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Hydraulic Model Investigation of Świna Strait

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Abstract

The paper concerns hydraulic model investigation of the area of the Świna Strait as a whole and part of it conducted in the laboratory of the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) over the past fifty years. The Świna Strait is part of the Odra Estuary, located on the southern coast of the Baltic Sea. The inlet structure (I Brama Torowa) located at the entrance from Szczecin Bay to the Piastowski Canal is a very important part of the waterway between the Pomeranian Gulf and the Szczecin Bay. In connection with modernising work, a detailed study of the Świna Strait and region of the inlet structure was carried out on hydraulic models.

The paper presents basic information on physical models. Some examples of the solution of engineering problems in the Świna Strait, on the basis of the results from model tests performed in IBW PAN, are described. A description of the models, the way of performing the experiments, investigated variants and results obtained are presented.

1. Introduction

At the end of the XIXth and beginning of the XXth century, hydraulic modelling developed rapidly as an important engineering tool for the solution of hydraulic engineering problems. Today, the use of hydraulic models in the solution of such problems is no so frequent, due to the high cost of such model, and the possibility of solving them by means of numerical models. There are, however, many problems that require the use of hydraulic models together with mathematical models and field measurements. Hydraulics is a part of experimental fluid mechanics, in which problems of hydraulic engineering practice are investigated. The results of the laboratory investigations make it possible to verify and supplement the theories and mathematical models, which are developed simultaneously. A well equipped hydraulic laboratory enables such investigations to be carried out, thanks to which it is possible to study complicated physical processes and solve some engineering problems.

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Hydraulic models, in general, are small-scale reproductions of nature in the laboratory. In such cases similarity between nature and the model must be achieved (Kobus 1980). This implies geometrical, kinematic and dynamic similarity. Geometrical similarity of a model is achieved, if all geometrical lengths L_n in nature represent a constant ratio to the corresponding lengths L_m in the model. This ratio is called length scale L_r of the model ($L_r = L_n/L_m$). Kinematic similarity requires that in a geometrically similar model time-dependent events always proceed in such a manner that corresponding time intervals in nature and the model show a constant ratio – time scale $t_r = t_n/t_m$. Dynamic similarity demands that corresponding forces in both nature and the model must also show a constant ratio – force scale $F_r = F_n/F_m$. This implies that the corresponding ratios among the various forces must be the same in the model as in nature. All similarity laws of fluid mechanics and characteristic numbers can be derived from this requirement. The conventional characteristic numbers in fluid mechanics are: *Eu* – Euler number, *Re* – Reynolds number and *Fr* – Froude number. They define ratios of the various types of acting forces.

Generally dynamic similarity demands that according to the acting forces, all characteristic numbers must simultaneously have the same values in both model and nature. The primary task in determining similarity requirements is the identification of the predominant forces influencing the flow processes. The flows under the dominant influence of gravity inertia e.g. free surface flows, require geometrical similarity and equality of Froude number in model and nature. In models for open channel flows, the influence of viscosity and boundary roughness is also of importance. Especially in the construction of a vertically distorted model, some basic assumptions must be considered and certain requirements maintained. In such kinds of flows the Reynolds number in the model must always remain large enough to ensure turbulent flow conditions in the model, when the flow in nature is turbulent.

For flows influenced by gravity, equality of the Froude number *Fr* in the model and nature is required. The Froude model law is:

$$Fr_r = \frac{v_r}{(g_r L_r)^{1/2}} = 1, \tag{1}$$

where:

- v_r – velocity scale,
- g_r – gravity scale ($g_r = 1$),
- L_r – length scale.

With this relationship and geometrical similarity ($L_r = L_n/L_m$) it is possible to obtain scales for areas ($A_r = L_r^2$), velocities $\left(v_r = L_r^{1/2}\right)$, times $\left(t_r = L_r^{1/2}\right)$ and discharges $\left(Q_r = L_r^{5/2}\right)$ for a model without distortion.

