The Impact of Operational Scenarios and Concrete Aging Factor on the Freeboard Height of an Irrigation Canal

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ABSTRACT

The prediction of operational freeboard in irrigation canals is a complicated issue, particularly when the cumulative effects of time-dependent factors, such as maloperation and concrete aging, are considered. While most classic approaches consider a fixed freeboard due to uniform flow as a fundamental assumption. This study proposes a flowchart considering the effects of nonuniform flow to determine the adequacy of the freeboard of irrigation canals under different conditions, including time-dependent and operational scenarios. The results of this method indicated that the freeboard values obtained by classical methods may not be sufficiently reliable in providing the appropriate level of performance in the operating conditions of agricultural canals. Regarding the case study of this paper, an irrigation canal in Kurdistan-Iran, the results showed that the formation of the M1 profile is the most critical scenario and the initial freeboard must be extended by 20cm at a distance of about 2.3Km at the end of the canal towards upstream.

Keywords-freeboard; concrete aging; irrigation canal; operational scenarios

I. INTRODUCTION

Despite the prevalent traditional methods that are widely used in the initial design phase of irrigation canals, water delivery performance and economically optimal design of canal sections are still hot topics in current engineering works [1-4]. The geometry of the canal section plays a key role in the total cost of an irrigation system. In [5], an optimal parabolic section with a freeboard was proposed to provide optimal flow capacity. However, mathematically designed sections are generally difficult to construct. In addition to the need for specific machinery, such parabolic sections may not perform well in geotechnical stability analysis without a thick concrete lining, especially in large canals. In [6], a power-law section was proposed that had similar disadvantages to the parabolic section. Therefore, traditional trapezoidal sections with concrete lining are still the most common sections in many irrigation systems. A trapezoidal section is an optimal choice in the design phase, not only compared to curved sections, but to other simple geometries. In [7], triangular, rectangular, and trapezoidal sections were compared, concluding that the optimal trapezoidal section has the lowest seepage loss and cross-sectional area among the three optimal sections. Consequently, practical approaches to refine the design procedure of trapezoidal sections can help engineers to consider various affecting factors which are usually ignored in the initial design phases.

In general, canal lining and banks are extended above a canal's normal water surface as a safety measure to protect the conveyance system from overtopping. Freeboard in a canal provides a water surface higher than normal, which may be caused by sedimentation in the canal, temporary maloperation of the canal system, excess flows caused by storm runoff entering the canal through drain inlets, additional water depth resulting from a higher friction coefficient than used in the design, and waves produced by wind or surges which accompany sudden changes in flow. In the initial design phase, the freeboard height is generally recommended to be 1/6 of the total depth in uniform flow conditions [8]. Figure 1 illustrates the freeboard of an irrigation canal. However, as a prevalent issue, overestimating or underestimating the freeboard can increase construction and operational costs [9, 10]. An overestimated freeboard can also increase the water loss in an irrigation canal, particularly in the compacted earth lining [11, 12]. On the other hand, underestimation of the freeboard can lead to difficulties in the operation or even to catastrophes in some cases [13-15]. The efficiency of the freeboard critically depends on the precise estimation of canal roughness. The effect of concrete aging on Manning's roughness coefficient (n) has always been a controversial issue. An uncertain assumption for this factor not only causes problems such as overflow, but also can disturb the controllability of an automated irrigation canal [16]. Although engineering codes recommend a standard range of 0.012-0.017 for Manning's n, there is evidence that the value could be increased to 0.023 in aged concrete-lined canals [17]. Increasing roughness can occur at a higher rate in smaller canals compared to large ones.

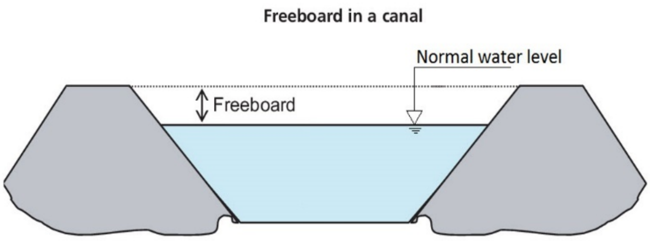


Fig. 1. Freeboard in a typical irrigation canal.

