Research Institute for Hydraulic Structures

Technische Universität München
Oscar V. Miller Institute

Report No. 24

Edited by Professor Dr. Ing. F. Hartung
München/Obernach
1972
Vortex in the inlet to the water power station (Investigations on the hazard of air entrance in the intake structures of the pump storage station Rodund II of the Voralberg Illwerke).

by

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Obernach, 1972.
ABSTRACT.

In answering the question for on air-entraining vortex to unsymmetrical approach flow conditions at the intake structures of the Pumped Storage System Rodund II, Austria, an extensive study of the respective publications was done including the application of the described methods of investigation to the example under consideration. The theoretical results of the investigated intake structure.

This report is thought as a subscription to the hydraulic problems of "Formation and Prevention of Air-entraining Vortices at Intakes" and is to give in the first place a general view on the respective publications and on the most important results of fundamental research, especially for model technics. The paper is to be continued in a report on "Measurement of Swirling Flow in the Penstock behind a Vortex prone Intake". 
A) **INTRODUCTION.**

1. **General.**

The pump storage station Rodund II of the Vorarberger Illwerke will be built in 1971-73 as a parallel structure to the existing unit Rodund I and will be used for the supply of peak energy. With a maximum efficiency of about 250 MW in the turbines or pumping action the most efficient European hydraulic engine would come into operation (1). The mean drophead or the hoisting height comes out to be 342.5 meters. The maximum flow through the turbines is 90m$^3$/s. The pumps can draw water upto 73m$^3$/s.

The upper basin lies about 1000 m above sea level and will be set up besides the existing shuffling basin. In these two basins taken together 2.1 million cubic meters of water could be stored. The upper region of the dam space will be jointly managed but a separation is possible in the lower region. At the unit 1 the ground plan of the enlarged shuffling storage basin is shown. The shape of the basin corresponds to the nature of the terrain.

2. **Statement of problems:**

   In the summer of 1970, at a discussion in the Obernach (1) E. Stefko. The alpine water power storage in the age of the nuclear power stations from the Austrian distribution of water, Vintage 22 Copy 7/8 July/August s. 193-201.
Research Institute, the management of the Illwerke introduced a design of the intake structures and the planned shape of the upper basin and were asked whether the chosen dimensions of the plants would be free from the danger of vortex formation at the inlet and the penetration of air into the power station.

Air entraining vortex, which is briefly called sucking vortex can form if as a result of geometrical conditions a certain eccentricity is present between the inflow to and the discharge from the intake structures and this eccentricity leads to a circulation of the discharged water in the inlet area. The shape of the storage basin around the point of outlet and the position of the inlet relative to the basin determine the approach flow rate and in case of an incorrect shape is the main cause of vortex formation. In the presence of rotatory motion above the inlet, there is a great danger of the entrance of air, if the spread-over depth, i.e. separation between allowed level drop and the capturing edge as well as the dimensions of the inlet cross section are too closely planned. The air entrance depends upon the strength of the externally stimulated vortex, the existing spread over depth and the rate of inflow. In most cases a nonuniform approach flow has to be reckoned with due to some local conditions (unit 1) vortex motion could be released. A further unfavorable condition occurs when as a result of legitimate economic consideration most exact structural dimensions have to be chosen. The possible spread-over depth will be considerably affected by two important view points.
The desire to retain peak energy as long as possible needs an optimal utilization of the available contents of the pump storage basin, i.e., extensive drop in the level of the stored water. But, on the other hand, for the reduction of building expenses, especially for expensive and deep foundations, the canturing edge and the base of the inlet should lie a little below this planned level drop. Hence, the spreadover depth and the inlet cross-section must be kept small.

But this is contrary to the demands of the hydraulics for protection against the air entraining vortex which requires a sufficiently large spreadover depth and a low rate of inflow.

An important design problem is the balance of these two contradictory conditions. For the planned intake structures in Rodundwerke II, an accurate test of the design in this manner and a thorough investigation of hydraulic processes regarding vortex formation, and air entraining is essential.

3. **Method of Solution.**

First of all, it was proposed by the Research Institute, that the answers to the question should be found with the help of a hydraulic test model. The design of the complete spreadover basin on a 1:30 scale model was not possible at that time due to lack of space in the hall of the Research Institute due to lack of space and the expenditure for such a large model too
could not be met with, so it was proposed that a basin area of about 180 m be made around the intake structures in a cut out model. The different conditions of inflow to the inlet from the main basin could similarly be simulated through appropriate installations. This smaller model could be made on a scale of about 1:20.

A thorough study of the relevant literature must be made before commencing the exact planning of the model. It is found that generally valid, and in the present case applicable evidence of the international subject literature about a natural representation of inlet a vortices are unsatisfactory and partly even contradictory. The later concerns the similarity mechanics of the air entraining i.e. how exactly could the process of a suction vortex formation the water outlets from the storage basin can be represented in a model and how far the geometrical reduction of the natural conditions can be carried out.

Apart from these experimental obscurities the literature shows that some theoretical assertions and practical experiences are directly applicable to the example under consideration and an estimation of efficiency is also made possible to determine the dimensions of the design. It could be ascertained from the data and experimental possibilities given in of this literature that for the planned intake structures of Rodundwerke II there is hardly any danger of vortex formation by air entraining some fundamental knowledge of the research and the constructive
inferences from it are obviously being incorporated from the very beginning in the installation design.

Further treatment of the problem is as follows:

For the demonstration of the action of a particularly important structural measure a small schematic model was operated and was demonstrated at the discussions in autumn 1970 and in the spring 1971. On the basis of this demonstration experiments and a fairly complete review and checking of the existing literature it was finally proposed that the problem should be solved theoretically and the questions that might arise should be resolved on schematic considerations. The small model was not only used for demonstration but special data of the fundamental research was confirmed by measurements.

The proposal was agreed by Illwerke and the order for the solution of problem in this manner was given in July 1971.

In literature search it was found that there is not a single new work in German on the present subject. Looking for it in the English, American and French literature needed a great deal of time and it seemed justified, rather more so in the present case than perhaps necessary for the carrying out of the commission, that the illustration, and discussion of different experimental results should be studied. As regards the supposed growing number of similar problem this literature references might be of interest.
While choosing the literature to be quoted attention was given to whether they contain results about the special question of "Origin and hindrance of the air entrance vortex". Data on this is very few. The fundamental works on "vortex with planned air entrance" are far more in number.

After a discussion on the special condition of the intake structure Rodund II the findings on the existing unit even reported and the results applied to the present case. In the main section of the report the available theoretical and experimental studies have been discussed and an application of the results to the example under consideration attempted. In the end a summary of the data generally valid for the topic is given and the technique and results of the demonstration experiments are described.

B) NATURE OF THE STORAGE BASIN AND THE INTAKE STRUCTURE.

1. Plan of the Storage Basin and Approach Flow Rate.

The final plan of the new basin and the connection to the shuffling basin have been taken from the Plan No. 71063 of Illwerke and so the simplified representation are formed the basis of units 1:

Looking in the direction of flow, by far the larger part of the storage basin II lies to the left, of the axis of pressure shaft which is extended upstream. In the immediate surroundings of the intake structures there is an approximate axis symmetry but this may mislead about the other wise extreme unsymmetry not
of the whole basin and particularly as the connection to the old shuffling basin. Contrary to the early (design plan No. 70244) however, there is an important modification, viz., the alteration, sketched below, of the pipe lines of the right wall which bend into the basin (figure 1) down position of the basin (Diagram 1). The present uniform bending of the two sides of the basin promotes a more uniform and continuous flow to the inlets. The same holds for the improved construction of a channel in the bottom of the basin.

Diagram 1.

1. New outline 2. Old outline.

The storage target lies at a level of 992.25 and the level drop target is at a level of 974.00 meter. At this lowest level about 3m deep channel in front of the inlet upto the channel to the basin I is filled with water. The upper edge of the dam between the two storage basins is at a height of 987.00 m, i.e. 5.25 m below the maximum level and 13.0 m above the maximum low level. The maximum quantity which can flow through the dam is 75 m$^3$/s. The same amount can flow through the diversion channel and the whirlpool basin which lying to the left of the upper
basin spandel. In an extreme case 50 m$^3$/s can pass through the deviation canal. In the new storage basin, these three methods of inflow can be used in combination or separately.

Therefore it is possible that the peak energy of the flowing water largely depends upon the basin water level. Then a clearly pronounced and directional motion impulse is expected which can produce an unsymmetrical approach flow to the area of basin in front of the inlet. The shortest distance between the supply from the basin 1, which is near the connecting canal, and the outlet to the pressure shaft is about 200 m. It is therefore expected that the introduced impulse of this strength is weakened and the flow becomes comparable. For the sake of safety however, one must reckon with the possibility of occurrence of a circulation flow through the inlet; and the dimensions of intake structures must be planned for an extremely irregular flow.

It is evident so far that if everything correspond to the local conditions then a regular flow in inlet region can be produced. This may perhaps not suffice and a transverse movement through the inlet is unavoidable. Now the aim of a sufficiently large model experiment would be to most accurately represent and measure these special approach flow conditions of the unit and e.g. to include the calculation of the magnitude and variation especially describe and measure out the swirling constant of the circulation in the flow conditions for unit 1 i.e. the value calculation relating to a suction vortex.
Apart from the difficulties in similarity mechanics of such a study a model with about 30 x 20 m base and about 2 meters height would be much too costly finally this expenditure shall not be incommensurate with the uses and results of this model.

It would be more useful to theoretically check the critical dimensions of the intake structures in presence of extremely unfavorable approach flow conditions and to modify them accordingly; one of these conditions is e.g. a totally one-sided and concentrated approach flow. The result of the calculation would then include a safety factor which is perhaps uneconomical as regards the construction cost but due to it a disturbance-free operation of the unit becomes more probable.

2. **Dimensions of the Intake Structures:**

The shape and dimensions of the intake structures are taken from the plans No. 71162 and 71163a. The unit 2 again shows a simplified representation of the design with the important measurements which are of interest here. In anticipation of the late justifications, three favorable construction characteristics of the planned intake structure are emphasized here:

1. The position of the inflow very close to the rear basin boundary.

2. The large outlet opening at the beginning of the construction and behind it the longdrawn and regular contraction of the inlet cross section.
3. The relatively steep outlet system which rapidly drops downward.

The inclination of the pressure shaft axis with respect to the horizontal is \(34^\circ\) behind the inlet. In the study of the literature, the authors have not come across even one example of inclined outlet direction. The preponderant part of these works concerns vertical inlets which are above or below. A small portion deals with the horizontally straight outlet structures.