2. The Świna Strait

The Świna Strait (Fig. 1) is one of the parts of the Odra Estuary located on the southern coast of the Baltic Sea. In the Świna Strait depending on the differences of water levels between the Pomeranian Gulf and Szczecin Bay, as well as wind velocity and direction, and density differences between the sea and fresh water, there may exist various flow conditions: outflow, inflow or two-directional flow. Because of the important role of this region, it has long been intensively exploited and changed by man. From the beginning of the XVIIIth century a great deal of work was carried out to obtain the navigable waterway through the Świna Strait. At the end of 1875 the decision was taken to construct the artificial Piastowski Canal and in the 90's the Mieliński Canal. The waterway was built along the Świna Strait, across Szczecin Bay and leads to Szczecin Harbour. The width of the waterway is 250 m, the depths changed due to erosion and sediment deposits and also as the result of dredging work. At the end of the XXth century the depths in the navigation canal along the Świna Strait exceeded 12.5 m and in some places even 15.0 m. Across Szczecin Bay they are around 10.5 m.

In the XXth century a whole series of modernisation work aiming at creating of the waterway along the Świna Strait was conducted. A whole system of structures was created to reduce the discharges in the Świna Strait in order to decrease high water velocities disadvantageous for navigation, sediment movement and bathymetric changes. One of the elements of the system, which consisted in the narrowing of the last part of the Piastowski Canal, is the inlet structure (I Brama Torowa – Fig. 1). The exploitation of the waterway e.g. deepening of the canals to suit navigational requirements, caused many problems, such as stability of constructions, canal bed and water exchange between the sea and Szczecin Bay. The solution of some of these problems required the usage of a hydraulic model to define precisely specific hydraulic solutions and their influence on local hydrodynamic conditions.

3. Hydraulic Models of the Świna Strait and its Parts

3.1. Introduction

In 1958 (Lipko et al. 1959) and in 1999 (Jasińska, Majewski 1999) hydraulic model studies of this area were carried out in the IBW PAN. The aim of the study in both cases was to find solutions for improving flow conditions in the area. In the seventies, due to the planned modernisation of the Świnoujście–Szczecin waterway in the inland part which runs along the Świna Strait, it was decided to test the proposed solutions on hydraulic models (Jasińska, Piórewicz 1975). All these models were operated in accordance with the Froude model law. The three models were constructed in different scales, with or without vertical scale distortion and with fixed or movable beds.

