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AIR ENTRAINMENT
BEHIND HIGH-PRESSURE GATES

BY

HANS BRETSCHNEIDER

DR. SUE ELLEN WRIGHT, TRANSLATOR

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AIR ENTRAINMENT BEHIND HIGH-PRESSURE GATES

Zur Belüftung der Strömung hinter Tiefschützen

by

Hans Bretschneider

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AIR-ENTRAINMENT BEHIND HIGH-PRESSURE GATES

Horst Reisenauer

[Abstract]

Results of model tests for air content measured behind high-head gates in two sluiceways in two different facilities are presented. The results are compared to known equations for calculating air requirements.

The comparison shows not only that air entrainment increases considerably when the gate is [partially] closed (decreased opening ratio), but also reveals that when the jet of water is aerated from all sides and the aeration features are installed on the bottom along the open channel, air content values exceed those indicated by Sharma's formula [8].

1 Introduction

Gates used for blocking a tunnel or changing flow rate are no rarity in dam construction. They take various forms depending on the functions they must perform [1]. Gates in sluices and service outlets represent a special group, and are situated far below the upstream water level. Often a great deal depends on their proper function--in catastrophic situations, sometimes everything depends on them.

While gates in sluices are usually operated only sporadically, e.g. when the water level in the reservoir must be lowered rapidly for safety reasons, high-pressure gates for outlets that are used to channel irrigation water from reservoirs are in continuous operation. During operation, these gates interrupt the current when they open and shut, as well as when they are partially opened; actually, water is always flowing under them.

In larger facilities, one of the diversion tunnels built during the initial construction phase is rebuilt as a sluice or service outlet. In these cases, the cross-section to be blocked is kept small in order to structure the gate design as simply as possible. This is achieved by installing a seal in the large tunnel cross-section and combining it with a gate chamber (Figure 1). If the measured discharge requires greater cross-sections, the opening required for maintaining critical water levels in the reservoir is divided into two or three separate cross-sectional areas.

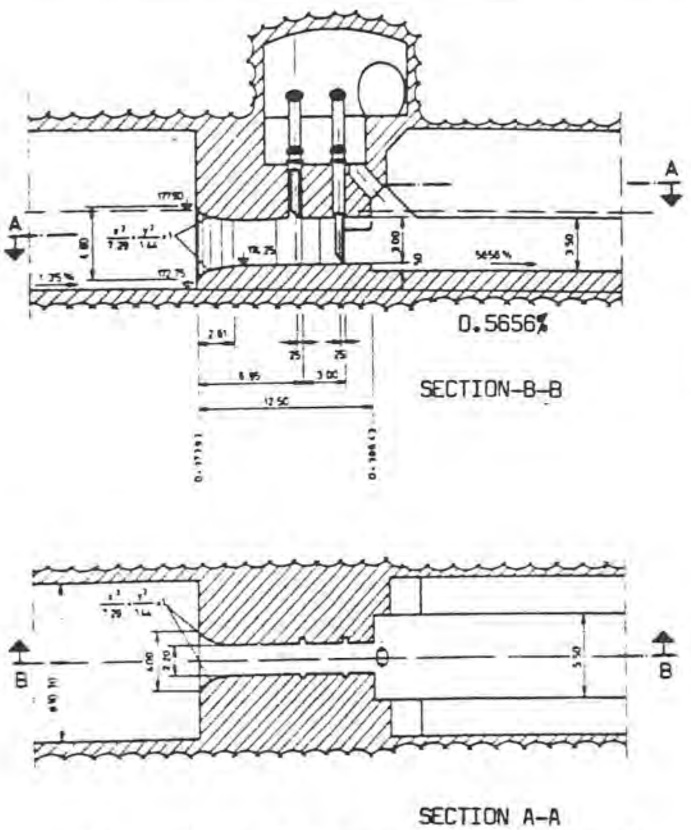


Figure 1: **Gate chamber after installation in a diversion tunnel bottom outlet in the Aghios Nicolaos Reservoir in Greece**