To increase the efficiency of water transport in irrigation canals, engineers offer slight modifications in the design phase that can influence construction prices and long-term maintenance costs. There is not a certain rule to guide water authorities in selecting the best option, and the selection procedure is performed case by case. On the other hand, it must be well thought-out that in many water transport projects, such as the studied case, the initial investment and construction costs are covered by governmental budgets while the operational costs rely on the stakeholders' payments, and most of them use leased facilities and cannot handle high costs of major rehabilitation for many years. This view is also amplified when considering that this project aims to improve the economy of a relatively poor region on the aging issue and the effectiveness of the freeboard depends on the appropriate prediction of operational scenarios. Most operational canals are designed based on a normal flow regime and predefined demand scenarios. Therefore, they would transfer the design flow plus a fixed freeboard to cover up fluctuations and waves. However, in constant geometric and roughness conditions, any change in demand nodes would disturb the water surface profile. Therefore, this factor plays an important role in the fundamental hydraulic analysis that determines the crest level of emergency spillways or the installation level of automated intake gates and is rarely considered in determining the general freeboard. The operational flow regime variation is more critical in long canals with multi-demand points, because of the effects of back-water and slight steepness in long distances in addition to the multi-stakeholders policies. In [18], it was shown that the conventional freeboard design did not suit a long-distance water transfer project [18]. There are also examples of aged canals, such as the Chashma Right Bank Canal in Pakistan, where the freeboard, adequate for the normal operational flow regime, could be over-stressed under specific flow conditions [19-22]. Therefore, unforeseen operational conditions must be considered for each irrigation canal. As there is no common rule for generally addressing this issue, it should be investigated case by case.

The current study investigated the following questions:

- To what extent a constant freeboard height calculated using classic approaches is reliable under different operational and time-dependent scenarios?
- How can some modifications help engineers to evaluate the freeboard height by considering operational and time-dependent scenarios?

II. CASE STUDY

The Garan water transport canal is part of an extensive irrigation project in the Kurdistan region, west Iran, next to the international borderline with Iraq. Having a length of 17Km, the Garan agro-industrial water transport system consists of a concrete-lined trapezoidal canal that conveys approximately 44 MCM of water annually. According to the design data, the maximum flow from the dam intake is $7m^3/s$. However, after supplying a pumping station, the flow decreases to $5m^3/s$ in the MPC2 canal, as shown in Figure 2, before arriving at a reverse-siphon pipeline. The main subject of this case study was the evaluation of the adequacy of the freeboard, as there are extreme operational scenarios in emergency conditions. Figure 3 shows the studied part of the canal and the control sill at the endpoint, which warrants a minimum water level for industrial demands upstream during winter when the irrigation demand is zero. The MPC2 canal was designed later and despite the supposition for the Garan canal, where Manning's roughness is

0.015, its roughness was assumed to be 0.016 in the design phase. During the construction phase, a design review was considered to evaluate the effects of different roughness coefficients assigned to these two canals. An optional retarder sill is planned at the endpoint of the Garan canal to maintain a minimum water level during winter to supply the constant industrial demand when there is no irrigation demand and the MPC2 canal must be shut down. This obstruction will create an M1 G.V.F flow profile towards the upstream that will raise the water level. However, there is a question to what extent it would affect the upstream. In addition, particular operational scenarios were considered to evaluate the capacity of the canal with different roughness values by considering the concrete aging effects. Based on a flowchart developed, shown in Figure 4, the surface profile of the water was determined using the G.V.F equations. This profile was then compared to the canal geometry, and the freeboard was increased accordingly in critical regions.

Fig. 2. Aerial view of the Garan irrigation canal and the location of the Garan dam and the MPC2 canal.

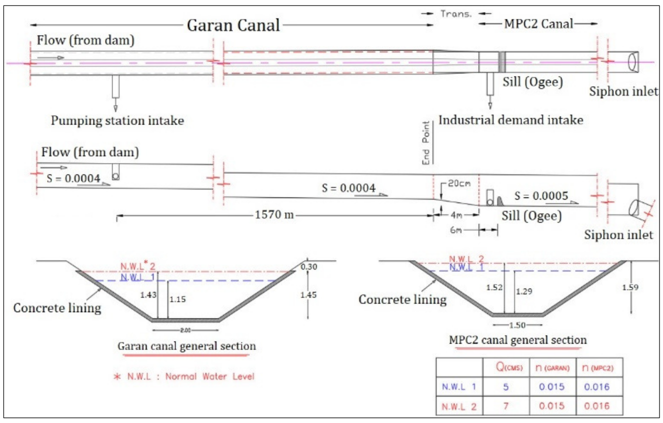


Fig. 3. The profile and cross-sections of the Garan and MPC2 irrigation canals in the attentive region.

