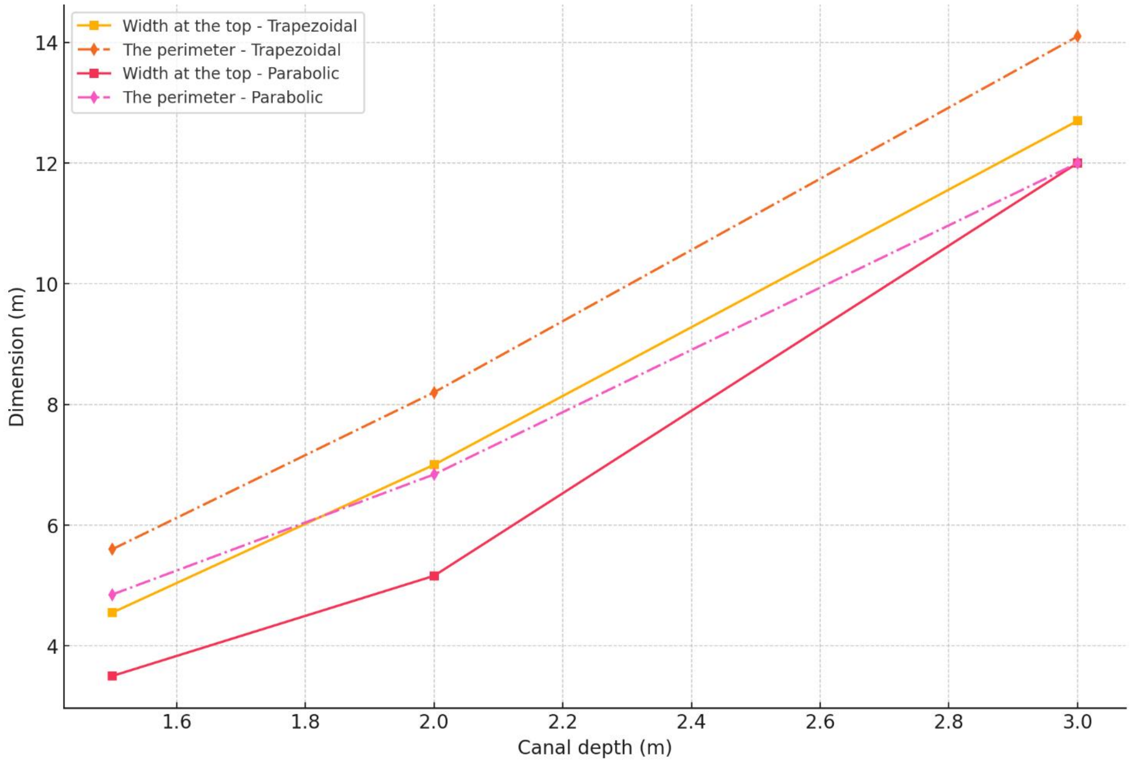

Figure 2 – Width at the top and the perimeter of the section vs Canal depth [author's material]

4 RESULTS AND DISCUSSION

A comparative analysis of the calculated parameters of canals shows that using parabolic section canals significantly reduces the volume of earthworks compared to trapezoidal section canals. Firstly, this reduction is due to the smaller cross-sectional area of the canal by 8.04...14%, which provides greater savings in earthworks than just the reduction in the cross-sectional area of the flow, because the dry slope of a parabolic profile canal is steeper than that of a trapezoidal canal. Secondly, the area of the bedding section is reduced by 12.0...26.0%. This reduction in bedding area is achieved because the top width of the parabolic profile canal is 20...26.2% narrower than that of the trapezoidal canal, thus allowing a corresponding reduction in bedding width. The nature of changes in the cross-sectional areas of canals and canal beddings for parabolic and trapezoidal profiles shows that with increasing canal depth, the difference in cross-sectional areas and savings in earthwork volumes increase (**Figures 3, 4 and 5**).

In the practice of constructing hydraulic structures, particularly in the construction of irrigation canals for water management systems, cross-sectional shapes commonly include trapezoidal, parabolic, and polygonal forms. Trapezoidal cross-sections are widely adopted due to their ease of mechanized construction, which has contributed to their widespread use. On the other hand, parabolic cross-section canals have not seen extensive application primarily because specialized equipment for their construction is lacking. They are typically used only in cases where material savings from lining justify their use and account for their specific cross-sectional shape.