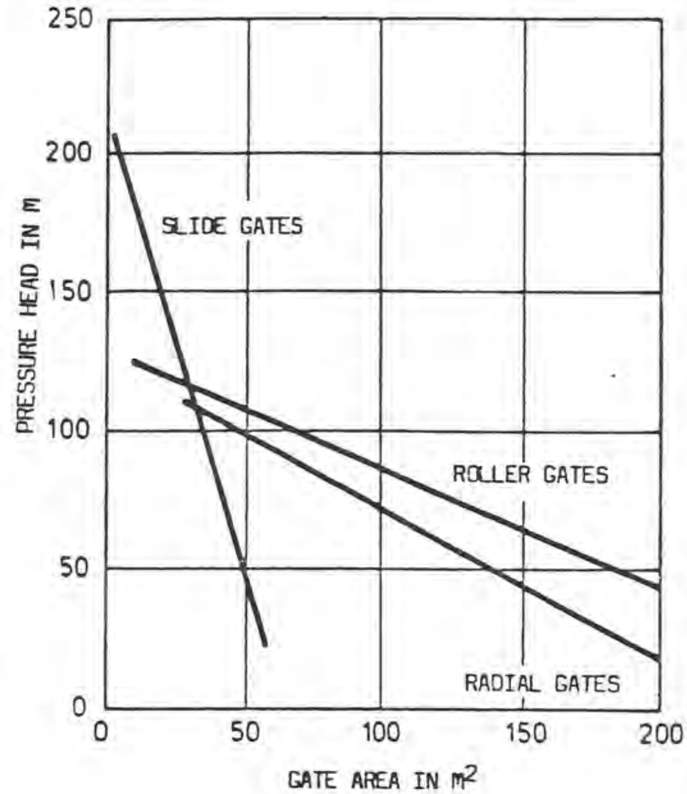


Figure 2: **Application range for high-pressure gates [2]**

Essentially, the gate opening in the cases discussed here is designed so that pipe flow ceases after passing through the gate or when it reaches the full opening after exiting from the drastically reduced gate cross-section. After this, the water shoots out into the open and flows off in an open channel. This study does not take into consideration facilities (for instance "ski-jumps" or stilling basins) used to transform the kinetic energy contained in the discharge. These features should also be situated far enough from the gate plane that they have no impact on the discharge from the opening.

2 Types of Gates

The most commonly used types are slide and roller gates, as well as high head radial gates. Erbiste has illustrated their application ranges in [2]. His 1981 graph (Figure 2), which is based on data from the 15 largest facilities in which each type of gate is used, indicates that slide gates are frequently used for small seal areas and high pressure heads and that roller and radial gates are used as high-pressure gates for average pressure heads. Because the air requirements for vertical and radial gates are discussed below, both types of gates will be briefly described.

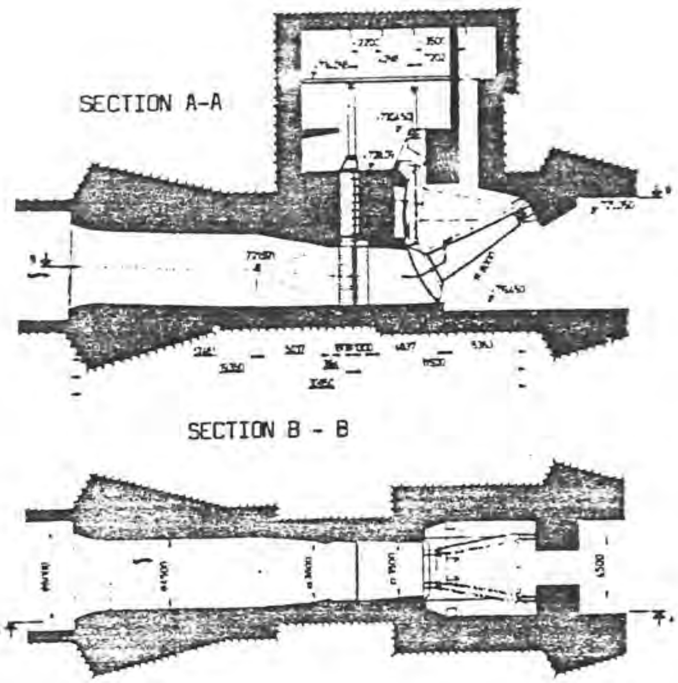
2.1 Slide and Roller Gates

Many sluices are equipped with gates requiring niches in the flank walls. Slide gates only require narrow niches, thus the danger of cavitation as a result of flow dissipation is not as great as it is with roller gates, which are also more susceptible to vibrations. The roller gate requires low operating power. However, the use of oil-hydraulic gate operating systems makes it possible to replace roller gates with sturdier slide gates because the frictional forces present during closing are overcome by the hydraulic presses.