III. METHODOLOGY AND CALCULATIONS

This study considered the change in roughness and the shutdown/running of the pumping station as the main factors to derive the critical scenarios shown in Table I. The G.V.F equation was used to develop the water surface profile:

$$\frac{dy}{dx} = \frac{S_0 - S_f}{(1 - Fr^2)} \tag{1}$$

where S_o is the bottom slope which is positive in the downward direction, S_f is the friction slope which is positive in the downward direction, y is the water depth measured from the canal bed to the water surface, x is the longitudinal distance measured along the canal from the endpoint toward upstream, and Fr is the Froude number. The friction slope was approximated using Manning's equation:

$$S_f = \frac{n^2 V^2}{\varphi R^{\frac{4}{3}}} \tag{2}$$

where S_f is the friction slope which is positive in the downward direction, n is Manning's roughness coefficient, V is the cross-sectional mean velocity, φ is a constant equal to 1.49 for English units and 1.00 for SI units, and R is the hydraulic radius.

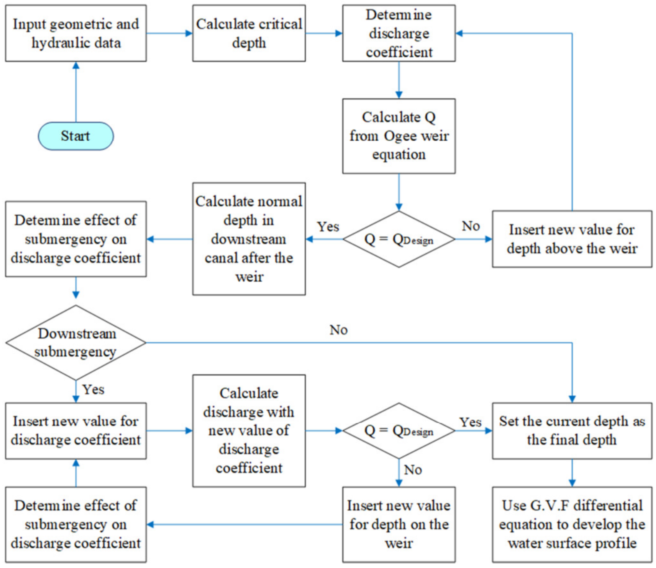


Fig. 4. Determination of the Ogee discharge coefficient and the G.V.F boundary condition flowchart.

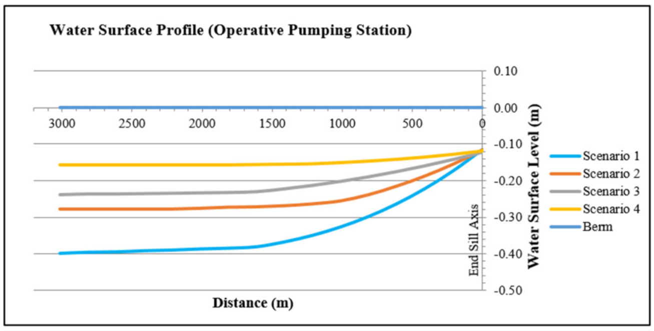
TABLE I. OPERATION AND AGING SCENARIOS

Scenario No.	Canal roughness		Pumping station condition
	Garan	MPC2	
1	0.011	0.011	Running
2	0.014	0.014	Running
3	0.015	0.016	Running
4	0.017	0.017	Running
5	0.011	0.011	Shut Down
6	0.014	0.014	Shut Down
7	0.015	0.016	Shut Down
8	0.017	0.017	Shut Down