It is therefore extremely difficult to introduce some necessary definitions for especially important quantities in the present case. It is important to know where the basin ends and where the inlet starts. Again what is the determinative dimension of inlet cross section and how could we define the spread over depth. Further, it is very difficult to preclude the spatial expansion of the possible circulation over the inlet and to enclose it at the present place.

At maximum level drop \(86 \text{ m}^3/\text{s}\) should be extracted at a level of 974.0 meter. Therefore a velocity of flow of exactly 1.0 m/s is attained in the grating sections. A flow drop of exactly 5.1 m is established shortly in front of the locking device of the actual inlet cross section with a height of 7.2 m and an area of 2 x 30 m. The flow drop finds itself in the ends of a cross-sectional narrowing over a relatively short section of about half the original size. The velocity of flow is exactly
2.0 m/s. The inlet here is vertically halved by a partition wall of 1.2 m thickness. (see appendix 2).

This bipartition of the inlet and the introduced gratings is, an additionally structural means to disturb formation of the air-sucking vortex and to possibly prevent it.

If the subdivided rectangle of the defined inlet cross-section is transformed into a uniformly circular profile, it would have a diameter of 7.4 m. At a length of 19.2 m the flow cross-section, is linear and gradually contracts down to square of 4.0 to 6.0 m, which corresponds to an acceleration of 2.0 to 5.3 m/s. The connected distorted line upto the circular pressure shaft profile is 60 m long with an internal diameter of 4.0 m. The flow cross section here is about 12.57 m². If 86 m³/s, is discharged the velocity of flow attains its limiting value of 6.85 m/sec, between the inlet and the actual Falleitung with a final magnitude of 6.85 m/s. The axis of the channel is thus 22.73 meter below the sinking.
In the investigations of the horizontal or vertical water outlets from the storage basin, the spreadover depth on the discharge point or the water head in the container can be determined in practice as follows (figure 2):

For the present case of an inclined outlet the boundary between the basin and the pipe line is similarly defined and the standard spreadover depth is defined as the vertical distance between the extremely low water level and the highest point on the chosen inlet cross section (figure 3). In the calculations of the vertical discharge process, $h$ is taken minimum container depth.

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Figure 3. Schematically deformed inlet.
Key: 1. Sinking; 2. Boundary between basin and conduit; 3. Inlet cross-section.
In order to apply here the results of the study of vertical outlet the inclined inlet must be schematically remodelled into a perpendicular one (figure 3). With the given transformation, rather similar conditions would prevail. The rectangular inlet cross section would be replaced by a circular one with a radius of 3.7 m. The chosen turning point of the pipe axis is 7.4 m in front of the rear perpendicular wall of the storage basin. As can also be seen from appendix 2, the standard spreadover depth for the defined inlet cross section, \( h = 5.65 \) m and for the final cross section \( h = 21.3 \) m.

A further important quantity for the estimation of the discharge process is the discharge coefficient \( c \) in the definition:

\[
C = \frac{v}{\sqrt{2gH}}
\]

where

\[
v = \frac{Q}{d^2 \sqrt[4]{\gamma}} \quad \text{(in m/s)}.
\]

\( v \) is the velocity of flow in the considered circular cross section of the closed inlet channel and \( \sqrt{2gH} \) in m/s is the maximum possible velocity of the free discharge. For \( Q = 86 \text{ m}^3/\text{s} \) and lowest drop in level. The initial and final cross sections of the inlet are:

- **Initial cross section**
  - \( d = 7.4 \) meter
  - \( v = 2.0 \) m/s.

- **Final cross section**
  - \( d' = 4.0 \) meter
  - \( v' = 6.85 \) meter
As shown later, $c$ should possibly be smaller than 0.5. The variation of $c$ along the inlet axis is shown in appendix 3.

Figure 4. Extremely one-sided flow.

The determination of the standard cross section, that spot is selected where the container that is to be emptied is present and where a circulation of flow would possibly occur over the entire basin depth. For the designed case of a vertical outlet one sided flow shown in figure 4 and the formation of a correspondingly strong circulation is reckoned with. Therefore the rear boundary of the basin assumed to be a curved vertical wall. The curvature radius according to appendix 2 is: $r_a = 7.4$ m. The geometrical ratio $r_a/r_o$, which is important for calculation is exactly 2.0 when $r_o = 3.7$ m is the exit orifice and thus describes the magnitude of circulation channel.
This data concludes the preparations for further studies.

Findings of the existing units with horizontal inlets.

1. General Literature References.

According to the general construction and application two types of inlets must be differentiated:

a) Inlets, which project free on all sides in the water basin, the suction nozzles of pumps or the tower of a shaft overflow e.g. for a high water discharge unit.

b) Inlets which are flush in the walls of the basin, e.g. reservoir works or in the filling pipes of ship locks, in which the upper edge of the inlet is always at a definite distance below the minimum level of water in the basin.

Type (b) such inlets whose upper edges project out of the vessel walls.

As in the present case, a typical wall inflow is dealt with relevant studies have been kept in view in the literature quoted here. As already mentioned, only horizontally or vertically directed outlets have been studied so far. Reports about the findings in the working of the present units are very few, because consequent and systematic research into the vortex problem at inlets was first started at the end of the fifties.
Details about the prevention of suction vortices at the wall-inlets with horizontal take-out direction are given by Wittmann in 1955 (2), by Denny and Young in 1957 (3), by Nelson and Johnson in 1959 (4), and above all, by Gordon in the year 1970 (7). Of these works, the last one is especially valuable as it gives exclusive results on measurements and observation on large-scale units and thus a comparison of the results of the model experiments becomes possible.

2. **Wittman's Data 1955.**

In the chapter on driving water structures, Wittman (2) unites under the heading "Deep lying inlet". In the extraction from reservoirs, the inlet is so much submerged that even with maximum drop in level air cannot enter. Upper edge of capturing edge is at $1.5 \left(1 + \frac{v}{c_f}\right) \frac{v^2}{2g}$ below the lowest level allowed, where 1.5 is the safety factor and $c_f$ is the drop height loss coefficient thus the formation of vortex is avoided.

An unfavorable loss coefficient $c_f = 0.333$ for the inlet under consideration the spreadover depth is roughly found to be:

$$h_{erf.} > \frac{v^2}{g}$$

A definition of "capturing edge" as well as that of determinative flow velocity is unfortunately not available. If $v$ means the rate of flow is the proper driving conduit behind the whole inlet then the value of $6.85 \text{ m/s}$ gives:
In 1970, the results of the Wittmann's calculation was verified in the publication of Quick (6), in which different conditions are mentioned which must be obtained if an air-centraining vortex is to be formed in a straight prismatic channel, in front of horizontal inlet. Here, of course it is not the so-called wall-inlet but it is a case of sucking nozzles of a pump with rounded conical front edges (figure 6), which freely project into a water basin.

Quick has given three conditions for the investigated example which are necessary for the excitation of an air entraining vortex:

- $h_{erf} \geq 4.8 \text{ m}$
- $h = 5.65 \text{ m} > h_{erf}$ if the determination of the capturing edge shown in figure 5 is allowed.
a) The vortex must be formed in the path to take-out and must change into a circulation inside the flow. Since in the case considered here, there are no irregularities in the limits of the inflow, therefore the vortex must be sought for in the boundary layers on the walls of the channel. The relevant experimental results shall not be discussed here any more. The second condition is of greater interest for the present problem.

b) The Froude’s number, which is calculated from the available spreadover depth $h$ and the velocity of flow in the extraction tube ($v = \frac{Q}{\pi d^2/4}$) must be greater than 1.0:

$$Fr = \frac{v}{\sqrt{gh}} > 1.0$$

If a sucking vortex is to be avoided then the spreadover depth is found to be

$$h_{erf} > \frac{v^2}{g}$$
For $v = 6.85 \text{ m/s}$ as given by Wittmann, $h$ must be greater than 4.8 m.

c) The third condition holds only for the system under study and it stipulates that the spread-over depth must be equal to or less than the half the depth of the channel, if there is a formation of sucking vortex.

$$h \leq \frac{t}{2}$$

With regard to the practical cases, Quick has reported a further important observation: If a small part of the running water in the inlet can pass in the rear part of the channel, the formation of stabilized vortex is prevented, because it will be, so to speak, washed off.

As regards the wall inlets a certain explanation for the favorable working of projected upper edge of the inlet is possible and it is correct only if the projection is long enough and the residual flow in the posterior part of the basin does not lead to a recirculation in front of the inlet (figure 7).

Figure 7.
4. **Vortex Protection according to Denny and Young, 1957.**

In a summary of numerous experimental results, the possible steps of preventing vortex formation in front of the inlet and swirling flow in the connected pipe have been discussed; here Denny and Young have studied pumps in the first instance (3). As the results however, are schematically formulated and are generally valid, they too can be applied to the wall-inlets:

a) **Vortex formation in front of and swirling flow** behind the inlet are direct results of a continuous "rotation flow" occurring in the flow-path towards the outlet. The efficiency of the connected hydraulic machines is considerably deteriorated on one hand due to simultaneous transport of air during vortex formation and on the other hand due to non-uniform velocity profile during the swirling motion.

b) The decisive reason for the above mentioned outflow problem lies in the stimulation of a continuous and sufficiently strong circulatory flow in front of the inlet due to the special condition of the flow channel. The three possible situations are schematically shown in figure 8.

If an improvement in the flow conditions is not possible then the problem of the prevention of vortex must be solved by operationally safe planning of the
important dimensions of the inlet i.e. inlet cross-section and spreadover depth. Both factors together affect the formation of suction vortex and flow swirl to a considerable extent.

c) In the experiments the boundary between vortex-free and vortex-susceptible out flow regions or between the air free and air entraining vortices, was determined. The conditions of discharge are thus described by the comparison of the rate of flow and the ratio of the spreadover depth to a characteristic dimension of inlet cross section. The boundary curves drawn have the following shape (figure 9). With increased rate of flow the curve at first shows a sensitive dependence of the
Figure 9.

Key: 1- Vortex-free region; 2- Curve for critical spreadover in ratio to tube diameter; 3- Inlet horizon; 4- Vortex-prone region.

Critical spreadover depth upon the magnitude of velocity but later however, it shows constancy.

d) An experimental result which is very important for the present case is about the effect of the basin walls on vortex formation; here above all, the distance of the inlet from rear wall is of greater importance (figure 10).