Slide and roller gates do not differ in basic design. In both cases the gate panel is supported either on a girder grillage or a box or truss girder.

2.2 Radial Gates

As a rule, radial gates have a circular arc face on the upstream side and pivot on two rigid arms. The pivot point is usually in line with the center of curvature for this cylindrically curved face (Figure 3). The essential advantage of radial gates is that in contrast to rectangular gates, they do not require niches, thus almost eliminating the danger of cavitation. In addition to the bottom seal, the radial gate features either a flank or face seal.



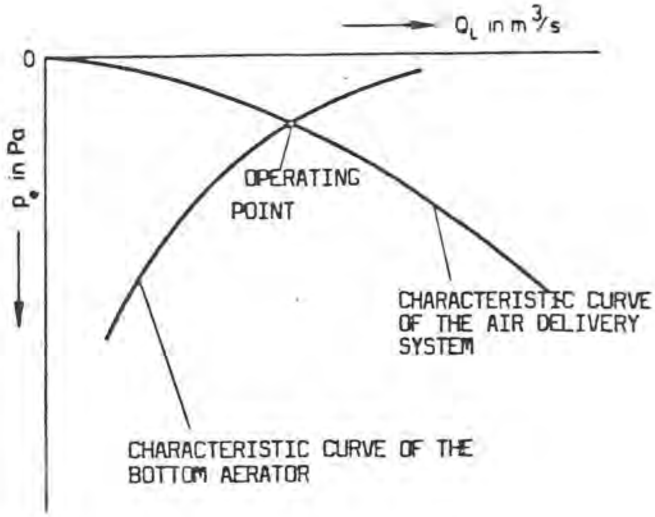


Figure 3: Radial gate used as a high-pressure gate. Bottom outlet in the hydraulic power plant at Pueblo Viejo in Guatamala

Figure 4: Characteristic of the aeration duct system (schematic)

3 Aeration

High-velocity, open flows generate air entrainment into the stream through turbulent movement and lead to air transport within and outside the stream. If the air mixed into and transported by the stream is not replaced in the space behind the gate, then, particularly in the case of high-pressure gates, this causes pulsations in the effluent due to the fluctuating negative over-pressure, and thus leads to vibrations in the gate. Therefore it is important to provide adequate air delivery behind the gate.

Until recently just about the only solution was to guide the jet emerging under the gate using flank side walls and the channel bottom so that only the surface came in contact with the air. If we assume unlimited pressure compensation between the atmosphere and the area behind the gate, the volume of air entrained and carried along because of the drag effect of the "rough" open discharge water surface represents a value that is dependent on the Froude number.

It has become evident that bottom zones that are endangered by cavitation can be protected by introducing air [3]; this realization has lead to the installation of steps or niches on the bottom behind the gate. Air ducts are installed to connect these features with the atmosphere; when the stream breaks up on the sharp corner [of the step], aeration occurs as a result of two different factors:

1. Water and air are mixed on their interface, and
2. When the jet impacts on the bottom, air is again entrained because of locally concentrated turbulence.

After the initial construction period is completed, sluices with relatively small gate openings are installed in the large cross-sections of the diversion tunnels. In order to aerate the stream of water, i.e. to mix additional air into the free-flowing stream, it is desirable to expose it to air on all four sides. These two factors have dictated the need for a sudden lateral expansion of the sluice, which has proven successful with respect to air entrainment. If, for instance, the ratio of the cross-sectional gate width with respect to tunnel width is too small, the resulting flow pattern is adversely affected, which will be discussed at another point.

The size of the stream volume Q_L is not just dependent on how it is guided. It is primarily affected by the size and form of the aeration duct and naturally also on discharge conditions, the type of gate, and the extent to which the tunnel is filled, among other factors.

The characteristic of the air delivery system determines the characteristic curve (Figure 4), which reflects pressure loss in the duct. Air entrainment by the water jet lowers the pressure behind the gate to below atmospheric pressure. This causes air to flow in the ventilation system, which causes pressure losses and thus leads to pressure compensation, but only insofar as the characteristic of the aeration duct will allow it. However, as a rule the characteristics for any given ventilation structure are not known during the planning stage, or even once the facilities are fully designed. Designers have to depend on air flow volumes established during model tests and to dimension aeration duct systems in the field accordingly.