A variety of mathematical techniques can be applied in a traditional method to generate the results [23]. In this case, due to the effect of the Ogee weir, the boundary condition of the G.V.F equation had to be determined carefully. The effect of downstream conditions on weir function was determined by the Ogee spillway discharge coefficient diagram recommended in [8]. Consequently, a flowchart was developed to perform the calculations considering the effects of different scenarios, as shown in Figure 4. The final goal was to evaluate the performance of the canal and its freeboard upstream of the Ogee sill. Table II presents the results and Figure 5 illustrates the water surface profiles generated by G.V.F for each scenario. According to the diagram, for the worst-case scenario (no. 8), a freeboard extension must be installed throughout the entire length of the canal. For scenarios 6 and 7, the water surface level never exceeds the berm level upstream of the pumping station. However, the desirable freeboard was not achievable for the entire length of the canal. For scenario 5, a minimum of 20cm freeboard was attainable if the berm level increased for 2,300m of the canal length from the sill, upward to the pumping station. In the other group of scenarios, where the pumping station was assumed to be operational, the current berm level was sufficient. However, for scenario 4, the aging effect would cause the maximum freeboard not to exceed 17cm. As an outcome of this calculation, the water surface profile converged to the normal water level in a shorter distance when the roughness increased. However, the final water level was higher.

TABLE II. RESULTS OF FREEBOARD EXTENSION

Scenario No.	Q (CMS)	Garan roughness	MPC2 roughness	Freeboard extension span (m)
1	5	0.011	0.011	120
2	5	0.014	0.014	180
3	5	0.015	0.016	300
4	5	0.017	0.017	960
5	7	0.011	0.011	2,300
6	7	0.014	0.014	Up to the pumping station
7	7	0.015	0.016	Up to the pumping station
8	7	0.017	0.017	The entire canal



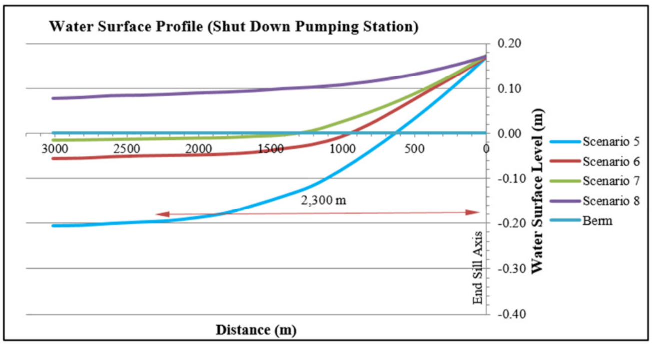


Fig. 5. G.V.F water surface profile for the Garan canal. Note scenario 5 where a freeboard extension is needed for a length of 2300m.

IV. DISCUSSION

Many challenging factors influence the hydraulic geometry of canals, including roughness, discharge coefficients, and the application of G.V.F. Although these factors have been used in many studies, the results show that there is no unique and theoretical method to solve the challenges of canal design. This calls for more empirical data to apply to specific sites. Any change in the estimation of the roughness coefficient influences the energy slope estimation, and any change in the discharge coefficient affects the velocity estimation. Consequently, the changes in these coefficients affect the water surface determination when applying (2). The effect of climate change (including changes in rainfall and evaporation), drought, and economic considerations force the designers to work on practical methods for canal restoration and modify the inputs in the G.V.F equation. One suitable and easy approach to canal design is to modify inputs including freeboard and hydraulic coefficients based on specific regional considerations. Figure 4 presents a practical approach to obtaining suitable results in irrigation canals.

V. CONCLUSIONS

Relying on the classic approaches to determine the freeboard height can lead to technical difficulties in multiple irrigation canals, particularly when there is a large gap between the demands during various seasons. In addition to the classic approaches followed in the initial design phase, operational scenarios must be considered through more sophisticated approaches. This study proposed a flowchart to determine the adequacy of the freeboard of a particular irrigation canal in different scenarios. The freeboard of the Garan canal was designed using the conventional approach that considers normal water level as the basic water surface profile. However, the results showed that there is a need for freeboard extension up to 20cm for a distance of about 2.3 kilometers from the next-added sill towards the upstream in a moderate scenario. The pessimistic scenarios indicated that a freeboard extension must be installed for the entire length of the canal. This output emphasizes the fact that the initial assumption about the freeboard and the conventional design approach must be revised. The sill and aging effects could influence the freeboard, which could be sufficient for the normal range of variation, but could be over-stressed under specific operation sets. The results of this study indicate that engineers should use the freeboard values obtained by traditional methods with more caution. In this regard, the development and use of methods such as the proposed algorithm can help engineers make the necessary revisions.

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