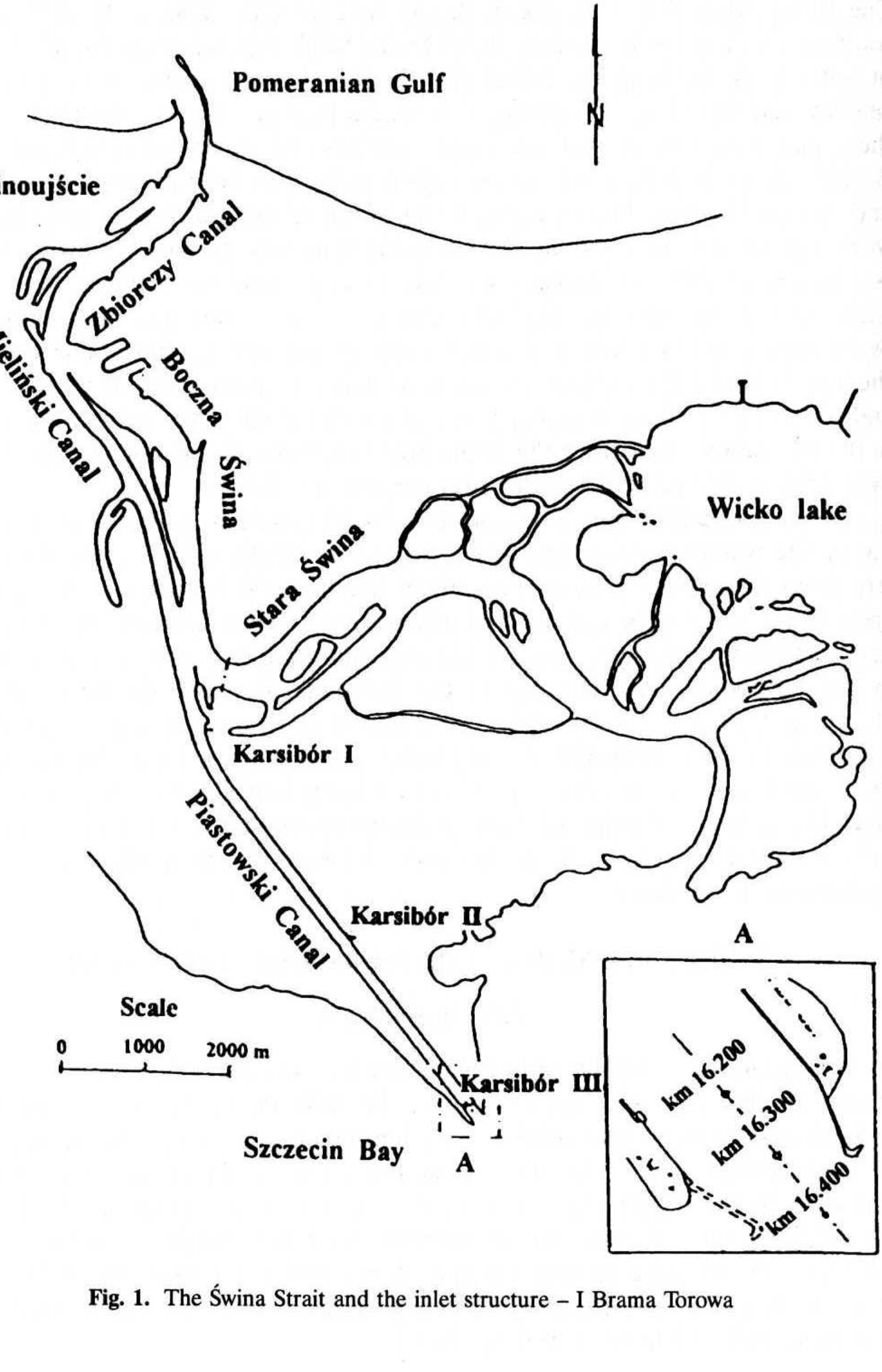

Fig. 1. The Świna Strait and the inlet structure – I Brama Torowa

3.2. The "first – 1958" Model of the Inlet Structure – I Brama Torowa

In 1958, at the request of the Maritime Office in Szczecin, the IBW PAN carried out a hydraulic model study of the region of I Brama Torowa (Fig. 1). In accordance with the design, in the area of the I Brama Torowa, a relatively large narrowing as compared with the width of the Piastowski Canal, was made and the bottom strengthened with concrete blocks. After several decades in operation, it turned out that thanks to the reinforcement of the bottom in I Brama Torowa bed erosion was small, whereas just upstream and downstream were huge erosions with depths exceeding 20 m.