If under-design occurs, there is always the hope that air from the end of the tunnel will be drawn through the open cross-section in the top of the tunnel counter to the direction of water flow, providing additional pressure compensation. Field measurements have indicated that this hope is not fulfilled in all cases [1, 4, 5, 6].

4 Calculation Formulas for Air Content Required behind High-pressure Gates

Open-channel discharge behind gates creates an air flow volume which can be described by the following equation, provided that the effects of capillary action and the viscosity of water are unimpaired:

$$Q_L = Q_W * f(\alpha,\ A_G/A_T,\ \frac{\Delta p}{\rho g h},\ Fr)$$

where

Q_L	Volume of the air stream
Q_W	Water flow
α	Gate opening in %
A_G	Gate cross-section
A_T	Tunnel cross-section
$\Delta p = P_{amb} - P_e$	Pressure differential between atmospheric pressure and the pressure in the area behind the [gate]
ρ	Density of water
g	Standard acceleration
$Fr = \frac{v}{\sqrt{gh}}$	Froude number with the water jet velocity v at the point where the water depth h of the shooting stream is measured

If the model is large enough and is operated so that the characteristic value $\Delta p/(\rho gh)$ in the field and in the model are about equal, then this characteristic is not a parameter. The same holds true for $A_G/A_T < 0.33$, e.g. in these cases the area ratio, which is often also written as the quotient of the cross-sectional area of the tunnel over that of the the water flow and the discharge, does not affect the air flow volume.

With the air content $Q_L/Q_W = \beta$, it follows that $\beta = f(\alpha, Fr)$. The function states that the air requirement behind the gate is clearly governed by the Froude number, if the opening factor does not change. Numerous measured results from model and field tests indicate that the forces of inertia and gravity generally determine this process to a great extent, as will be demonstrated here by a few significant comparative function curves.

At the IAHR Congress in Minnesota (USA) in 1953, Campbell and Guyton [1] presented an equation that for the first time contained measured values from the field. It applies for a discharge under gates with open channel flow supported on the sides and the bottom, that is, that are only aerated from above:

$$\beta = 0.04\ (Fr - 1)^{0.85}$$

This equation replaced the then ten-year-old formula introduced by Kalinski and Robertson [1], which was derived from the results of model experiments, yielded essentially lower values for air content, and led to under design of air delivery systems.

The next field measurements yielded even higher β values. For instance, many publications cite test results [4] at the Lumiei Dam in northern Italy, which indicate maximum air contents of $\beta = 0.4$ for $Fr = 0.8$. The results are discussed in [5], and it is determined that small gate opening percentages yield larger β values than do 100% gate openings. Furthermore, the tests indicate that the β values are independent of head levels.

At the eleventh IAHR Congress in Leningrad, Wisner presented a new equation:

$$\beta = 0.024\ (Fr - 1)^{1.4}$$

and included Lumiei values that are twice as high as the familiar values measured in the USA. Bibliography item [8] contains an explanation for the larger β values at the facility in Italy, where Petrikat found that the stream exiting the gate via the Lumiei sluices is aerated downstream of the gate from three sides because of the layout of the tunnel along its horizontal projection (there are a total of three outlets arranged at various heights). As will be shown, this finding is critical, as is consideration of whether the resulting effluent forms a rough spray-like discharge stream or a closed shooting stream.

Sharma [8] reached a tentative conclusion with his equations for the water-air mixture discharge $\beta = 0.2$ Fr and for the water discharge $\beta = 0.09$ Fr.

The curve derived from the formula $\beta = 0.09$ Fr includes most of the results from model and field measurements that were known at the time the formula was published. It does not indicate how the opening ratio affects the air content, but it does make clear that a value of $\beta = 1$ can be achieved, which means that the air flow volume drawn into the system can be equal to that of the water discharge.

Figure 5 shows the curves within the limits indicated by the individual authors.

Finally, one other formula was published last year that for the first time takes both the characteristic loss value for the aeration duct and the cross-section of the tunnel below the gate into consideration. For top aeration alone and open discharge, it is

$$\beta = 0.94 \left(\frac{A_L^*}{AT}\right)^{0.9} * Fr^{0.62}$$

and applies for Fr < 40 and $\alpha \leq 0.12$.