The smaller the wall separation the smaller is the spreadover required. Up to a wall separation of five inlet diameters, the critical spreadover is nearly proportional to the separation. As shown later, the demonstration model of this research institute gives quite a similar result.

e) Denny and Young have concluded from their observations that the shape of inlet has a very
little effect upon vortex formation, that vertically upward or vertically downward outlets behave in a similar way, that in horizontal inlets, however, their position relative to the vortex zone is important.

While the external circulation in vertical outlets continues in the shape of a pronounced swirling flow behind the inlet, it is not expected in horizontal inlets. In sloping inlets the extremely complicated processes occur due to "overlapping of rotations in two planes" but these processes have not been studied by Denny and Young.

For the elimination of vortices in the present units, additional installations have been suggested.
which either prevent the circulation in the inlet region or shift the end of the vortex from the inlet (figure 11). Swirling flows can be reduced through the conducting walls in the inlet.

g) If the inlet cross section considerably increased in comparison to the pipe cross-section, the requisite spreadover is reduced (figure 12).

h) The four summarized principles given below show how the vortex formation and swirling flow can be reduced:

1. Reduction of conducted circulation
2. Increase of inlet cross section.
3. Increase of the spreadover depth.
4. Reduction of the space between the walls.

i) Regarding the similarity conditions in the
model experiments, it is proposed that the maximum geometrical reduction could be up to 1:16 and that the rate of flow in model should be same as in nature.

Observation of Nelson and Johnson, 1959.

On the filling installations of the lock units undesirable sucking vortices have been observed. Here it is matter of typical wall inlets with sloping flow where in certain cases the circulation in flow is externally excited due to wind, blowing diagonally in the canal. By comparing the model experiment with the large scale operation, it was observed by Nelson and Johnson (4) that the vortices are greater in nature than in the model. They have given the following precautionary measures:

a) Spreadover of the wall inlets as large as possible

b) Symmetric and uniform flow.

c) No loosening or vortex formation on the geometrical boundaries of the flow.

d) Uniform acceleration of outflow in the direction of extraction.
e) Least possible rate of flow in the inlet.


Gordon was the first to ascertain that there are very few publications about experiments on vortices on inlets and that even less details are available about what spreadover is necessary to prevent the vortex formation and that too in 1970.

Spurred on by a case of damage, Gordon investigated 29 units for their vortex susceptibility and found four inlets in which air entraining vortices were observed of low water levels in the storage basin. The structures under consideration had the shape shown below. (Figure 13).

Figure 13.

Key: 1- Asymmetric flow; 2- Symmetric flow; 3- Sinking; 4- Defined inlet; 5- Square or rectangular x-section.

The comparison of the measured rate of flow with the defined inlet cross section the height $h$ is chosen as the characteristic dimension gives with the present spreadover the
following determining equation for the level drop $h$ of the inlet upper edge below the lowest water level in the storage basin:

$$h_{\text{erf.}} = 0.725 \cdot v \cdot \sqrt{d} \text{ (m)}$$

The factor 0.725 includes a reserve for the influence of unsymmetric flow. In a symmetrical inflow the empirical factor is 0.545. The necessary spreadover for the symmetric inflow is therefore:

$$h_{\text{krit.}, \text{sym.}} = \frac{3}{4} \cdot h_{\text{krit.}, \text{unsym.}}$$

Applying it to the inlet Rodund II studied here with $v = 2.0 \text{ m/s}$ and $d = 7.2 \text{ m}$ for the fixed inlet cross section the above formula gives a necessary spreadover of:

$$h_{\text{erf.}} = 3.9 \text{ m} < h_{\text{vorh.}} = 5.65 \text{ m}$$

For the sake of comparison $h_{\text{erf}} = 7.8 \text{ m}$ was calculated for the quadratic cross section, at the beginning of the extraction on the circular profile with $v = 5.4 \text{ m/sec}$ and $d = 4.0 \text{ m}$. At this position the present spreadover is already 17.9 m (see appendix 3).

Apart from the exact question which is not clarified, i.e. whether the present results for the horizontal outlets can be directly applied to the inclined inlet, Gordon's calculation proves that a suction vortex shall not occur in Rodund II. Gordon's formula has the great advantage that it was obtained on a so-to-speak, 1:1 model and so it is free of the similarity problems of other investigation.
D) General theoretical and experimental study of vortex in outflow from circular opening on the bottom of cylindrical vessels.

1) General, Literature References.

Differentiation and types of vortices.

In the so-called cylinder experiments, the vertically downward outflow from a large circular vessel through a small circular opening into the horizontal bottom of a container is studied. The vortex formation is caused here by the flow of water in direction eccentric to the outlet axis and is stabilized by steady flow conditions. The aim of these studies, which began 25 years ago, is an accurate knowledge of the vortex mechanism and its effect on the outflow process. According to the system and purpose of uses one must differentiate between "vortex intake flow and "vortex orifice flow" i.e., between vortices on inlets and vortices on the outlets (figure 14).

The vortices formed are of the same type in both cases; in the inlets the behavior of flow in the connected pipe (air intake, twist) is of interest. While in the outlets, the conditions in the orifice (outlet coefficient, angle of shift) are studied. Results of fundamental studies on inlets were published in 1955 by Einstein (7), in 1959 by Haindl (8), in 1961 by Quick (9) and from 1965 onwards by Anwar (10). The work of Anwar published in 1967 is particular interest in connection with our topic.
The above authors, in connection with the problems of the inlets by hydroelectric installations, were concerned with the general physics of the vortex, the stability criteria and questions of air-inlet. A large number of works treat, moreover, the special outflow conditions from sharp-edged, circular bottom orifices under the influence of an alleged vortex motion. The reports of Kolf and Zielinski of 1957/1959/1968 (12) and of Mecorquodale et al (13), may be compared with the results of inlet studies.

While in inlets, one always speaks of a "vortex problem" or of "undesired vortices", some special constructions utilize certain advantages of vortex motion and work, so to speaks with "desired vortices". The vortex fall shafts and the so-called vortex chambers, which are used in sanitary water installations as control and separating devices, belong to this group. Much fundamental information about vortex mechanics has been obtained from shaft overflows on outlet towers. The works of Binnie (14) and Helmert (15) are of particular importance in this connection.
Figure 15.

1. Spreadover 2- Shaft spreadover.

With the exception of (13), all the studies from (7) to (15) are based upon the same general experimental conditions, i.e. a cylindrical vessel with a central circular outflow orifice. While in (7) to (13) the orifices are directly placed in the bottom of the container, in (14) and (15), spring outlets (figure 15) in the vessel have been studied.

In all these works, the attempt has been to correlate the theory of vortex formation of an ideal liquid with the model experimental results. A brief discussion of this general vortex theory is given in the next chapter before discussing the experiments and giving the particular interesting results. The explanations of "ideal vortex theory" (combined vortex) have been taken from the text books of Schroder (16) and Tietjens (17).

According to the shape of their free surfaces one must distinguish between two types of vortices in the inlets, for which the following relations have been given in the literature cited here (figure 16).

As shown by the terms proposed by Haindl and Anwar, the so-called Rankin's vortex is a preliminary stage of the pure
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potential vortex when it exceeds the circulation forced from outside. Since in the present case, an air-drawing vortex should be basically avoided it is necessary to define a critical development phase (figure 17).

The possibility of a persistent drawing-in of air arises when the tip of the combined vortex reached the position of maximum outflow contraction and a steady pure potential vortex is formed. Before this stable state is attained, an intermittent
drawing-in of air is possible in the vicinity of the inlet if the tip of the vortex is drawn forward. If the maximum possible vortex depth with the chosen minimum spreadover is given and if the sizes of vessel and orifice are known the critical externally circulation or the maximum permissible non-uniformity of flow can be determined. In contrast to the previous chapter, where the required spread-over has been calculated, in this chapter the flow conditions for the present spreadover and chosen installation-dimensions are proved in this section and the critical conditions are determined.


A good concept of the mechanism of the undeveloped or weak vortex, which is of particular interest here, is obtained when the movement is composed of two different types of flow: a surrounding circulation flow with the rules of potential theory and a closed rotation flow, like that formed in a rotating vessels. The process of vortex formation depends upon the externally
applied rotation moment, when a closed ring of water is drawn downward by outlet flow in a narrow circulatory path with a definite rotation speed, so that the speed of rotation is correspondingly increased. In the external potential flow, where the water particles are accelerated only by the variation of pressure forces, the velocity field for circular motion is determined by the well-known relation $v = c/r$. The region of potential flow is called vortex field and is separate from the so-called vortex core where the velocity-distribution corresponds to the laws of rotational flow. It is shown in figure 18, how this combined vortex is defined and how it can be calculated in a simple way.

With the circular ring $2\pi r_1$ the vertical boundary between the two types of motion is marked. It marks the saddle point in the curved shape of water surface. $v_t$ denotes that component of outflow velocity which is tangential to the vortex axis. It is seen in the direction of eccentric inflow and is constant in vertical sections.

The magnitude of circulation caused by the eccentricity is determined by the constant twist value $c$ and is $\Gamma = 2\pi c$. It is particularly important that a closed circulation is actually present and that the surrounding field is determined as primary and the vortex core as secondary.

If the maximum tangential velocity $v_t$ at the point $r_1$
Combined Vortex
Calculation scheme for ideal liquid.

Figure 18: Key = 1- Vortex core; 2- Vortex field;
3- Closed motion; 4- Vortex depth; 5- Simplified velocity
distribution; 6- Actual velocity distribution; 7- Velocity
distribution in a planned perpendicular to vortex axis;
8- Motion $v_t = \frac{C}{r}$ (potential flow); 9- Motion $v_t = \frac{C}{r^2} r_0$.

Equations for water surface

Circulation region $h = \frac{C^2}{2gr^2}$
Rotation region $h = \frac{C^2}{2g} \left(1 - \frac{r_2^2}{r_1^2}\right) \frac{1}{2r_1}$

With $C =$ circulation or twist const: $\Gamma = 2\pi C = 2\pi v_t \cdot r = 2\pi v_{t_1} r_1$
Also $C = r_1 \sqrt{g_0 h^2}$ and $= 2\pi r_1 \sqrt{g_0 h^2}$ (circulation)
is known, the vortex depth comes out to be:

\[ h^* = \frac{v_{t1}^2}{g} \]  \hspace{1cm} (A)

If the depth of vortex \( h^* \) is set equal to the given spreadover depth \( h \) and if a relationship between \( r_1 \) and outflow orifice diameter is experimentally found, then the desired critical circulation constant is calculated out as:

\[ c_{krit.} = r_1 \cdot \sqrt{g \cdot h} \]  \hspace{1cm} (B)

Anwar (10/11) has established in his experiments that the point of maximum tangential velocities \( v_{t1} \) at \( r_1 \) can be placed in good approximation at the edge of the outflow orifice, so:

\[ r_1 = r_o \]  \hspace{1cm} (C)

and

\[ c_{krit.} = r_o \cdot \sqrt{g \cdot h} \]  \hspace{1cm} (D)

with the previously defined quantities of the inlet structure.