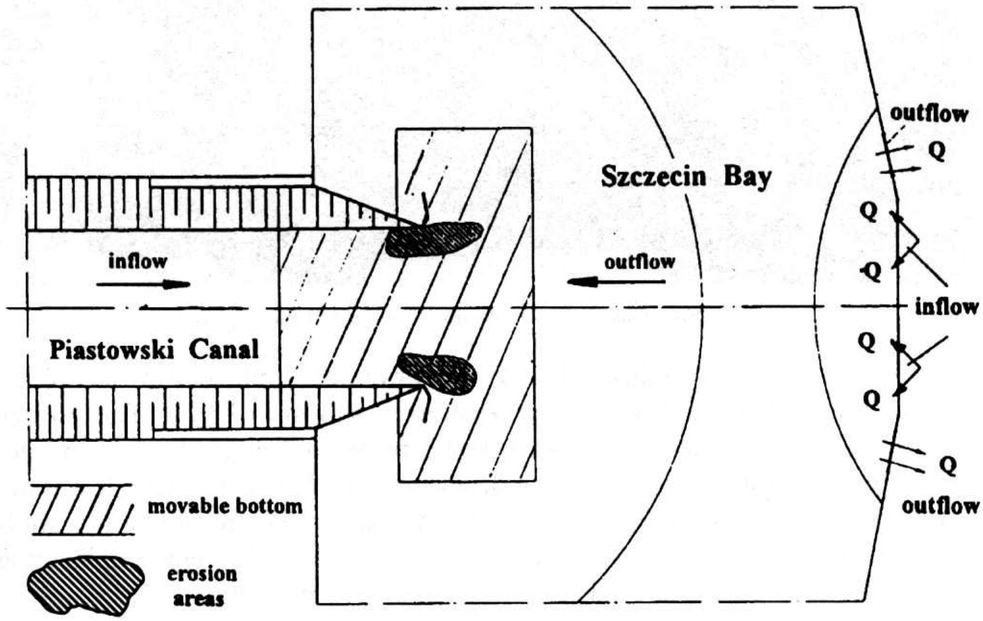

Fig. 2. The "first" model of the I Brama Torowa

The "first" model of I Brama Torowa (Lipko at al. 1959) was built in geometrical scale 1 : 75 (Fig. 2) without vertical scale distortion. For the assumed geometrical scale and Froude similarity law the velocity scale v_r and time scale t_r were 8.65 and discharge scale was Q_r = 48 600. The Reynolds number *Re* on the model was greater than 2000, so the flow on the model was turbulent. Part of the model had a movable bottom made of coal particles with a diameter of ϕ = 2–3 mm. The flows in the model, according to nature, were simulated in two directions. There were simulated inflow and outflow conditions. The maximum discharge reproduced on the model was 3000 m^3/s.

After verification of the model, different solutions for the I Brama Torowa were tested and their influence on the flow conditions, stability of the proposed

Fig. 3. Erosion around the breakwaters of the I Brama Torowa

bottom protections and stability of breakwaters were determined. An example of the erosion around the end of the breakwaters is shown in Fig. 3. The bottom deformations obtained from the model should be treated as qualitative and not quantitative. This way, it was possible to decide which solution was best. It was not possible to determine real values of the bottom changes. The results of this study constituted the basis of the project and were developed by the Hydroengineering Design Office in Szczecin and subsequently realised in prototype.

3.3. The Model of the Świna Strait

In 1969 in connection with modernisation of the Świnoujście–Szczecin waterway it was decided to carry out a study of this region. The program of experiments took into account field measurements, measurements on the hydraulic model and calculations using mathematical models. The aim of the hydraulic modelling was to determine the best solution from the hydraulic point of view and to predict flow conditions after realisation of the structures. The studies were carried out on the hydraulic model (Fig. 4) under steady flow conditions and for the extreme discharge, having in mind the existing state and proposed modernisation variants.

This was a very difficult and complicated model in view of the extensive area, to be taken into account and the varying flow conditions. The relatively large area and small depths required a vertically distorted model. In the construction