For example, in the construction of canal networks, reducing the perimeter of the cross-section with parabolic shapes can result in up to 20% material savings compared to trapezoidal sections due to reduced lining requirements.

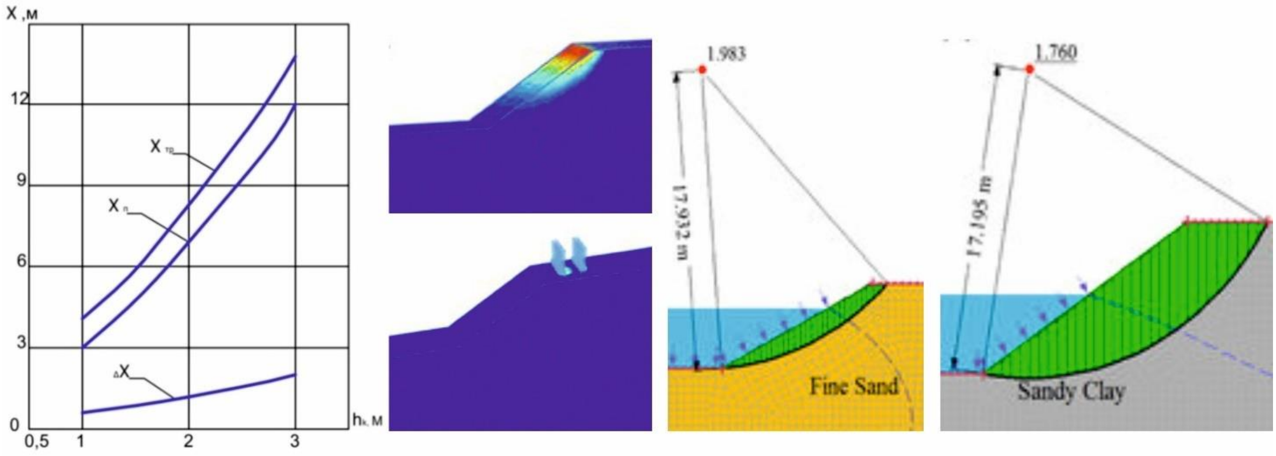

Figure 3 - Graph of changes in the perimeter of the trapezoidal χTP and parabolic χn profiles of canals of different depths $h_к$ (author's material)

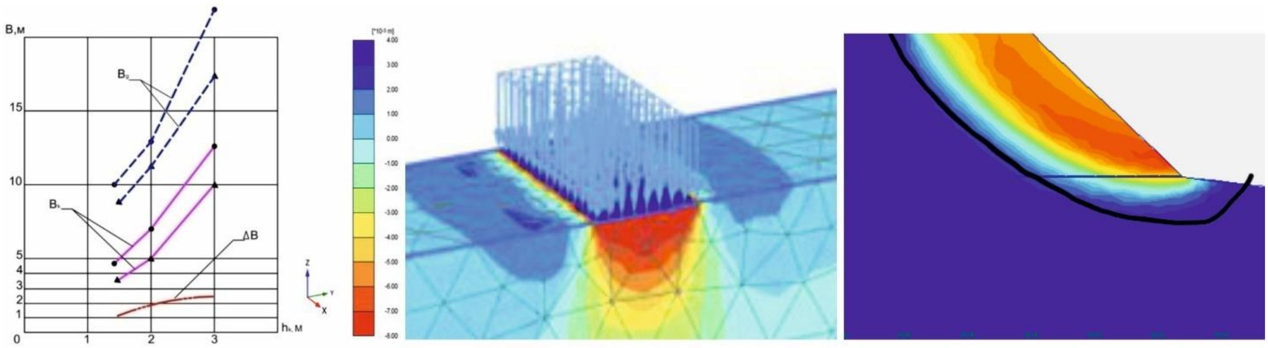

Figure 4 - Graph of changes in the width of the canal $B_к$ and the cushion along the top B_g of the trapezoidal and parabolic profiles of different depths:

● – trapezoidal; ▲ – parabolic canals (author's material)

