DEVELOPMENT OF A FLOOD PROTECTION SYSTEM BY THE USE OF MODEL TESTS

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Abstract: The Szentgotthard Flood Protection Project is located in the southeastern part of Austria, very close to the Hungarian border and to the Hungarian town of Szentgotthard situated near the junction of the rivers Lafnitz and Raab. During heavy rainstorms, this area has always been liable to severe floodings, affecting the town itself and upstream reaches, where major industrial and commercial development is planned.

In order to solve these problems, several solutions have been developed by means of a series of model tests performed at the hydraulic laboratory of the Technical University of Graz, Austria. The model was constructed to scales 1:75 (lengths) and 1:25 (heights). This trebled scale allowed greater accuracy in the measurement of discharge depths. The results from the model tests have led to the following proposals:

- Construction of a flood relief trough with an inflow section 3.5 km upstream of the junction of the rivers Lafnitz and Raab.
- Use of a former river bed for the flood relief trough.
- Design of a lowered embankment crest section to pass one-third of the maximum flood flow of the river Lafnitz.
- Connection of the flood relief trough to the Lahnbach stream, a tributary of the river Raab.

Key Words:

1. INTRODUCTION

The changes that have taken place in Europe in recent years have led countries to move closer together, bringing new chances and development potentials for regions and river basins. Austria's situation at the southeastern end of the European Union, of which it is a member, and at the doorstep, as it were, towards potential future member states, calls for efforts towards fruitful cooperation across historical borders in order both to create new areas of commercial development and to preserve the necessary habitats.

The river Lafnitz flows in flat country in south-eastern Austria and over a short reach forms the border between Austria and Hungary. Some 500 m downstream of the border, in the Hungarian town of Szentgotthard, the Lafnitz flows into the river Raab. In the confluence area, extreme floods constitute a major risk to property. Certain flood situations in those two rivers lead to inundations threatening residential areas, in particular the town of Szentgottgard in Hungary, as well as the Neuheiligenkreuz polder and the newly created industrial zone including a large-scale water treatment plant on Austrian territory.

Dealing with these problems is the responsibility of the Austro-Hungarian Waters Commission. As past flood protection measures have become insufficient for the requirements of the newly created areas of industrial development, the flood risk is now being met by the construction of a relief trough conveying part of the incoming flood flow in a new channel to the left of the main river system, by-passing the affected areas. Apart from its protective function, this measure also helps to preserve the aquatic environment itself as a habitat by retaining existing bank structures and wetland areas and by creating new ecological areas.

2. PLANNED CATALOGUE OF MEASURES

2.1 Flood Protection Measures on the River Lafnitz

Since a decision taken in 1968 by the Austro-Hungarian Waters Commission the Lafnitz-Raab river basin has been the subject of flood defence project planning and structural measures. At first flood defences structures were provided within the town of Szentgotthard and floodbanks were constructed for the protection of the Neuheiligenkreuz polder area. Then followed protection measures on the Lafnitz for the fixation of the Austro-Hungarian border along the centreline of the natural riverbed. Then the construction of flood defences was continued on the river Raab. Now the design studies for the confluence area of the rivers Lafnitz and Raab have been completed. The optimal solution for this area as has resulted from feasibility studies combined with scale model tests is the Szentgotthard Flood Protection Project providing for a relief trough in the Lahnbach stream valley described in the following. The complex flood situation - in particular the interaction between runoff from the flood plain and river flow - has called for scale model tests to be performed for the detailed design. The tests have been carried out at the Hydrological Laboratory of the Department of Hydraulic Structures and Water Resources Management of the Technical University of Graz.

2.2 Hydrological Studies

The flows used in the design as are follows:

Based on an agreement between the Austrian and Hungarian authorities, the design flow has been taken to be 700 m³/s for the total flow of the river Lafnitz upstream of Szentgotthart at a 1 in 100 year flood event. In order

Table 1. Flood flows and return periods for the river Lafnitz at the gauge upstream of Szentgotthard

River	Cross section	Catchment [km²]	MQ [m³/s]	HQ_5 [m³/s]	HQ_{10} [m³/s]	HQ_{30} [m³/s]	HQ_{50} [m³/s]	HQ_{100} [m³/s]
Lafitz	Eltendorf gauge	1956.3	14.5	380	431	536	600	693

to answer the flood protection requirements of the town of Szentgotthard, the total flow has been divided up into a maximum discharge of 460 m^3/s for the river Lafnitz at its entry into Hungary and 240 m^3/s for the planned flood relief trough along the Lahnbach valley. Downstream of Szentgotthard, the relief trough will join the original river basin. As past flood records allow the assumption that a discharge of 140 m^3/s passes into the Lahnbach valley by itself, an overflow will have to be provided to make the balance of 100 m^3/s leave the bed of the river Lafnitz.