Rodund II. one gets:

\[
\begin{array}{ll}
\text{Initial cross section} & \text{Final cross-section} \\
\hline
r_o &= 3.7 \text{ m} \\
h &= 5.65 \text{ m} \\
c_{krit.} &= 27.6 \text{ m}^2/\text{s} \\
v_{t_{max.}} &= 7.45 \text{ m/s} \\
\end{array}
\]  \hspace{1cm} (E)

\[
\begin{array}{ll}
\hline
r'_o &= 2.0 \text{ m} \\
h' &= 21.3 \text{ m} \\
c_{krit.}' &= 28.9 \text{ m}^2/\text{s} \\
v_{t_{max.}'} &= 14.45 \text{ m/s} \\
\end{array}
\]

For \( r_a = 7.4 \text{ m} \) and with \( v_{ta} = v_{t_{max.}} \cdot \frac{r_o}{r_a} \), the required flow velocity outside on the edge of the vessel is
found to be:

\[ v_{ta} = 3.7 \text{ m/s or } v_{ta} = 3.9 \text{ m/s} \quad (A) \]

This value is nearly twice as much as the mean outflow velocity \( v = 2.0 \text{ m/sec} \) prevailing in the defined inlet cross-section with an outflow of \( 86 \text{ m}^3/\text{sec} \), and is again half as much as the mean shaft velocity with \( v = 6.85 \text{ m/sec} \).

The presence of an extreme one-sided inflow, as in figure 4, the mean velocity of flowing water is about \( 4.1 \text{ m/sec} \), assuming a flow-width of \( 3.7 \text{ m} \) and a discharge depth of \( 5.65 \text{ m} \). In this very unfavorable case, therefore, the prerequisites for the formation of a sucking vortex are present. Referring to the actual conditions, the occurrence of such a narrowly confined and eccentric in-flow towards the inlet is generally highly improbable, as the schematic adjustment of the planned sloping inlet structure is very much random under the conditions of cylinder experiments. Such a consideration is exaggerated and produces extreme boundary values.

On pp. 510 and 511 of his text book, Teitjens (17) has described the process of extinction of vortices in the vicinity of a rigid wall as a result of mutually opposite rotations of vortex core and wall boundary layer (figure 19).

All studies regarding measures of vortex-protection showed that the best solution was to turn the outlet orifice as
Figure 19.

Key: 1- Vortex core; 2- Boundary layer.

near as possible on the rear wall of the container. The satisfactory working of this suggestion is explained in figure 19.

3. The combined whirlpool in the viscous liquid. Special result of the investigation by Anwar, 1966.

A direct comparison of actual conditions with the ideal theory has been made possible by Anwar's (10) experimental results. Under the heading "Formation of a Weak Vortex", Anwar in 1966 described the application of his very exhaustive and fundamental vortex studies on the problems in inlets with small spreadover. After a special integration of the Navier-Stokes equation for three-dimensional vortex motion, the experimentally determined effect of viscosity on the definition of a radial Reynolds's number and an integration constant, depending upon it are included in calculation and a simple formula is obtained for the depth of combined eddy:
The maximal tangential velocity is observed in the neighborhood of \( r_0 \) in these experiments. With a given spreadover depth \( h \), one gets as before:

\[
c_{krit} = 1.796 \cdot r_0 \cdot \sqrt{g \cdot h} \quad (A)
\]

i.e.

\[
c_{krit} \text{ (viscous liquid)} \approx 1.8 \cdot c_{krit(ideal liquid)}
\]

Anwar studied vortices with maximum tangential velocities up to 4 m/sec where the vortex depth \( h^* \) in the extreme case was half as much as the given water height \( h \) in the container. Apart from the effect of viscosity, the effect of actual circulation distribution in vortex core, as different from simple assumptions of theory, is included in the comparison number.

4. **Pure Potential Vortex in Ideal Liquid.**

In 1948, Binnie and Hookings (14), using the external principle, proposed the following method for calculating the pure potential vortex on "outlet". As subsequently experimentally verified by Quick (9) the method of calculation can also be applied to the study of strong vortices on "inlets". The only assumption is that the critical cross-section in the treatment with extremal principles is defined at the same point (figure 20).
Assumption for calculation:

a) liquid is ideal
b) radial velocity-components are neglected
c) tangential velocity-components at large distance from inlet are neglected.
d) stability criteria:

For a given twist $c$ the out-flowing amount of water is a maximum.

\begin{align*}
(1) \ h^\prime + \frac{v^2}{2g} + \frac{c^2}{2gr^2} = h \ (\text{Bernoulli equation}) \quad (A) \\
(2) \ h^\prime + \frac{v^2}{2g} + \frac{c^2}{2gr^2} = 0 + \frac{v^2}{2g} + \frac{c^2}{2ga} \quad \Rightarrow \\
- \ h^\prime &= \frac{c^2}{2g} \left( \frac{1}{a^2} - \frac{1}{r^2} \right) \quad (B) \\
\text{in (1)} \quad h &= \frac{v^2}{2g} + \frac{c^2}{2ga^2} \quad (C)
\end{align*}

transformed to:
\[ v = \sqrt{2gh - \frac{c^2}{a^2}} \]  \hspace{1cm} (D)

and

\[ Q = \frac{\pi}{2} \left( r_0^2 - a^2 \right) \sqrt{2gh - \frac{c^2}{a^2}} \]  \hspace{1cm} (E)

**Extremal principle**

\[ \frac{dQ}{da} = 0 \]

gives

\[ a^2 = \frac{c^2 + \sqrt{c^4 + 16r_0^2ghc^2}}{8gh} \]

**Equation for the determination of the radius of free cross-section.**

and

\[ Q = \pi \left( r_0^2 - \frac{c^2 + \sqrt{c^4 + 16r_0^2ghc^2}}{8gh} \right) \]

\[ \sqrt{2gh - \frac{8ghc^2}{c^2 + \sqrt{c^4 + 16r_0^2ghc^2}}} \]  \hspace{1cm} (G)

For \( Q = 86.0 \text{ m}^3/\text{sec}, r_0 = 3.7 \text{ m} \) and \( h = 5.65 \text{ m} \), the evaluation of this equation gives the magnitude of twist constant, viz. \( c = 26.5 \text{ m}^2/\text{sec} \). If the externally given circulation exactly corresponds to this value, a stable potential vortex can form over the inlet which reaches down to the outlet.

In order to present the above equation in dimensionless form, two coefficients are defined, both of which are special forms of Froude's number:
Pure Potential Vortex
Calculation scheme of Binnie / Hookings.

Figure 21.
Key: Assumption ideal liquid; 2- Critical x-section; 3- Radius of air neck in critical x-section.
Outflow coefficient \[ C = \frac{Q}{r_0 \pi \sqrt{2gh}} = \frac{v}{v_{\text{max}}} \quad (A) \]

"Vortex number" \[ X = \frac{v_{t, \text{max}}}{r_0 \sqrt{2gh} v_{\text{max}}} \quad (B) \]

One gets:

\[
C = \left[ 1 - \frac{x^2}{4} \left( 1 + \sqrt{1 + \frac{8}{x^2}} \right) \right] \left[ 1 - \frac{4}{1 + \sqrt{1 + \frac{8}{x^2}}} \right], \quad (C)
\]

This equation is plotted in figure 22.

In the present case: \( C = 0.19 \)

and \( X = 0.68 \)

5. **Pure potential vortex in viscous liquid, results of the studies of Quick, 1962 and Kolf, 1959.**

Quick (9) studied potential vortex in a cylindrical vessel of 53.3 cm diameter with central inlet sections of 0.95 /1, 27/1, 58/2, 22/2.54 cm internal diameter. In order to test the similarity conditions, he carried out his measurements on an exactly 4 times as large a model. In the results, shown in figure 22, he found a relatively good agreement between theory and experiment. At low \( C \) - values the calculated curve lies above and at large \( C \) - values, below the experimental values.
For large vortex numbers \( X \), the equation of Binnie and Hookings gives too small values of outflow coefficient \( C \). In other words, this special experimental result means that at low outflow coefficient, i.e., for \( C \approx 0.3 \), the externally impressed circulation must be large, if stable outflow conditions are to be met. For \( C = 0.19 \) in the present example:

\[
\frac{C_{\text{exper.}}}{C_{\text{theor.}}} \approx 1.2 \quad \text{and so} \quad c_{\text{erf.}} = 32 \text{ m}^2/\text{sec}.
\]

Quick's measurements are confirmed by Kolf's studies (12) which were carried out on cylindrical outlet model representing "vortex orifice flow". Results are shown in figure 23. The experimental points group close to the straight line, which have been represented by Kolf with the equation:

\[
C = 0.686 \cdot (1-X) \quad \text{for} \quad X > 0.25 \quad A
\]

and this gives the experimental relation between outflow coefficient \( C \) and vortex number \( X \).

For comparison purposes this straight line is also drawn in figure 22. The influence of geometry has been included in the study by varying the ratio \( D/d \) (of vessel diameter to outlet orifice diameter). While Quick varied \( D/d \) only from 21 to 56, Kolf varied his geometric boundary conditions from \( D/d_{\text{min}} = 4 \) to \( D/d_{\text{max}} = 50 \). With a dimension analysis Kolf found that, apart from depending upon geometry \( D/d \) and vortex number \( X \), \( C \) also depended upon Reynolds's number. Compared to the effect
of given circulation, however, the effect of geometry and viscosity is negligible. Like Quick, Kolf also found that the graph points for $c > 0.3$ lie above the smoothing straight line. In this region the calculation with this equation undervalues the actual values.

In contrast to the complicated formula of Binnie and
Figure 23. Results of Kolf and Zielinski 1959 and 1968 respectively.

Key: 1- Scalter range in measurements;
2- Measurements of Kolf 1959.

-------

Hookings, the twist value \( c \) can be obtained from Kolf's equation:

\[
C = 0.686 \cdot (1 - x)
\]

\[
x = 1 - 1.458 \cdot c
\]

\[
\frac{r_0}{\sqrt{2gh}} = 1 - 1.458 \cdot \frac{Q}{\frac{r_0^2 \pi \sqrt{2gh}}{0.686 \pi r_0}}
\]

\[
= r_0 \cdot \sqrt{2gh} - \frac{Q}{0.686 \pi r_0}
\]

6. **Results of cylinder Experiments with Reference to Experimental Technique and similarity conditions of Model Experiments, as well as Vortex-protection.**

If the results of cylinder experiments are applied to practical cases, a value of twist coefficient is required, i.e. the numerical description of the externally applied circulation
is needed. In the experiments of Einstein/Li, Haindl, Quick and Anwar, this circulation is variously produced, as the geometrical dimensions of the cylinder and the inlet are very different from each other (table follows).