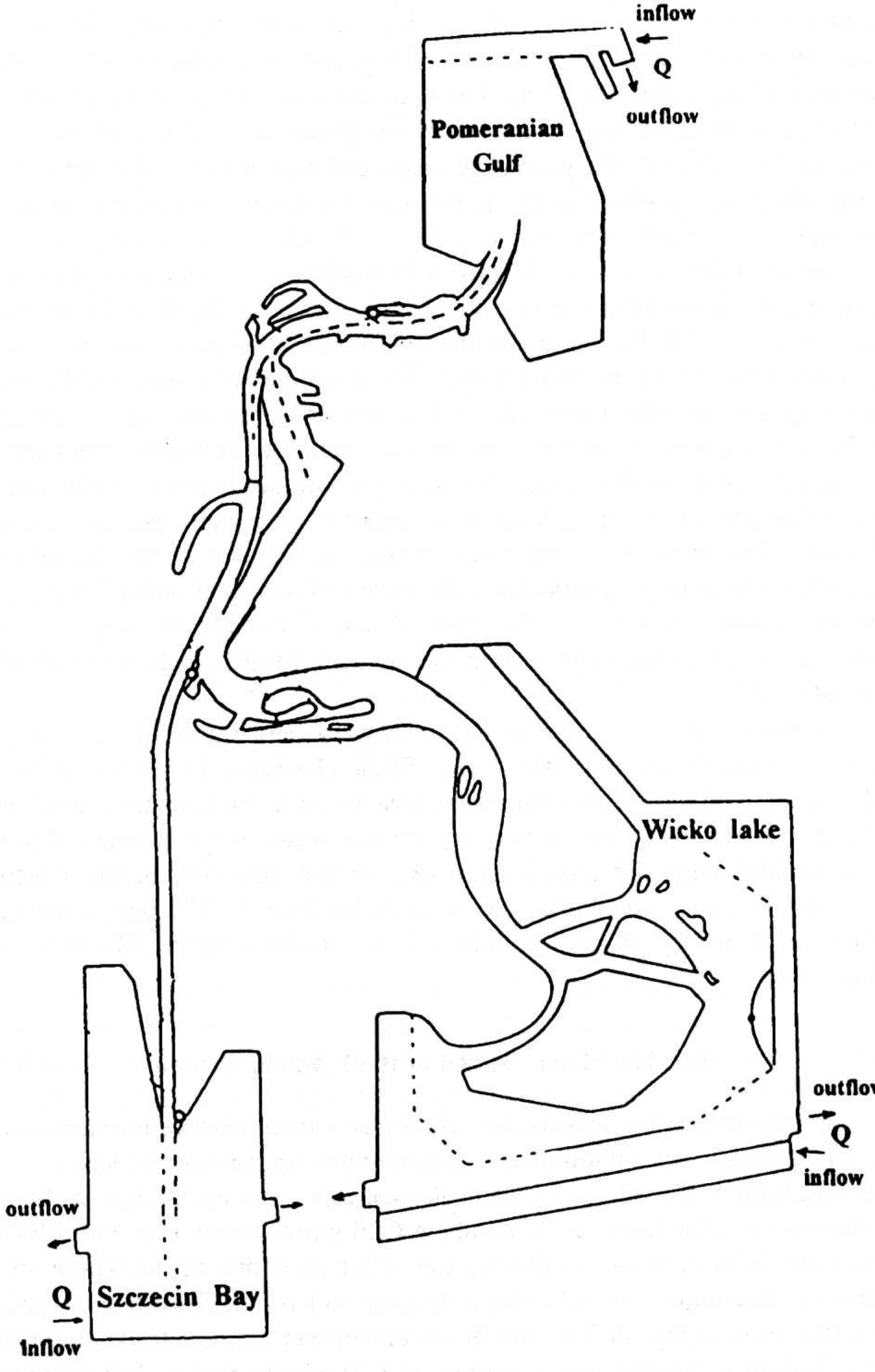

Fig. 4. Model of the whole Świna Strait

of a vertically distorted model certain requirements must be maintained. The distortion factor n describes the relation between horizontal and vertical scales. As the upper limit of the distortion $n \approx 5$ was assumed, basing upon laboratory experience (Press, Schröder 1966). The scale numbers for distorted models must take into account distortion n and all other requirements (Kobus 1980).

Taking into account the geometric characteristics of the Świna Strait region and the laboratory possibilities the model was constructed on the distorted scale; horizontal scale 1 : 250 and vertical scale 1 : 50. The scales and distortion were in the range of the limit in such kind of hydraulic model and afforded the possibility of correct modelling of flow conditions (Jasińska, Rynkowska 1972). The model was made with fixed bed and the differences in density between fresh and salty water were not taken into account. The distortion of model needed special roughness elements, which were adjusted by trial and error procedure. The model was about 100 m long, 50 m wide and the maximum depth was 0.40 m. Construction and operation of this unusually large part of the estuary model required considerable knowledge in such areas as construction, electronics and operation techniques. The main operational and measuring features of the model of the Świna Strait consisted, in particular, of constructed inlet and outlet structure that allowed to simulate flow in two directions. A series of electronic gauges for registering water level changes and current meters for measuring velocity distributions were installed.