2.3 Project Measures

The Szentgotthard Flood Protection Project comprises several components:

- Provision of a flood relief trough including a lowered embankment crest section (controlling inflow to the relief trough) extending from the left-hand flood plain of the Lafnitz from River Kilometre 3.0, along the Lahnbach valley and to the crossing with the road between Rabafüzes and Szentgotthard on Hungarian territory. The length of the inflow section is 556 m, that of the flood relief trough is 2,077 m.
- Continuation of the flood relief trough to join the Lahnbach valley as part of a project planned by Hungarian agencies. On Hungarian territory, the flood relief trough is about 2,000 m long.
- Crossing Provincial Road 116 in Austria as well as the road between Rabafüzes and Szengotthard on Hungarian territory by means of new bridges, including ramps, to be built across the flood relief trough.
- Closing the gap between the raised areas of the water treatment plant and the closure embankment of the Neuheiligenkreuz polder on the left-hand bank of the river Lafnitz downstream of the bridge of Provincial Road 116 to form a continuous dyke system

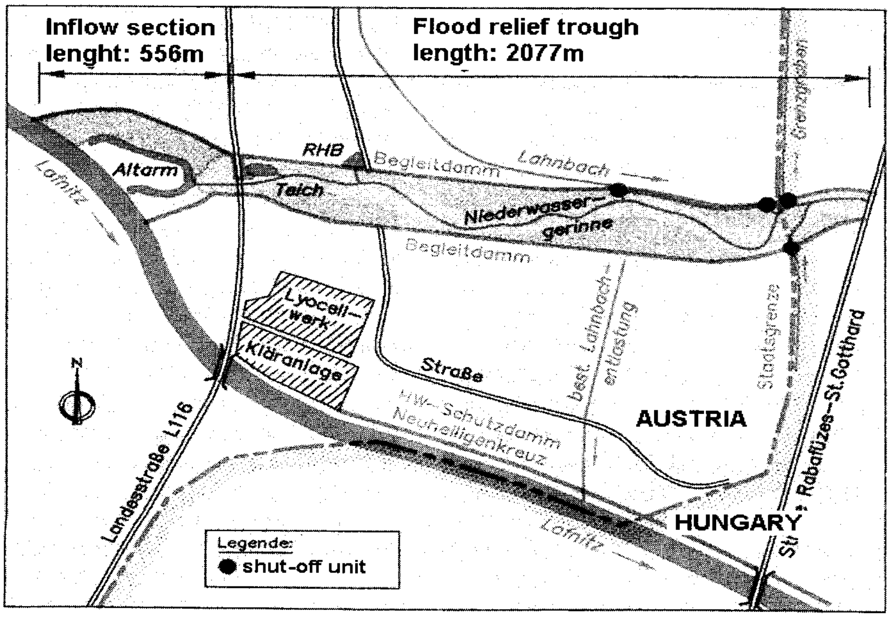

Fig. 1. Location plan of project area

enclosing a total area of 160 hectares.

- Abstraction of a certain minimum flow to feed the dead stream branch system in the left-hand flood plain of the Lafnitz to maintain a low-water discharge in the flood relief trough.

2.4 Flood Relief Trough and Inflow Section

When studying the details of the design, we realised that we had to focus our attention on the 556-m long overflow towards the flood relief trough to ensure the good functioning of the project. The hydraulic conditions are extremely complex in this area, and mathematical treatment of the spatial flow conditions by means of simple flow programs is bound to be inaccurate and calls for many diverse assumptions and estimates. Therefore, the one- dimensional calculations carried out by the project engineer were checked by a scale model test to allow accurate determination of the flow conditions in the approach area.