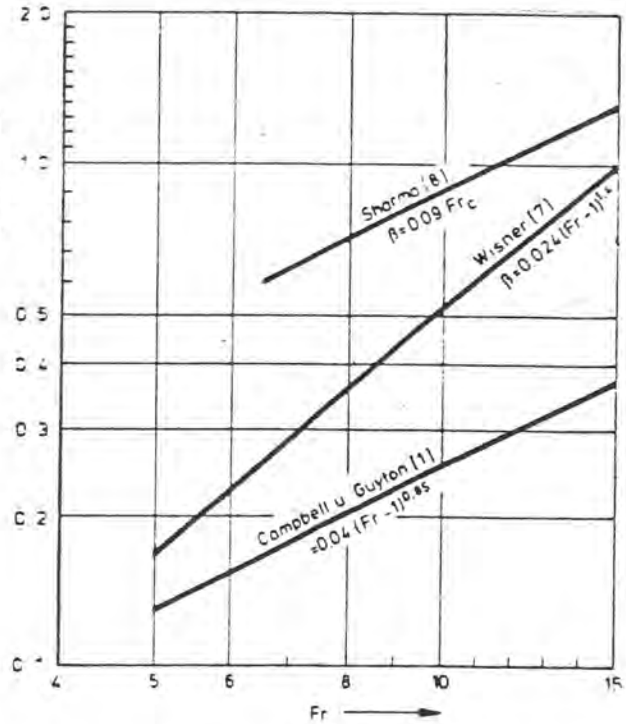


Figure 5: Air content as a function of the Froude number Fr (based on known formulas found in the literature).

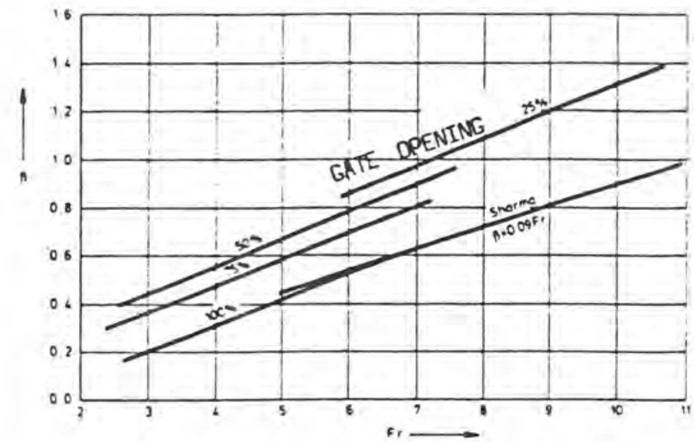


Figure 6: Measured results for $\beta = f(\alpha, Fr)$ on the model of Sluice II in the hydraulic Pueblo Viejo hydraulic power plant in Guatamala

In the formula A_L^* represents the hydraulically active cross-section of the aeration duct and A_T the tunnel cross-section.

The formula was introduced by Rabben, and does a good job of representing the ratios in several field tests. However, it must be applied with care if the water discharge takes up a great portion of the tunnel cross-section. Application of the formula assumes that A_L^*, the so-called reduced cross-sectional area of the aeration duct system, is known. This is the equivalent of determining a loss coefficient for the aeration duct system, which is not always possible in the planning phase.

5 Air Content Measurements on the Model for Sluice II at the Pueblo Viejo Hydraulic Power Plant in Guatamala

The hydraulic power plant was designed by the Motor-Columbus Engineering Company of Baden, together with its partners [12] and went into operation in 1983. During the construction stage, a second sluice was installed that the Institute for Hydraulic Engineering and Water Resources Management at the Technical University in Berlin studied for its functional capability using a physical model with a scale of 1:26.

Sluice II consists of a 300 m long pressure tunnel whose longitudinal section runs straight for about 120 m and then feeds into a gate chamber with a 90° elbow (r = 100 m).

The flow cross-section of this part of the pressure tunnel is a so-called horseshoe profile (crest d = 7.16 m). As it exits the elbow, this cross-section transitions to a circular cross-section of d = 4.5 m. After running about 12.5 m, this circular cross-section narrows over a stretch of about 12 m to a square gate cross-section with the dimensions 3.5 x 3.5 m. The gate is a high head radial gate with face seals (Figure 3).

An approximately 400 m long tail race with a bottom gradient of 1% begins at the gate chamber. This tunnel also has a horseshoe-shaped cross-section. It is designed to be operated as an open-channel tunnel.