Hence throughout it is a case of a vessel which is relatively larger than the outlet opening.

For the presentation and investigation of vortex problems in hydraulic models and their application to large-scale use, the above-mentioned authors have given the following similarity conditions:

<table>
<thead>
<tr>
<th></th>
<th>D(_{\text{cylinder}}) (cm)</th>
<th>d(_{\text{inlet}}) (cm)</th>
<th>D/d main experiment</th>
<th>Min. D/d</th>
<th>Max D/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einstein</td>
<td>21.7</td>
<td>1.27</td>
<td>17.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haindl</td>
<td>29.3</td>
<td>2.23/3.12</td>
<td>13.1</td>
<td>9.4</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>(0.7(D_H))</td>
<td>2.23/3.12</td>
<td>13.1</td>
<td>8.2</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>57.3</td>
<td>3.12/4.0/7.0</td>
<td>8.2</td>
<td>8.2</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>(1.4(D_H))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quick</td>
<td>53.3</td>
<td>0.95/1.27/1.58</td>
<td>24.0</td>
<td>21.0</td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>213.2</td>
<td>2.54</td>
<td>21.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4.0(D_H))</td>
<td>8.88(4.0(d_H))</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table contd.
The work of Einstein and Li (7), as regards the similarity questions on the measurements on vortex motions of Hoeffken (19) in 1940 was verified and expanded in 1964 by Holtroff (18). Holtorff found that, while considering the combined vortex, the vortex field \( r = r_0 \) follows the Froude's law of similarity, while the vortex core \( r = r_0 \) depends upon viscosity and requires the involvement of Reynold's similarity law. He defines Froude number for rotation or circulation by

\[
Fr_\text{rot} = \frac{v_t}{\sqrt{g \cdot r}}
\]

and a Reynold number for radial motion by

\[
Re_\text{rad} = \frac{v_{r_0} \cdot r}{\sqrt{g \cdot r}}
\].

According to Einstein and Holtorff the radial component of velocity cannot be neglected. The shape of water surface and the vortex depth, which is of particular interest here, is determined, beside geometry \( r_0 = \text{radius in inlet orifice} \), by the value of these hydraulic coefficients:

\[
\text{for } r > r_0 \quad \text{WSP-shape} = f_0 \left( Fr_\text{rot} \right)
\]

\[
\text{for } r \leq r_0 \quad \text{WSP-shape} = f_0 \left( Fr_\text{rot} \cdot Re_\text{rad} \right)
\]
There is similarity between model and nature when the coefficients are equal in magnitude. As the difficulty of a simultaneous presentation of Froude's and Reynolds' similarities in model experiment can increase, it is not discussed.

Haindl (8) has confined his experiments especially to the question of similarity conditions for the state of transition from undeveloped to developed and air-drawing vortex. In three geometrically similar models, he found that in the presence of an exactly similar circulation, the ratio of critical spread over depth to inlet diameter is the same only when the Reynolds numbers of outflow $Re = \frac{vd}{\nu}$ are equal in all models. Hence Froude's similarity law does not hold for the presentation of critical conditions of drawing-in of air. The amount of air drawn in depends upon the strength of vortex.

When a vessel, in which water is at complete rest is emptied, a stable vortex is formed first with the lowering level. This critical water level, found by Haindl, is considerably higher than the water surface is disturbed from outside and set into motion in some manner, so that a certain circulation impulse can be formed. This observation can, so to speak, be confirmed at home whenever a bath tube is emptied; the stopper is drawn immediately after emerging from the tub and an air-drawing vortex is rapidly formed, while the vortex is formed shortly before the complete emptying, in case of standing water and subsequent emptying. If the outlet hole is directly in
front or in the real wall of the bath tub and not, usual, at a distance in front of it no vortex is formed since the required circulation space is not available.

The geometric dimension ratio between the smallest and the largest model in Haindl's experiment was 1:2.

For his similarity studies Quick (9) chose a ratio of 1:4 between the small and the large cylindrical tank. In contrast to Haindl, Quick found that the natural condition can be analogous represented in model only on the basis of Froude's law. He, of course, studied only the stable pure potential vortex with open air neck, where the radial velocity components can be neglected in comparison with the vertical and tangential ones. As the experiments have shown, this certainly holds only at a certain distance from the free surface of the vortex and slightly above the bottom of the container. Quick established that according to Froude's similarity law only those vortices are exactly described which are formed by the action of a circulation from outside, i.e., e.g., through the asymmetry in the inward flow (figure 24a). If on the contrary vortices are released from the corners or rough walls of the supply channel and reach the vicinity of the inlet and they lead to a transient drawing-in of air, then Reynold's similarity law must also be taken into consideration (figure 24b). The formation and release of such a vortex occurs in direct relationship with the magnitude of Reynold's number of inflow. Quick has subsequently exactly
investigated this for straight parallel channels and the results are given in (6).

For practical cases he has proposed that the model, according to Froude's similarity law, be made as large as possible in order to keep the necessary reduction of Reynolds's number within feasible limits. Under certain conditions a geometrical reduction of inlet cross-section is useful to obtain the same velocities in both large-scale and model experiments for the outlet region, as proposed by Denny and Young (3).

As found in the investigations of horizontal pump inlets (6), in his cylinder experiments (9) Quick too came to the conclusion that a "restriction" of mean inlet velocity to about $\frac{1}{2} \sqrt{\frac{2gh}{\rho}}$ inhibits a vortex formation when flow conditions are unfavorable. The spreadover depth $h$ is established at the point where the critical out flow condition are present.
Hence
\[ h_{erf.} > 2.0 \frac{v^2}{g} \quad A \]

In the present example one gets
\[ v = 2.0 \text{ m/s} \rightarrow h_{erf.} > 0.8 \text{ m} \quad B \]

and
\[ v_{\text{max.}} = 6.85 \text{ m/s} \rightarrow h_{erf.} > 9.6 \text{ m} \quad C \]

In case the reduction of inlet cross-section cannot be

\[ Q_{\text{red.}} = r_{0}^{2} \pi \cdot \frac{1}{2} \cdot \sqrt{2gh} \quad D \]

For the representation of strong vortices with wide open

air neck the Froude's similarity law holds when the geometrical

reduction in the model does not exceed the value 1:20, when

the expansion of the copied outlet region is sufficiently large so

that the entire circulation is encompassed and when the radial

Raynold number is defined by \( \text{Re} = \frac{Q}{\sqrt{gh}} > 10^{3} \). Under these

conditions an open vortex is always formed in the model, but with

a neck narrower than it is in the nature. If \( Q, h \) and \( d \) are

given then the twist value \( c \) in the model experiment must be

measured much above the outlet opening in the circulation flow.
Hence a further dimensionless quantity, the so-called unit circulation. \[ R = \frac{2 \pi c_x R}{Q} \] is formed and compared with the discharge coefficient \[ C = \frac{\sqrt{2g}}{\sqrt{\text{discharge}}} \] in a relevant diagram. When there is an agreement with the corresponding curve of the diagram (Water Power, April 1965), the similarity conditions are fulfilled. For \( C \), which is predetermined with \( Q \cdot h \) and \( D \), the strength \( c \), so to speak, of the open vortex is determined; this is permitted by stable discharge conditions in which a given part of inlet cross-section is taken up by the inlet cross-section of the air-neck of the vortex.

Anwar has attached great significance to the low range of radial flow towards inlet on the vessel bottom for the stability of the process. In case there is considerable roughness then full development of vortex can be prevented. A rough basin bottom can contribute toward vortex-protection.

While the strong vortices are to a certain extent dependent upon the Reynold's similarity law, weak vortices for \( \text{Re} \quad 10^3 \) can also be formed, in Anwar's opinion, according to Froude's law. This statement has been verified in two cylinders of different dimensions with a scale-ratio of 1: 4.5. For the weak vortex with a narrow air neck, a similarity diagram of the same shape has been developed as for the strong and wide vortices (Journal of Hydraulic Research, vol. 4, No. 1, p. R). The radial Reynold number \( \text{Re} = \frac{Q}{\sqrt{gh}} \), used by Anwar, may be transformed
into \( \text{Re} = \frac{v \cdot d}{\sqrt{\frac{\pi}{2}} \cdot \frac{r_o}{h}} \). In contrast to other authors, Anwar has enlarged this characteristic number by the ratio \( \frac{r_o}{h} \) and has established that the existence of a combined vortex of the three above-mentioned dimensionless quantities \( \frac{Q}{2\pi c \cdot r_o^2} \), \( \frac{Q}{\sqrt{h}} \) and \( \frac{r_o}{h} \) is determined.

The geometrical coefficients under consideration lie in the range \( 0.01 \leq \frac{r_o}{h} \leq 0.08 \). Hence this is a case of very stretched vortex. A given unit circulation \( R = \frac{2\pi c}{Q} \) is of the form of a Froude number and is similar to the vortex number \( x = \frac{c}{r_o \sqrt{2gh}} \) used by Binnie and Hockin (14), when one substitutes \( Q = c \cdot \frac{2\pi c}{r_o \sqrt{2gh}} \) and \( r/r_o = n \):

\[
R = \frac{2}{c} \cdot \frac{c}{r_o \sqrt{2gh}} \cdot n
\]

In the studies of Kolf and Zielinski (12) on the "vortex orifice flow" and the effect of viscosity on a dynamically similar vortex formation in models, it was found that for \( \text{Re} = \frac{v \cdot d}{\sqrt{\frac{\pi}{2}}} > 10^4 \), the vortex number \( x \), i.e., a Froude number alone determines the discharge conditions. Below these limits the discharge coefficient \( c \) for a given \( x \) is also dependent upon the Reynolds number. In contrast to Anwar, Kolf also observed low vortex depths (\( \frac{r_o}{h} > 0.1 \)) in far thin vessels (\( D/d_{\text{min}} = 4.0 \)).