After the calibration of the model, tests were performed for nine proposed variants of modernisation of the Świna Strait (Jasińska, Piórewicz 1975). The results of the model tests gave the characteristics of hydrodynamic conditions for all the proposed variants and in this way the best solution was selected. Optimum flow conditions were obtained for the case of the extension of the Piastowski Canal with simultaneous closing the Stara Świna branch. The best solution was taken into account by the design office and was realised by the Maritime Office in Szczecin.

3.4. The "Last" Model of the I Brama Torowa

The currently designed modernisation of the Świnoujście–Szczecin waterway takes into consideration the requirements of contemporary navigation, safety of constructions, bottom stability and such ecological aspects as estimation of the range of saltwater intrusion from the Pomeranian Gulf into Szczecin Bay. The IBW PAN defined the hydrodynamic conditions and water exchange in the whole area by means of mathematical models. The area close to I Brama Torowa was tested on a hydraulic model (Fig. 5). The aim of the model research was to define precisely specific hydraulic development solutions of I Brama Torowa and their influence on the local hydrodynamics and movement of sediment.

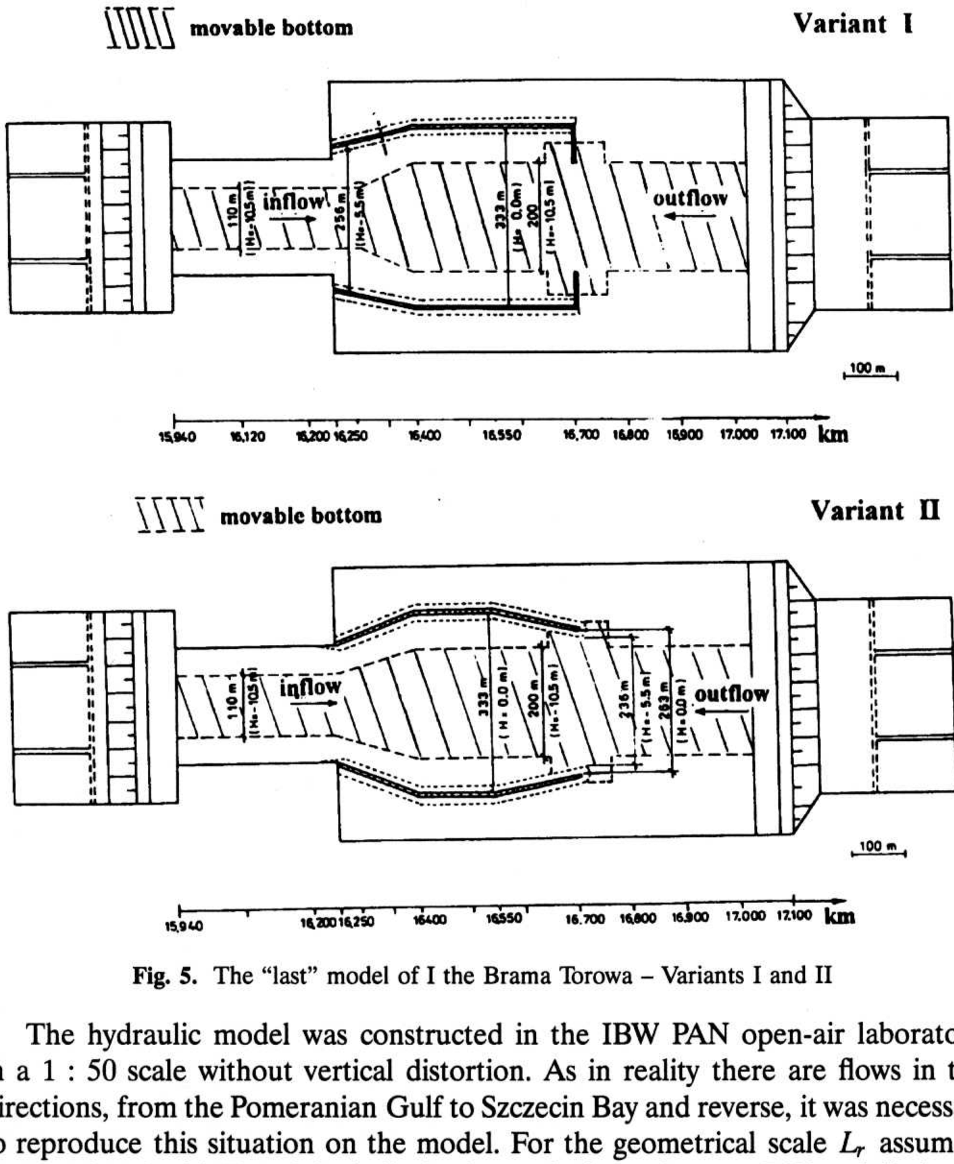

Fig. 5. The "last" model of I the Brama Torowa – Variants I and II

The hydraulic model was constructed in the IBW PAN open-air laboratory, in a 1 : 50 scale without vertical distortion. As in reality there are flows in two directions, from the Pomeranian Gulf to Szczecin Bay and reverse, it was necessary to reproduce this situation on the model. For the geometrical scale L_r assumed, in accordance with Froude's similarity law, velocity scale $v_r = 7.07$ and discharge scale $Q_r = 17\ 678$. The flows that were reproduced on the model changed in range from 113 l/s to 240 l/s to correlate with 2000 m^3/s to 4250 m^3/s in nature. The Reynolds number *Re* for such flows was greater than 2000, thus the flow on the model was turbulent.

The model reproduced a section of the waterway measuring 1.0 km (in nature) comprising part of the Piastowski Canal, I Brama Torowa and adjacent to it, part of Szczecin Bay (Fig. 5 and 6). On the first stage of research, which reproduced the current state of this area, a model with a fixed bottom was created. Research