Figure 6 shows the β values as a function of the Froude number for four different gate openings (25, 50, 75 and 100%), which indicated greater air contents when the discharge is cut back than are indicated by the Sharma equation. Before discussing the reasons for the larger air requirement, it is necessary to describe the conditions under which this results were obtained.

First of all, it is necessary to comment on the geometry behind the gate. At the transition point from the pressure tunnel to the open channel tunnel, both the walls and the bottom are abruptly set back. This sudden expansion of the cross-section causes the free jet to be aerated from all sides. These improved aeration conditions must therefore be one cause for the fact this configuration creates an air stream volume of transported and entrained air that is greater than in structures where entrainment on all sides of the stream is impossible. This condition is augmented by the fact that additional local turbulence is generated where the stream impacts on the bottom, mixing more air into the stream.

All measurements for gate aeration that have appeared in previous literature have been conducted in structures where there were no aeration features (niches or steps) in the sluice tunnels. The Pueblo Viejo Tunnel has eight of these niches with ramps positioned one after the other at 50 m intervals. If we can assume that part of the square niche at the end of the tunnel obtains air from the mouth of the tunnel, part of the total volume flow behind the gate is needed for niche aeration. For this reason the system will yield larger β values than for sluices without any bottom aeration features.

One reason that higher air contents are measured for a given Froude number is that as a rule the Froude number is determined with the water depth in the area where the stream is constricted. However, in the sluice at Pueblo Viejo it is not possible to localize the narrowest discharge depth because of the because of the jumps in the bottom, with the result that the Froude number has to be determined based on the height of the discharge cross-section in the gate plane.

When the model was planned and constructed, there were no data available on the air delivery duct (length, cross-section and path of the duct). Consequently, the cross-section of the aeration duct including the gage nozzle is selected large enough that losses will not have a significant effect on the the air flow volume. The greatest pressure differential during measurement occurred with the reservoir filled to the flood pool level with the gate completely open; converted to field values, it amounted to Δp = 10 mbar.

The ratio for the flow cross-section A_W to the tunnel cross-section A_T in the most unfavorable case comes to $A_W/A_T = 0.34$. It has no effect on air entrainment.

Finally, just a few words on applying the β values measured in the model. Under the critical operating conditions for measuring the aeration duct system (gate opening $\alpha = 100\%$ and $Fr = 6.4$, corresponding to water flow in the field of $Q_{W,N} = 440\ m^3/s$) an air flow volume measured and converted according to Froude's model principle yields a flow volume of $Q_{L,N} = 250\ m^3/s$. In order to compensate for the model scale of 1:26, this value must be increased by a factor of $N = 1.6$ to $Q_{L,N} = 400\ m^3/s$. The correction factor is based on data from the literature.

6 Air Content Measurements for the Sluice Model of the Aghios Nicolaos Project in Greece

The Public Power Corporation (PPC) in Athens is planning to build two dam stages in the central stretch of the Arakhthos River in northwestern Greece for the purpose of energy production. One of the two facilities is the Aghios Nicolaos Dam, for which the Institute for Hydraulic Engineering and Water Resources Management at the Technical University in Berlin studied the sluice.

The sluice is to be installed in one of the two diversion tunnels. The renovation calls for installing a gate chamber about in the middle of the over 700 m long tunnel. In the vicinity of the gate chamber, the 10.3 m high horseshoe-shaped tunnel will be narrowed to a 3.0 x 2.2 m rectangle (Figure 1). The intention is to use two slide gates spaced 3.0 m apart to shut off the flow. Behind the main gate, the water jet enters the open channel. All four sides of the enclosed free jet are aerated. The bottom will be lowered 0.5 m for this purpose, and the side walls will be set back on the right and left by 1.65 m.

The cross-section of the open channel is rectangular; it begins with a width of 5.5 m. At the end, the width is 8.0 m, having been expanded in five steps of 0.25 m each on each side. The sudden expansion provides air delivery to the bottom, which is also set back by double this dimension (0.5 m). The slope amounts to 0.5656%. The side walls are 3.5 m high throughout. Nothing has been changed on the roof section; it is identical to the upper section of the diversion tunnel.