McCorquodale (13) in 1968 performed a cylinder experiment of special type. His aim was an accurate determination of possible dimensional effects in the study of "vortex orifice flow". The work was stimulated by the very different statements on similarity conditions in vortex studies, made particularly by Denny and Young.
Haindl, Quick as well as Kolf and Zielinsky. The experimental setup, which is very different from cylinder experiments, is shown in figure 25. Three geometrically similar models with \( d = 5.1 \text{ cm/10}, 2 \text{ cm} \) and \( 15.3 \text{ cm} \) were used. The ratio of vessels diameter to outflow opening, therefore amounts \( D/d = 10 \).

\[ \text{Figure 25.} \]

McCorquodale found that both the large models gave nearly the same results, while the results of the small model showed considerable deviations, general and localized. Dimension effects were checked and it was finally proposed to use outflow openings of diameters greater than 5 cm in such vortex studies.

An evaluation of experimental results regarding the dependence of outflow coefficient \( c \) on the given vortex number \( x \) for two large models gave the curve shown in figure 26, comparison with the formulae of Binnie and Kolf, as well as the measurements Quick and Kolf confirmed the theory, when the relatively side scattering of all experimental values is considered to be an indication of an average condition of flow process under very different boundary conditions. Since the simple empirical formula
Figure 26.

Key = 1- Out-flow coefficient; 2- Pure vortex - Comparison of theory with experiment; 3 - Theoretical equation Binnie/Hookings and Quick; 4- Empirical equation of Kolf/Zielinski; 5- \( X = 0.538 \) for \( h - 3.45 \cdot \frac{C^2}{2gr_0} \)

(Anwar); 6- Range of scatter of the results of; 7- Lowest region; 8- Result of McCorquodale; 9- Range studied; 10- Vortex number.

Theoretical equation of Binnie and Hookings, this relation shall be used below for testing the special conditions on the inlet to Roudundwerke II. For \( c = 0 \), therefore, exact radial flow towards

---

(55)

PURE VORTEX
inlet with sharp edges the maximum discharge coefficient
$c = 0.686$ according to Kolf is physically more significant
than $c = 1.0$ according to Binnie. If the $c \cdot x$ results of
the experiments of Quick in his large model ($d = 8.9$ cm) and
of Kolf with $d > 7.6$ cm are compared with the results of
McCorquodale $d > 10.2$ cm, a very good agreement is found.
McCorquodale's proposal to use outlet openings of $d > 5$ or
better still $d > 7.5$ in model experiments is thereby strengthened.

7. Testing of Critical Flow Conditions for the
Schematically Deformed inlet Rodund II with
the Results of Cylinder Experiments.

In order to calculate the velocity of eccentrically
flowing water required to form a stable air-drawing potential
vortex, we shall use the simple empirical formula of Kolf and
Zielinski:

$$c = 0.686 \cdot (1-x) \quad (A)$$

With this equation one gets an approximately linear
dependence of outflow coefficient $c$ upon the vortex number $x$:

$$\frac{Q}{r_0^2 \sqrt{2gh}} = 0.686 \cdot \left( 1 - \frac{c}{r_0 \sqrt{2gh}} \right) \quad (B)$$

from this relation one obtains the vortex depth $h^* = h$:

$$h^* = \frac{1}{2g} \cdot \left( 1 + \frac{458}{r_0^2} \frac{Q}{h} + \frac{c}{r_0} \right)^2$$
\[ v = \frac{Q}{r_o^2 \cdot \pi} \quad \text{and} \quad v_{\text{t max}} = \frac{\zeta}{r_o} \quad (C) \]

\[ h^* = \frac{1}{2g} \left( 1.458 \cdot v + v_{\text{t max}} \right)^2 \quad (A) \]

For a further externally situated circle of the surrounding circulation current of radius \( r_a \) the following hold:

\[ v_{\text{t max}} \cdot r_o = v_{\text{t a}} \cdot r_a \]
\[ \frac{r_a}{r_o} \cdot v_{\text{t max}} = \frac{r_a}{r_o} \cdot v_{\text{t a}} \quad (B) \]
\[ v_{\text{t max}} = n \cdot v_{\text{t a}} \]

The geometrical ratio number \( n \), therefore describes the spatial expansion of the externally excited circulation. Hence the equation for vortex depth is:

\[ h^* = \frac{1}{2g} \cdot \left( 1.458 \cdot \frac{Q}{r_o^2} + n \cdot v_{\text{t a}} \right)^2 \quad (C) \]
\[ h^* = f \cdot (v_{\text{t a}}, Q, 1/r_o, n) \quad (D) \]

The vortex depth depends upon the twist, the amount of water extracted, the chosen inlet cross-section and the container-size, i.e. on the area of reservoir basin in which a closed circulation (\( \Gamma = 2 \pi c \)) about the inlet is possible.
\[ v_t = \frac{1}{n} \left( \sqrt{2gh} - 1.458 \cdot v \right) \]

With \( n = 2 \) corresponding to figure 4, \( h = 5.65 \text{ m} \) and \( v = 2.0 \text{ m/sec} \) the above relation gives the following for schematically deformed inlet (figure 3).

\[ v_t = 4.3 \text{ m/s} \quad (A) \]

and

\[ \frac{v_t^2}{2g} = 0.94 \text{ m} \quad (B) \]

Since in the start of reservoir basin, the energy line can be assumed at the height of the prevalent water level, the eccentric flow with \( v_t = 4.3 \text{ m/sec} \) required for vortex formation means an about 1m drop of water level in front of the inlet, which is quite unexpected.

If instead of the chosen wide inlet cross-section with \( r_0 = 3.7 \text{ m} \) and \( v = 2.0 \text{ m/sec} \), the outlet opening is formed of narrow tunnel opening with \( r^* = 2.0 \text{ m} \) and \( v^* = 6.85 \text{ m/sec} \), one gets for \( r_a = 7.4 \text{ m} \) and \( n = 3.7 \):

\[ v_t = 0.15 \text{ m/s} \quad (C) \]

i.e. a value which is quite probable.

In his "Vortices at Low Head Intakes" (11), Anwar has given approximate formula for the determination of the depth of a weak vortex with narrow open neck which can suck air:
\[ h = 3.45 \frac{v_{t \text{max}}^2}{2g} \text{ at point } r_0. \]

Hence the vortex depth depends upon the pronounced twist only. The equation holds only when the circulation in the container surroundings is closed and constant, i.e., a uniform circulation energy is steadily supplied to the outflow process when stable conditions should be produced.

In contrast to the data of depth of a combined vortex ("dimple \[10\]), the above formula gave considerably larger vortex. Anwar produced "shallow or deep dimple" in his cylinder experiment in the following way: A constant amount of water is supplied in the tangential direction at the edge of container and is taken the center of the vessel through a connecting pipe. A regulating value is joined to the end of the tube. After constant in- and outflows are obtained without vortex, the value is slightly turned for a short time. The tangential velocity component in the inlet is thus reduced; a flat vortex is formed (figure 27). If the valve is now opened again, the open vortex bores through the entire water body up to the inlet opening and suction of air becomes possible (figure 27).

With twist constants \( c \), the formula becomes:

\[ h^* = 3.45 \frac{c^2}{2gr_o^2} \quad (A) \]

and is transformed into:

\[ \sqrt{\frac{1}{3.45}} = \frac{c}{r_o \sqrt{2gh}} = X \quad (B) \]
Figure 27. Combined vortex at inlet.
Comparison of theory with experiments.

Key: 1- Viscous liquid; 2- Sought: \( r_1 = f (r_0) \)

Hence a constant vortex number \( x = 0.538 \) is obtained when the results of Anwar are correlated to the data of Binnie, Quick and Kolf. The Kolf's equation \( C = 0.686 (1 - x) \) gives, for \( x = 0.538 \), outflow coefficient \( C = 0.317 \), hence:

\[
C = \frac{v}{\sqrt{2gh}} = \frac{Q}{r_0^2 \pi n \sqrt{2gh}} = 0.317 \quad \text{(C)}
\]

and

\[
r_{\text{krit.}} = \sqrt{\frac{Q}{0.317 \pi \sqrt{2gh}}} \quad \text{(D)}
\]

or \( h_{\text{krit.}} = 9.95 \cdot \frac{v^2}{2g} \sim 10 \cdot \frac{v^2}{2g} \sim 5 \cdot \frac{v^2}{g} \)

for \( Q = 86 \text{ m}^3/\text{sec} \) and \( h = 5.65 \text{ m} \), \( r_{\text{krit.}} = 2.87 \text{ m} < r_{\text{vorh.}} \); with \( v = 2.0 \text{ m/sec} \) for \( r_0 = 3.7 \text{ m} \), \( h_{\text{krit.}} = 2.04 \text{ m} < h_{\text{vorh.}} \).
Comparing this result with calculated value of the required spreadover according to Gordon (5) for symmetric supply and keeping in view the data of inlet under consideration, one gets:

\[ h_{\text{krit. (Gordon)}} \sim \frac{v^2}{g} \quad (F) \]

Hence as before it can be established as an end result of this chapter about the data of cylinder experiment that at the inlet installation of Rodund-werke II, an air-drawing vortex is not expected during the drop of basin water level on the given falling column at the level 97.0 with \( Q = 86 \text{ m}^3/\text{sec} \).

E. Studies on Air-drawing Vortex in Inlet to Pumps.

In the testing of similarity conditions for the representation of air-drawing vortices on pumps in hydraulic models, Iversen (20), Fraser (21) and later Hattersley (22) found that the Froude's similarity law holds to a limited extent and a better agreement of experimental results with natural conditions with large flow velocities in the model can be obtained.

\[ v_{\text{Model}} > \frac{v_{\text{Nature}}}{\sqrt{\lambda}} \quad ( \text{according to Froude}) \]

\( \lambda \) denotes the chosen geometrical scale-ratio.

The reason for this suggestion is that when Froude's similarity law is used, the velocity distributions in supply channel and in the pump sump are not the same. As Denny and Young (3) already said, Berge (23), on the basis of his experiments in chatou also stipulated that a similar representation of air-sucking
is only possible when the inlet velocity in the model is the same as in large-scale installation. The applied circulation, i.e. the vortex field, can be simulated according to Froude's similarity law.

The model design of Berge is shown in figure 28.

Depending upon $Q$ and $h$, he determined the magnitude of circulation $\Gamma$, required to produce a stable vortex in the chosen pump chamber and he marked the critical depth of water at which the air begins to be drawn in. The experiments were unfortunately carried out in a very small model ($d = 5$ cm) so that the results cannot be directly applied in a quantitative sense.