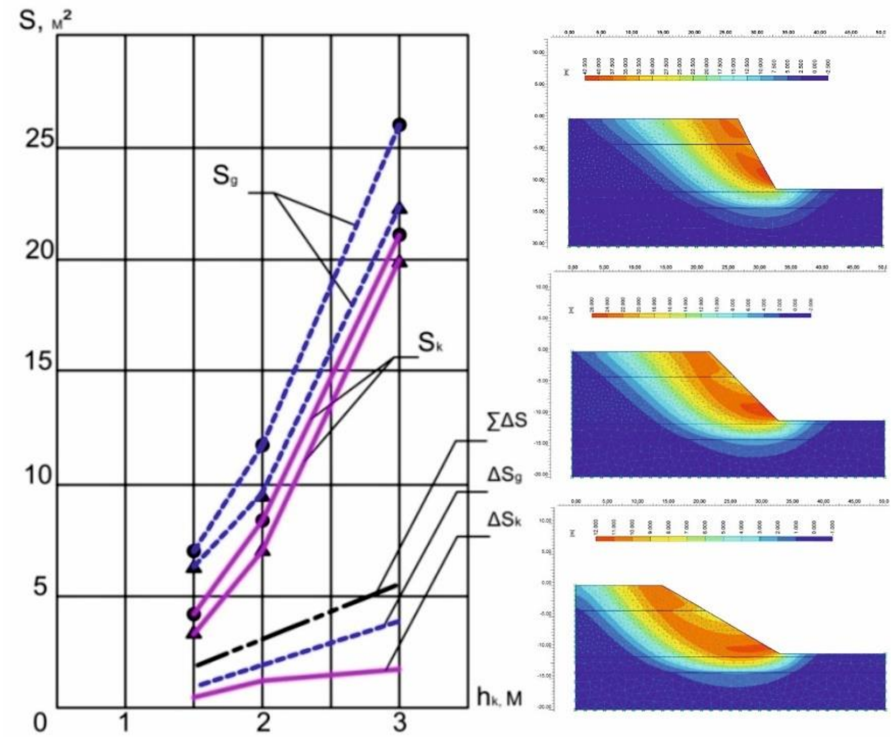

Figure 5 - Graph of changes in the area of the recess sections $S_к$ and dams S_g canals of trapezoidal and parabolic profiles from depth h: ● – trapezoidal profile; ▲ – parabolic profile (author's material)

The analysis of research shows that the most straightforward and acceptable methods for calculating the stability of earth slopes in irrigation canals are those based on the analogy between shear curves and slope stability. Methods based on the theory of limit equilibrium for calculating the stability of earth structures are the most rigorous and accurate. However, these methods are not widely applied in practice primarily due to the complexity of calculations and the specificity of assessing the stability of a given slope based on the critical load uniformly distributed on the crest.

The analysis of the equal-strength slope curves for irrigation canals with depths of 1.5, 2, and 3 meters, and parabolic slope profiles, shows that the adopted parabolic canal profiles have more stable slopes in cohesive soils with a cohesion value $K_c \geq 1$ t/m². Calculations performed to determine the slope stability factor for three scenarios (flooded slope, sudden complete water drawdown, and zero boundary neutral pressure) demonstrated that the minimum factor of safety against slope failure (shear strength) is $F_s=1.42$ for an irrigation canal with a depth of 3 meters, with the slope steepness adopted at the maximum steepness in the upper part of the slope (i = 45°).

Therefore, irrigation canals with rational parabolic cross-sectional shapes are more resistant to deformations in various soil conditions, especially in less stable soils such as sandy, sandy-loam, and heterogeneous soils. They have smaller cross-sectional areas and reduced construction volumes, wetted perimeter and material volumes, lining works, top width of the canal, and land acquisition areas for the canals.

5 CONCLUSIONS

Based on the conducted research on hydraulic assessment considering hydromorphological factors, it can be concluded that irrigation canals with parabolic cross-sectional shapes are optimal according to the following parameters:

1. Increased resistance against deformation of the cross-section.
2. Reduction in earthwork volumes during construction and cleaning of irrigation canals by 20-25%.
3. Decrease in materials and work volume for possible lining (strengthening) of irrigation canals by 13-18%.
4. Decrease in the top width of the canal (land acquisition zones) of irrigation canals by 11-17%.
5. Reduction in labor costs by 13-16 %.
6. Decrease in construction costs (production costs) by 14-18%.
7. Decrease in specific adjusted costs by 15-18%.

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