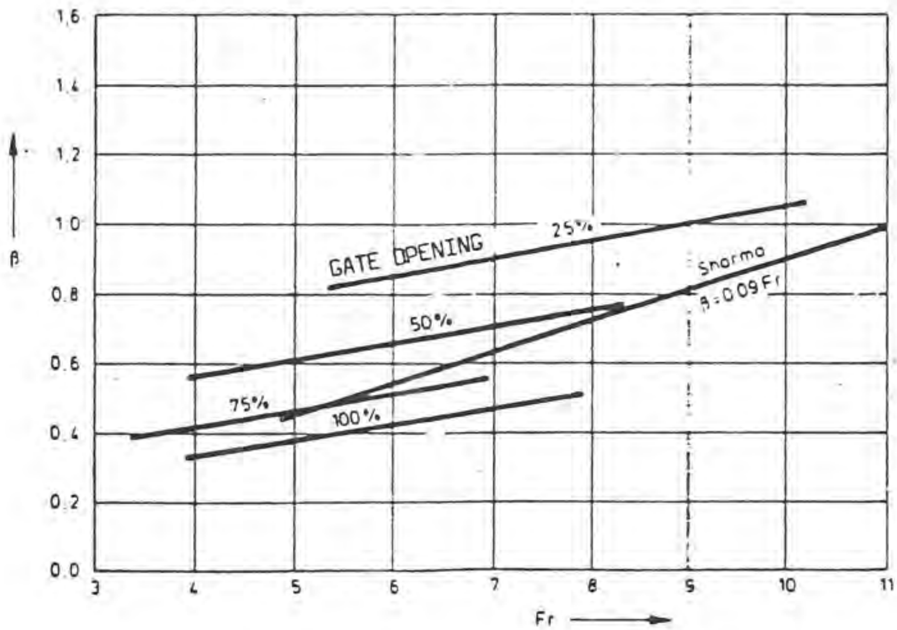


Figure 7: Measured results for $\beta = f(\alpha, Fr)$ for the model of the sluice at the Aghios Nicolaos Reservoir in Greece

The sluice is designed so that it can discharge $Q = 240\ m^3/s$ at the targeted flood pool level. Figure 7 shows the β values, plotted again as functions of the Froude number for four different gate openings. At first glance, it is apparent that the linear rise angle is not as great as for the segment of the Pueblo Viejo sluice (Figure 6), and that the absolute values achieved are not as high. Nevertheless, the β values during throttled discharge are much greater than the Sharma curve, which is also plotted on this graph.

There are no solid explanations for the curve patterns. Here again, the Froude number was determined using the gate opening height. The critical model scale of 1:20 used to convert values derived from model results to field proportions is more likely to produce high air content values than low ones. Since the same air delivery system was used as for the Pueblo Viejo sluice, and about the same pressure curves where measured around the jet behind the gate, it cannot be assumed that there was any effect in this regard. The same applies for the ratio of the flow cross-section to the tunnel cross-section (when measured $A_W/A_{St} = 0.1$), which also exercises no influence on the β value. Considering the fact that the steps in the bottom mix in considerably more air than do niches, there would actually have to be a greater air stream volume than in the case of the sluice with niches.

Finally, it remains to be seen that this could be attributable solely to the type and form of the gate used, as well as the dimensions of the shooting stream. For instance, the height-to-width ratio when fully open is 1.0 for the Pueblo Viejo sluice, and 1.35 for the Aghios Nicolaos sluice. Similar differences occur for partial opening. That the β value for all gate opening positions is smaller than for the sluice at the Pueblo Viejo Dam could also lie in the fact that the size of the free stream is considerably greater than for the Aghios Nicolaos sluice. For the smallest gate opening tested (25%), the quotient still amounts to almost 1.5.

The air content for the model was determined at $\quad = 0.47$ for measurement conditions, and $Fr = 7.3$ was converted using Froude's model theorem corresponding to reflect an air stream volume of $Q_{L,N} = 123$ m^3/s. As was the case in the model tests for the Pueblo Viejo Project, these values were increased by a nearly identical correction factor to $Q_{L,N} = 200$ m^3/s for designing the air delivery system in the field.

7 Outlook

When planning sluices, there is a clear tendency to structure the area downstream of the gate so that a free jet can form. This solution is favored particularly if a very large profile diversion tunnel is to be rebuilt to form a sluice. The explanation for this design is usually the fear of cavitation, not so much in the area of the gate, but rather of cavitation erosion in the free channel tunnel. Designers are afraid of this material destruction on the walls and bottom of the channel, and seek to counteract it by using natural means to mix air into the discharge jet to form a highly turbulent stream [10].