Iversen (20) carried out experiments on the effect of geometrical shape of pump sump on the critical spreadover depth in symmetric supply-orifice. His results on the effect of a reduction of wall-separation are plotted in figure 30. The most important result obtained was that a transfer of the outlet opening directly on the rear chamber wall completely inhibits vortex formation. The value $h_{krit} = 4/4$ has been given as the required
Figure 29. Effect of symmetric and asymmetric supply conditions on the critical spreadover depth.

spreadover depth. It was further recommended that in order to protect against vortex formation, sharp edges or pillars in the supply channel, i.e. irregularities in the velocity distribution of in-flow, should be avoided.

The results of similar experiments as those of Berge and Iversen, obtained from the report of Wijdieks (24) have been shown in figure 29. The comparison of critical spreadover depths under symmetric and extremely asymmetric supply conditions deserves notice. Compared to the outlet pipe diameter \(d = 10\text{ cm}\) the pump chamber in this case is generally very large \((D/d = 24)\).

F. Summary.

Measured for protection against air-drawing vortices and similarity conditions for relevant model studies, supplements.
Iversen's studies on the effect of wall distances on critical spreadover depth.

**Figure 30.**
Key: 1. Outline; 2- Axis of symmetry; 3- Strong vortex;
4- Weak vortex; 5- Section; 6- Independent of \( \frac{x}{d} \);
7- Weak; 8 Strong; 9- Vortex.
1. **The most important measures for protection against air-drawing vortices.**

As shown repeatedly in the previous chapters, one must distinguish between primary and secondary measures. The primary protective measures are the choice of more useful dimensions in the design of new installations while the secondary measures involve error-free constructions, which are subsequently modified.

In the design of inlet structures, which should achieve an air-free outlet of water for water-power machines from reservoir basins with least possible spreadover depth the following basic points should be noted:

1. The basin geometry, particularly the linearity of lateral boundaries and the position of inlet relative to flow from the basin must be so planned that in the region of outlet, no circulation flow can occur ($\nabla^2 = 2 \nabla \cdot c = 0$). In case a certain eccentricity between inlet and outlet is unavoidable due to the local conditions, it should be as small as possible.

II. When a circulation in the supply to the outlet has to be reckoned with, and air-suction through the vortex is to be avoided, **three main rules** should be kept in view in the construction of inlet structures:

a) It should be fundamentally noted that the planned sinking column does not exceed the critical
spreadover depth, for the water level in the reservoir basin.

b) For the designed water quantity $Q (m^3/sec)$ and a given flow twist $C (m^2/sec)$ this critical depth is inversely proportional to the inlet cross-section $r_0 (m)$: with sufficiently large inlet cross section and a correspondingly reduced inlet velocity, the critical spreadover can be kept small.

c) An equally important construction factor is the position of inlet relative to the basin: With respect to the outlet position an attempt must be made for a position directly at or in the rear wall. Since the critical spreadover depth is directly proportional to the wall separation, a greater drop in the water level can be permitted with a wall-inlet. As regards the outlet direction of a wall-inlet, a sloping position of the outward pipe is to be prepared to a horizontal or vertical pipe. In a sloping inlet, the spreadover depth rapidly increases with respect to the pipe edge as compared to horizontal outlet and undergoes an acceleration of flow, due to decrease in cross section behind the inlet, which favorably affects the outflow process. As the vortex axis is always perpendicular to the water surface, the possible circulation space and hence the vortex strength is reduced, in contrast
to vertical outlet, when the inlet is placed in a sloping position in the rear wall.

The following basic corrections are possible in the modification of inlet structures in which air-sucking vortex disturbs the operation of water-power units:

I. The circulation flow is excluded or so much reduced with the help of auxiliary constructions that the desired sinking limit can be attained with the designed amount of water. The nature and working of auxiliary constructions must be adjusted to the special conditions which are prevailing; and this can be achieved in most cases by hydraulic model experiments. The various constructional possibilities shall be discussed in due course.

II. In case such auxiliary measures are unusable or lead to partial improvement, either the planned level drop limit must be given and placed higher or more suitable outlet conditions must be ensured by a reduction of total water capacity in the critical range. In practical case, therefore, the search for suitable auxiliary constructions is reversed according to the most useful operational conditions. The hydraulic model experiment can also give the most reliable answer if there is sufficient similarity between large scale operation and model.
2. **Practicable similarity conditions for model experiment on vortex problem.**

From the large number of partly divergent data about similarity conditions in the model-technical representation of inlet vortices in the relevant literature the following method, considered as best-suited and practicable is proposed:

I. **Flow-through.** Circulation flow and vortex field are treated with Froude's similarity law. Hence the chosen scale ratio should not possibly exceed the value $\lambda = 20$. The modelled basin region must fully contain the causes of circulation formation water capacities are shown with $\lambda^{5/2}$ and flow rates $\lambda^{1/2}$.

II. **Discharge, vortex cores and air entraining** are simulated against Froude's value as in nature by increasing the inlet velocity. The inlet cross-section has another geometrical scale. If it is desired to have equally large inlet velocities in extreme representation in model as in the nature, $\lambda_{\text{Einlauf}}^{5/4} = \lambda^{5/4} \text{Becken}$ (inlet) (basin). The reduction of cross-section must, however, be limited to two conditions: The diameter of reduced inlet must be at least 7.5 cm so that scale effects are excluded, and the increase in discharge coefficients should not exceed the value $C \sim 2/3$.

With this combined representation procedure, acceptable similarity conditions for model experiments on vortex problems might be attained in agreement with fundamental experimental
studies on the present theme; thus the special questions about critical discharge conditions, which determine air-entraining, can be answered correctly.

3. Complete observation for prevention of strong current in the pipeline behind the entering (inlet).

For an optimum utilization of water-power installations, it is important not only to preclude operational disturbances due to an air-sucking strong vortex but also to suppress or reduce a twist flow in the pipe between inlet and machine which is caused by a weakened vortex. This twist flow can attain quite undesired proportions since the externally applied twist is in fact damped against air-suction by protective measures, but the rest remains in the pipe. According to the data of machine construction, angle of rotation of over 10° are to be avoided.

Analogous to the relief measures against air-suction, the permitted outlet conditions must be checked in this case and sharpened as much as possible. With suitable auxiliary constructions like slightly crossed guiding walls, the twisting flow is directed straight behind the inlet.

4. Supplementary remarks on time-progress of take-off process.

As shown in the description of Anwar's experiments, an air-suction can suddenly occur by rapid variation of the amount of water taken out in the presence of a weak undeveloped vortex, if the twist energy is locally increased. This transient air-suction can, above all, occur in temporary throttlings of the
take-out just as they are quite possible in preparation of tip energy. Hence greater variations in take-out should be avoided.

5. Supplementary remarks on excitation of vortex from outside.

In his emptying experiments, Haindl has shown that a disturbance and motion of water surface in the basin can be the only reason for a vortex formation. As Nelson and Johnson have observed, an unfavorable blowing wind can also produce an air-sucking vortex. If this is possible then it must be kept in view when selecting the reservoir site. The installation of a floating grid over the inlet is an auxiliary measure which can be incorporated later.

Finally it may be remarked that the effect of the rotation of earth on vortex formation is insignificant.
G. Investigations on Demonstration Model of the Obernach Research Institute.

1. Description of the experimental stand, model operation and similarity conditions.

The demonstration model could be easily and rapidly assembled on a set-up, which was being used for other experiments. The present installation consists of a 3.0 x 1.4 m base plate with 40 cm high plexiglass walls. The plate is at a very desirable observation height of 60 cm above the hall floor. An accurately measured amount of water can be poured into the experimental basin at its front side by means of two nozzles.

The experimental stand and the model are shown in figure 31. The photos 1 and 2 show a top view of the entire model with and without water.

In the front portion of the basin with the installed equipment one-sided inflow in rear portion is produced. The nature of asymmetric supply to the schematic model of inlet structure corresponds to the experiments of McCorquodale (figure 25), Berge (figure 28) and Wijdieks (figure 29). As the results of Wijdieks have clearly shown, a one-sided supply with exactly half the basin-width determines the unfavorable outlet conditions. The spread-over depth required to avoid an air-sucking overtop attains a maximum value here.
Figure 31.

Key: 1- Regulating Valve; 2- Outlet (measurement conduit); 3- Valve; 4- Outlet; 5- Hall floor; 6- Inlet.

In the rear part of the basin, a section of the direct inlet region is built as shown in a very simple schematic form (figure 32).

The schematic representation should reproduce the following important construction characteristics of the planned inlet constructions position at the rounded rear basin wall including the capturing edge jutting out of the planned slope with relatively long horizontal podium on the level 977.0, sloping direction of out flow and relatively large inlet cross-section in horizontal
Figure 32. Schematic diagram of inlet model.

Key = 1- Sinking; 2- Horizontal inlet plane; 3- Sloping inlet.

direction with the assumption of a single basin bottom at level 971.0 and a narrowing of cross-section in the direction of flow.

In the horizontal and sloping inlet plane (figure 32) buttresses could be built which had smaller outlet openings. At the end of the schematic outlet pipe a regulating valve was installed with which any chosen water level could be adjusted in the basin (figure 31).

In the experiment, the desired model water capacity was regulated with valves in inlet and the measuring channel in the outlet, and then a given amount of water was introduced into the reservoir. After this state had become stabilized after a long time the observations on vortex formation were taken.
In order to obtain most extensive possible circulation flow with the given basin water, which is rather small as compared to the dimensions of the inlet structure, a geometrical scale-ratio of $\lambda_B = 30$ was chosen. This ensured that this unsuitable value was sufficient for the demonstration of basic processes.

With $\lambda_B^{5/2} = 4925$ the amount of water in the model according to Froude's similarity law, was found to be $Q_M = 17.45 \text{ l/sec}$ for $Q_N = 86 \text{ m}^3/\text{sec}$. The one-sided supply ($B_M = 0.7$, $B_N = 21 \text{ m}$) and the externally impressed twist were formed with this quantity in all experiments. The minimum spreadover depth in the large scale operation for the given inlet cross-section of $h = 5.65 \text{ m}$ was $18.85 \text{ cm}$ in the model ($M = 1:30$). The desired dimensions of the inlet structure of figure 32 was reduced to the desired scale.