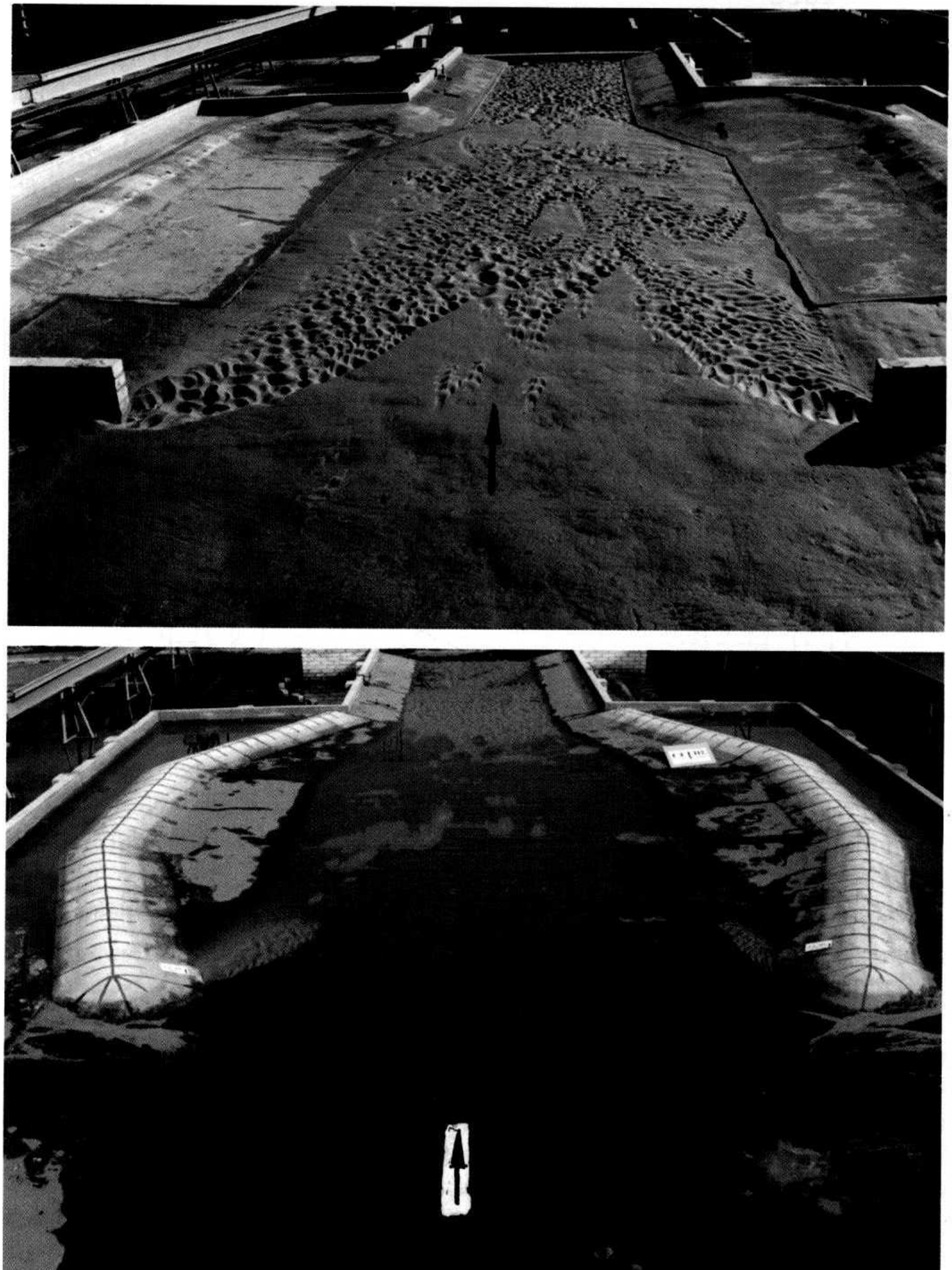

Fig. 6. The bottom changes in Variants I and II

on the proposed solutions was carried out on the model with a movable bottom. The selection of suitable sediment for the model was a serious problem (Jasińska, Majewski 1999). Taking into consideration velocities created by the minimal flow, fine-grained sea sand from the beach, of $d_{50} = 0.23$ mm was used. This sand moved at velocities created by minimal flow. According to the limitations for hydraulic models with movable bottom, the results obtained from the model should be treated as qualitative not quantitative. But thanks to these and their analyses it was possible to decide that one solution is better than the other (Fig. 6). It is impossible however, to define the real values of the bottom erosion.

On the first stage, the model reproduced the existing bottom in the area of I Brama Torowa. The distributions of velocities obtained from measurements were compared with the data from field measurements. Comparison of data showed good similarity. The model with the movable bottom was used to compare various proposed solutions of arrangement of the breakwaters of I Brama Torowa. Two variants of the arrangements were examined in detail on the model, taking into account different flow conditions. Variant I proves that when flows $Q > 2600$ m^3/s (150 l/s on model) there is intensive erosion in many places in the region of I Brama Torowa, especially around the breakwaters. Variant II assures much better hydraulic conditions in the examined area. This conclusion arises from the measurements of the velocity distributions and local bottom erosion.

4. Conclusion