The flood relief trough begins with an inlet sill upstream of Provincial Road L 116 and ends where the Rabafüzes - Szentgotthard road is crossed. The trough is 2,077 m long. The shallow water table in this area does not allow of any major lowering of the ground surface. The bottom slope is 1.0 ‰ over its upper reach and 2.5 to 3.1 ‰ in its lower reach. The selected cross section is wide and shallow for the above reasons. The hydraulic analysis has given a normal width of 190 m and a water depth of 1.50 m. A continuous low-water channel in the bottom will ensure permanent flow in the flood relief trough. Water is fed to the low-water channel from an existing oxbow lake, which will be provided with an intake structure with ground sill. The approach area comprises the whole stream bed and flood plain of the Lafnitz upstream of the crossing with Road L 116 down to approximately River Kilometre 3.5. The shallow and extensive inundation of the flood plain during floods, interactions with the stream bed, the irregular bank configuration, the apparent presence of secondary flows in places, etc. result in complex flow conditions within the area under consideration, which has been reproduced on the model.

Initial calculations have shown that a flow of 240 m^3/s as needed for the flood relief scheme prepared by the engineer is not available within the approach area above the trough. The flow proportion expected to occur in the left-hand flood plain during a 1 in 100 year flood is estimated at about 140 m^3/s. So it is necessary to take further structural measures to feed the trough. The right-hand flood plain of the River Lafnitz has been neglected as rising terrain next to the riverbed forms a natural barrier to inundations.

In order to improve the flow conditions within the approach to the trough, the terrain will be excavated over a length of 560 m and an average width of 50 m, with the ground level being lowered by a maximum 1.50 m between the left bank of the Lafnitz and the inlet sill above the flood relief trough. The discharge section produced by the excavation will integrate the oxbow. At the height of River Kilometre 2.45, the terrain of the left flood plain will be raised over a length of 325 m so as to make the top approximately correspond to the level reached by the 1 in 100-year flood. This ensures that runoff from the flood plain is separated from the inlet sill of the relief trough.

The hydraulic system governing flow towards the relief trough consists of two components, the bridge of Road L 116 with a clear width dimensioned to produce the desired upstream impoundage (practically designed as a flow reducing element) and a 140 m long inlet sill as another flow controlling cross section. A quarry-stone ground sill will also serve to retain minor floods in the area of the Lafnitz flood plain. Flood discharge to the relief trough is intended to begin as late as possible during a rising flood wave. A ditch provided upstream of the inlet sill is intended to divert sediment loaded flows to the oxbow during rising flood waves.

2.5 Accompanying Ecological Measures

Among the requirements to be met by the project is the adequate protection and preservation of the habitats along the river and, consequently, the ecological functioning of the river and its banks. The existing bank configurations have to be preserved to the greatest possible extent and wetland areas along the margins of the river have to remain untouched to maintain existing biotope systems.

This requirement has been met by designing the flood relief trough and the required engineering structures so as to merge with the surrounding landscape and by integrating the existing dead river branches. Actually, the hydraulic requirements of the project will call for the removal of some parts of the existing vegetation. But it is considered one of the principal purposes of the project to preserve existing vegetation as far as possible and to create a pond of appropriate dimensions, within the retention basin or between the Lahnbach stream and the path on the crest of the dyke, to provide a new habitat in exchange for areas lost to the project.

The oxbow will remain and in addition receive water discharge to improve the overall ecological situation and to allow water to be fed to the low water channel. Thus, the relief trough will assume the character of a natural stream basin with large reed and wetland zones.

3. HYDRAULIC SCALE MODEL TEST

3.1 Construction of the Model

The modelled part of the flood relief trough covered the hydraulically relevant approach area. The principal components were the intake, the ground sill and the new culvert under the road (63 m in span). So we had to reproduce the river over a length of 1,340 m and the left-hand flood plain to a width of about 500 m (corresponding to model dimensions of 18 m by 12 m). The length and height scales selected for the model test were:

$$\lambda_{HOR} = L_{REAL\text{-}LIFE} / L_{MODEL} = 1/75 \quad and$$
$$\lambda_{VER} = H_{REAL\text{-}LIFE} / H_{MODEL} = 1/25 \qquad (1)$$

By trebling the height scale in relation to the length scale, we increased the discharge depths in relation to the lengths so as to improve measuring accuracy. The relationship between the dimensions of real-life conditions and model was based on Froude's law of similitude, that is to say, the Froude numbers - that is, the relationship between inertia and gravity - of the model had to correspond to those of the prototype.