The test results presented here clearly show that the goal of mixing as much air as possible into the stream is achieved by aeration on all sides. The tests do not indicate whether the increased air content is necessary for safe, reliable gate operation. Given existing knowledge and design principles for sluice gate designs, this seems questionable. Because the shooting stream solution has considerable disadvantages from the standpoint of stream engineering, it is advisable to separate bottom aeration from gate aeration. A later publication will report on this concept.

Tests on the sluice for the San Roque facility in the Philippines [11] show how the different the results of measuring air contents can be. Without going into additional details, one fact should be noted: the air requirement was greatest with the gates 80% open. This not only contradicts the values shown in Figures 6 and 7, but other results as well [6]. The reason could be that the pressure tunnel in the San Roque plant is closed off by three adjacent gates and other underwater discharge situations lead to results that deviate from the "norm." This kind of abnormal behavior can only be determined in model tests. The design engineer is therefore well advised to use this planning aid.

These tests were conducted under contract to the Engineering Firm Lahmeyer International GmbH; Frankfurt, Salzgitter, Consult GmbH, and ASAG Consulting Engineers, Athens. The author thanks all colleagues involved in this project for their cooperation.

Bibliography

[1] Wickert, G. and Schmaußer, G.: Stahlwasserbau [Hydraulic Steel Structures], Springer Verlag, Berlin, Heidelberg, New York 1971.

[2] Erbiste, P.C.: "Hydraulic Gates: the State-of-the Art," Water Power and Dam Construction, April 1981.

[3] Naudascher, E.: "Kavitationsprobleme in Grundablässen" ["Cavitation Problems in Sluices"] Wasserwirtschaft [Water Resources Management] 72 (1982), Vol. 3.

[4] Dettmers, D.: "Beitrag zur Frage der Belüftung von Tiefschützen" ["Aerating High-Pressure Gates"], Mitteilungen der Hannoverschen Versuchsanstalt für Grund- und Wasserbau [Reports of the Hannover Research Institute for Foundation and Hydraulic Engineering], TH Hannover, Vol. 4, 1953.

Bibliography, cont.

[5] Wunderlich, W.: Beitrag zur Belüftung des Abflusses in Tiefauslässen [Aeration of the Discharge in Low-level Sluices], Dissertation, TH Karlsruhe, 1961.

[6] Liebel, A.: "Die Grundablaßschützen des Kaunertalkraftwerkes" ["Sluice Gates in the Kaunertal Power Plant"], Der Bauingenieur [The Construction Engineer], Vol. 11, 1968.

[7] Wisner, P.: "Sur le role du critere de Froude dans l'etude l'etrainement de l'air par les courants a grande vitesse" ["On the Role of the Froude Criteria in the Study of Air Entrainment in High-Speed Currents"], XI. IAHR Congress in Leningrad, 1965, Paper 1.15.

[8] Sharma, H.R.: "Air Entrainment in High Head Gated Conduits," Proceedings of the ASCE, Vol 102, No. HY 11, Nov. 1976.

[9] Rabben, St. L.: "Untersuchung der Belüftung an Tiefschützen unter besonderer Berücksichtigung von Maßstabeffekten" ["Studies of Aeration in High-pressure Gates with Special Attention to Scale Effects"], Mitteilungen des Instituts für Wasserbau und Wasserwirtschaft der RWTH Aachen [Reports of the Institute for Hydraulic Engineering and Water Resources Management of the RWTH Aachen], No. 53, 1984.

[10] Kobus, H.E.: "An Introduction to Air Water Flow in Hydraulics," Mitteilungen des Instituts für Wasserbau der Universität Stuttgart [Reports of the Institute for Hydraulic Engineering of the University of Stuttgart], Vol 61, 1985.

[11] Anastasi, G.: "Besondere Aspekte der Gestaltung von Grundablässen in Stollen" ["Special Aspects of the Structure of Sluices in Tunnels"], Wasserwirtschaft [Water Resources Management], Vol 12, 1983.

[12] Balissat, M., R. Wilhelm: "Design and Construction of the Pueblo Viejo Dam," Water Power and Dam Construction, July 1986.

Address of the author: Prof. Dr.-Ing. H. Bretschneider, Institut für Wasserbau und Wasserwirtschaft der Technischen Universität Berlin, Postfach 100 320, 1000 Berlin 10