To solve numerous hydraulic engineering problems is it possible to use physical hydraulic laboratory scale models. They are mainly used for various hydraulic structures and free surface flows. Their advantage is the possibility of seeing immediately, both flow characteristics and the effect of any changes in boundary conditions on the flow.

Field studies are indispensable in research. Knowledge of the natural system is the basis for the study of the human activities on the behaviour of this system. Nature, however, is always changing and does not provide the opportunity to study the effect of a variation in a single boundary condition at a time. Laboratory experiments allow for detailed measurements and a perfect control of relevant conditions.

Hydraulic modelling belongs to the application of experimental fluid mechanics, in which hydraulic problems of engineering practice are investigated. There are many problems that need to use hydraulic models together with theoretical analysis, mathematical modelling and field measurements. Such an example constituted the problems of the Świna Strait modernisation. Some problems concerning the modernisation of the Świna Strait needed to use hydraulic models to define specific hydraulic development conditions precisely. The results obtained from hydraulic models over fifty years and their analysis, help to decide which proposed solution was the better. In all cases the results of modelling testing help the designer in his works.

Today, the use of hydraulic models in the solving of engineering problems is not as popular as few years ago, especially in view of the high cost and time necessary for building the model and performing the measurements. In addition, the hydraulic models of new problems require modern measurement techniques and more sophisticated considerations of hydraulic similitude.

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