The following method is proposed for demonstration of air-sucking vortex:

For the given inlet cross-section with $v_N = v_M = 2.0 \text{ m/sec}$ and $\lambda_E = \lambda_B^{5/4}$, the extreme similarity condition gives with $\lambda_B = 30$ the required reduction of cross-section with $\lambda_E = 70.2$ of $d_N = 7.4 \text{ m}$ to $d_M = 10.5 \text{ cm}$. Comparatively, a reduction of the shaft diameter of $d_N = 4.0$ with $E = 30$ gives $d_M = 13.3 \text{ cm}$. The reduction of the diameter in the inlet cross-section for $v_{N_E} = 1.0 v_{N_E}$ on a scale controlled by Froude's similarity for bottom outflow seems unrealistic. Hence it was decided to reduce the inlet only so much that $v_{N_E} = v_{N_{St}} / \sqrt{\lambda_B} = 1.25 \text{ m/sec} = 0.625 \cdot v_{N_E}$ when the maximum shaft velocity is replaced.
by \( v_{N_{St}} = 685 \text{ m/sec} \). The reduction scale is therefore:

\[
\lambda_E = \frac{d_{N_E}}{d_{N_{St}}} \quad \text{and} \quad \lambda_B = 55.5
\]

For \( v_{N_E} = 2.0 \text{ m/sec} \), Froude's reduction with \( \lambda_B = 30 \) gave an inlet velocity of 0.365 m/sec. in the model. The extreme inlet velocity chosen is thus about \( 3\frac{1}{2} \) times greater.

2. **General and Special Results of Demonstration Experiments.**

Three series of experiments were performed. The important results are shown in the photographs 3 to 19.

In the experimental series A (photos 3 to 8), the schematic inflow for the given minimum spreadover depth was tested (\( h_M \approx 20 \text{ cm} \)). In the three different forms of inlets, no penetrating air-sucking vortex could be established. In the form \( a = d/2 \), \( d = \frac{7.4}{30} = 24.7 \text{ cm} \) (photo 7) with \( h < 20 \) flat combined vortices appeared time and again from the tips of which single air bubbles were released and transported away in the inlet. The chosen form corresponds to the schematically deformed sloping inlet in a perpendicular outlet with a surrounding circulation grove of \( a/d = 0.5 \) minimum corresponding to figure 3 and 4 with an illustration in the model according to Froude's similarity law for \( \lambda_B = \lambda_E = 30 \).

In the experimental series B (photos 9 to 14) the chosen geometric reduction of the inlet and the associated nature-like
Photos 1 and 2

Overall view of the demonstration model without and with water, classical suction vortex for \(d = 13.3\) cm and \(a = 2.7\) d.

representation of a possible air-suction, were studied.

Simultaneously with the testing of the critical take-off conditions, the favorable effect of one the important structural vortex protection measures were demonstrated and surveyed; this is the decrease in the distance between inlet and basin-wall. 3 shapes were constructed with \(a = 2.7\) d; \(a = 1.35\) d and \(a = 0\) for \(d = 13.3\) cm, where \(a\) denotes the distance from the edge of inlet orifice upto the front wall of the basin. The results

\[
\frac{h_{krit}}{d} = f \left( \frac{a}{d} \right)
\]

are plotted in figure 33.

While at the maximum wall distance of \(a/d = 2.7\), a stable penetrating vortex with air-suction was found at a water depth of \(h_m = 36\) cm, half as large a value of \(a/d\) gave a reduction of critical depth to \(h = 18\) cm. No stable vortex
Experimental series A: Testing of schematic inlet structure

for $h_{\text{min}}$.

No penetrating vortex in all the three shapes.

* Same outlet center as in photo 11.

could be observed when the inlet was directly on the wall ($a = 0$).

Temporary weak vortex with the intermittent air suction was

formed at $h_m \leq 18$ cm. Comparison of photo 7 with photo 11.
Experimental series B: Determination of \( \frac{h_{krit}}{d} = f \left( \frac{a}{d} \right) \)

for \( d = 13.3 \text{ cm} \).

\[ \text{Photos 9 - 14.} \]

* Same outlet center as in photo 7.*

where different inlet cross-sections were studied with the same take-out center, the favorable effect of the reduction of inlet velocity on vortex protection is shown.
Experimental series B: Determination of $h_{krit} = f_c \left( \frac{a}{d} \right)$ for $d = 13.3$ cm.

Photos 9 - 14.

Same outlet center as in photo 7.

where different inlet cross-sections were studied with the same take-out center, the favorable effect of the reduction of inlet velocity on vortex protection is shown.
Figure 33. Demonstration model, results of experimental series B.

Key: 1. \(a\) = distance from edge of orifice to front rear wall; 2- No air-entraining penetrating vortex; 3- Unsteady small vortex with air-entraining; 4- Single air bubbles; 5- Steady large vortex with air-entraining; 6- Single vortex; 7- Standing vortex.

Assuming that the chosen similarity - mechanical assumptions give applicable conditions, the critical spreadover depth with \(h_{krit} \approx 1.4\) \(d\) may be read off from the diagram obtained for \(a/d = 0.5\), i.e. for the schematic inlet of figures 3 and 4, when the transient air-suction is also to be avoided.
Hence

\[ h_{k_{r i t}M} = 1.4 \times 13.3 = 18.7 \text{ cm} \]

and

\[ h_{k_{r i t}N} = 18.7 \times 30 = 560 \text{ m} \sim h_{v o r h}. \]

This particular result of the demonstration model confirms that the presence of an extremely one-sided inflow to the inlet the given spreadover depth shall be sufficient to prevent air-suction.

Finally in the experimental series C (photos 15 to 19) it was optically demonstrated with the inlet shape of photo 9 how the vortex strength increases when the spreadover depth decreases. In the slightly diffuse photograph of the air neck, taken through plexiglass walls of the container (photos 17 and 19) the spiral movement of the outflowing water may be seen; one can also see a slight inclination of vortex axis towards the rear wall of the basin, which here at depths \( h > 20 \text{ cm} \), is a result of the circulation flow occurring on the capturing edge of the inlet at the back of the basin.

3. **Comparison with Other Experiments.**

If Berge's experimental set-up (figure 28 in (23) is taken as a model of Obernach experimental setup and assuming a general Froudian similarity for the geometry of inlet orifices
Experimental series: C. Demonstration vortex strength

\[ x = f \left( \frac{1}{h} \right) \]

Photos 15-19.

Vortex strength increases downwards.

\[ \lambda = \frac{13.3}{5.0} = 2.67, \] the corresponding water capacity is found to be 1.5 l/sec. (figure 34), then the critical spreadover depth of \( h_{krit} = 21.5 \) cm can be read off from Berge's diagram.
Figure 34.

Key: 1- Froude Similarity;
2- Berge model "pump sump";
3- Demonstration mode "Inlet structure".

(La Houille Blanche 1966, No. 1, p. 25). Relative wall distance is a $\frac{y}{d} = 2.5$ in Berge's model. For this value the Obernach model gives $h_{krit} = 35.3$ cm. With respect to the inlet diameter here, one gets:

Demonstration model: $h_{krit} \frac{y}{d} = 2.65$

Berge $h_{krit} \frac{y}{d} = 4.3$

Difference between the two results can be explained as follows: A complete geometrical similarity of the two models would require that the width of the supply channel in Obernach model should be $B = 40$ cm instead of $B = 70$ cm (figure 34).
Referring to this width ratio, Berge's experiments are based upon a relatively large velocity inflow to the vortex chamber. Since according to Anwar (II) the square of maximum tangential velocity at the inlet is directly proportional to the vortex depth and $v_t$ is determined by hydraulic and geometric conditions of the eccentric supply the greater critical depth of Berge is explained. Added to this is observation of McCorquodale (13) that in his smaller model ($d = 5.1$ cm) considerably stronger vortices are formed than in the larger ones ($d = 10.2$ and 15.3 cm), and, hence, a certain scale effect has to be allowed for in the application of Berge's experimental results. As regards the data of the demonstration model the model comparison means that with an increase in the supply conduit the critical spreadover depth can be reduced; this is provided for in the large-scale reservoir by a line guide of the side-walls.
"Suction vortex" means a vortex at the inlets to water power installations which suck in air towards the machine (pump or turbine). The most frequent cause of a vortex formation is non-uniform flow of the inlet. With a supply orifice, eccentric to inlet axis, the out flow is in the shape of a spiral motion during water off-take. When the pressure drop in the liquid in the center of spiral flow attains the magnitude of the water depth over the inlet, air may be sucked in or more accurately drawn-in through the tunnel-shaped depression in the water-level.

According to Gordon (5), "vortex problems" first arise in water power units when the air-suction is the result of a suitably strong vortex flow. Denny and Young (3) and particularly Hattersley (22), on the contrary found that the excitation of a twist flow in the pipe due to a weak circulation over the inlet exerts considerable effect on disturbance-free operation of axial water power machines. In pumps either there are efficiency losses or over-rotation of machine depending upon the direction of twist.

Greater evil is the air-suction which has to be prevented if reductions in efficiency, stoppage periods and damages to the installation are to be avoided.

The primary negative effect of vortices of any type at the water power machine inlets is the reduction of off-take water when other off-take conditions like inlet cross-section reservoir
water level and twist flows in the connecting pipes, remain unchanged. Strong vortices intensify the unfavorable hydraulic conditions and with the possibility of air-suction, give rise to further damages due to secondary pneumatic effects like partial or total interruption of water flow due to enclosed and mostly compressed air bubbles. The result if oscillation simplification, corrosion and cavitation damages on machines and in the pipe system.

According to Denny and Young (3), an air component of just 1% in the supply line to a centrifugal pump reduces the efficiency to 15%.

For the largest European pumping turbine in Rodund-werke II of Vorarlberg Illwerke, efficiency losses and operation disturbances are not expected even when the planned sinking in reservoir Latschau II is started with the given extension in water capacity, since the present study has shown that the air-drawing vortex can be formed as a result of suitable size and construction of inlet construction only when supply flow conditions are exceptionally extreme and also improbable. The question of the Auftraggeber given at the very start of this report is thus answered in affirmative.
Pump-Storage works Rodund II.
Ground plan for Basin II and connection to basin I:
Key: 1- Sinking limit; 2- Bottom; 3- Inlet structure Rodund II; 4- Bottom;
5- Ground drainage; 6- Inlet structure; 7- Bottom; 8- Basin I;
9- Top of intermediate dam 989.00; 10- Leading channel.
Pump reservoir works Rodund II. Main dimensions of inlet structure. Upper Basin.
1- Schematic transformation of sloping inlet into perpendicular one; 2- Sinking limit; 3- Defined inlet cross-section; 4- End of inlet structure; 5- Section A...A; 6- Elevation.
According to Gordon for unsteady flow

\[ s_{krit_{sym}} = \frac{3}{4} s_{krit_{unsym}} \]
VORTICES AT INTAKES OF HYDRAULIC POWERPLANTS
(Wirbel en Einlaufen zu Wasserkraftanlagen)

Translated from German

Prepared for Bureau of Reclamation, U.S. Department of the Interior and National Science Foundation, Washington, D.C. by Mrs. Geti Saad

1974