Particular attention had to be given to the reproduction of the substantial variations in vegetation in the project area by providing greatly differing roughnesses (Manning-

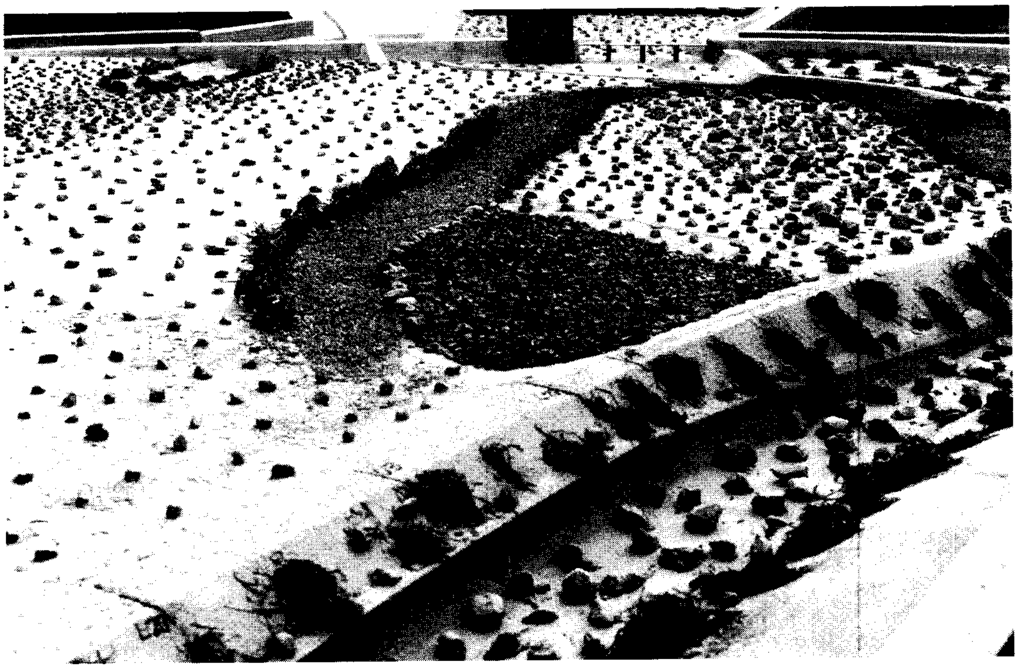

Fig. 2. The "extreme roughness" case for the modelled area

Strickler values: $5 < k_S < 35$). As a matter of principle we had to assume two very different roughness cases as extremes, which we reproduced using materials which experience had shown to be comparable. In the first – "smoother" - case, we assumed the fields in the flood plain not to be used for agricultural purposes or to be covered with very low plants, with a well-tended meadow in the excavated trough; willows are sparse along the oxbow banks and there is little mudsilting in the dead branch. The second case described the "maximum expected roughness condition": All the fields are planted with maize or similar vegetation, the relief trough is partly covered with shrubs, the oxbow is lined with willows, and the oxbow has been silted up by the floods.

Calibration for both the hydraulic dimensioning of the prototype and the scale model test was based on a major flood event that had occurred in April 1996 with a peak flow of 315 m^3/s. A comparative analysis gave maximum differences of 0.05 m for the real-life case. This proved the modelling of the roughnesses to be sufficiently truthful.

3.2 Execution of the Scale Model Test – Optimisation for the Final Proposal

After calibration of the model with respect to the different water levels, we checked all the data underlying the design of the project. It was the range of possible vegetation varieties that determined the conditions for checking the various flow patterns for the case of maximum discharge. We had to impose restrictions regarding the plant cover in the flood zone and the clear span of the culvert was taken as 63 m to serve as a flow-reducing element, while retaining the respective embankment heights and the dimensions of the flood relief provided for in the original project. The results of the model tests established the good functioning of the project, but then had to be complemented by in-depth study of the project details for optimisation in each individual case.

Optimising the individual features of the project meant analysing different distribution ratios for the flood flows from river bed and left flood plain, determining the configuration of the approach area above the relief trough, determining the crest level of the flow-control ground sill as well as designing the low-water channel downstream of the road culvert. In addition we studied the implications of potential agricultural uses within the area liable to flooding. At the end of the model tests we added studies regarding certain areas requiring appropriate protection from erosion caused by high flow velocities and the great shear stresses involved, so as to be able to optimise the dimensions of flood relief areas.

3.3 Project Features and Flood Defence Measures

For the optimisation of the individual project features, we assumed, in addition to the various roughness alternatives, a less favourable discharge distribution between flood plain and river bed - a case that cannot entirely be excluded from consideration: The maximum flow of 700 m^3/s is split into approx. 600 m^3/s from the riverbed and approx. 100 m^3/s from the left flood plain; that is, an additional flow of about 140 m^3/s has to be discharged across

Table 2. Extreme cases and variation of flow distribution (in m^3/s)

Total flow	700	700
Lafnitz river bed	600	530
Left flood plain	100	170
Discharge over inlet section	140	70

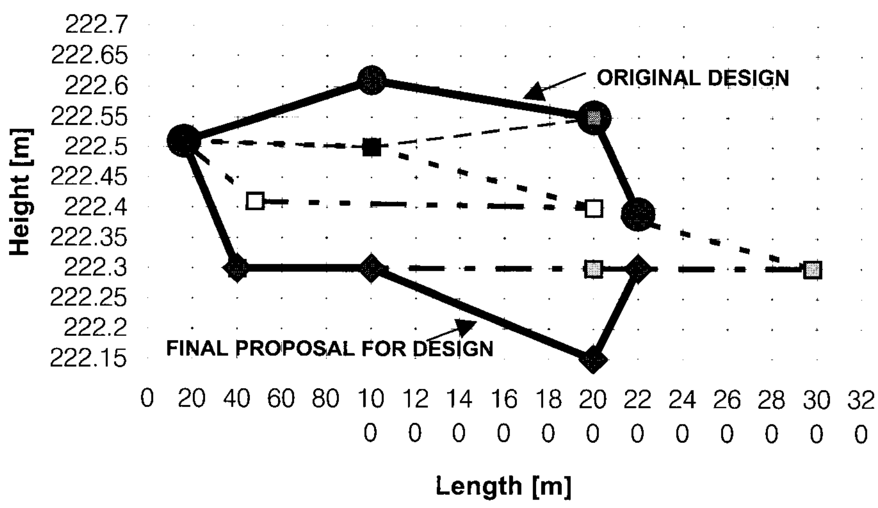

Fig. 3. Contour of the inlet section of the embankment

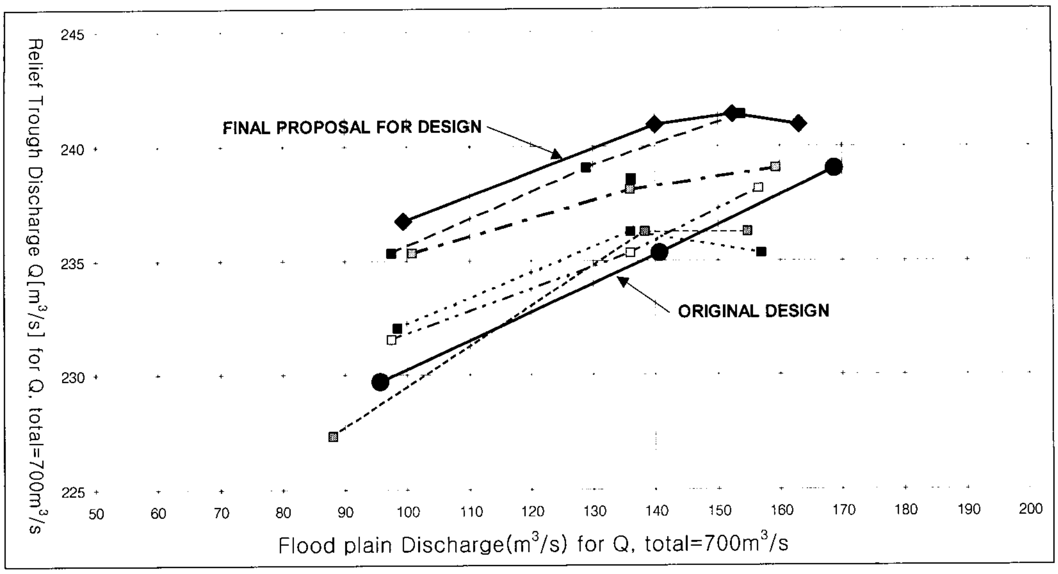

Fig. 4. Discharge capacity curves for the inlet section for different flood plain discharges

the inlet section of the embankment. For the final proposal, we also studied the case of an increased flood plain runoff. We split the flow of 700 m^3/s into about 530 m^3/s from the river bed and about 170 m^3/s from the flood plain, corresponding to an additional 70 m^3/s having to be discharged over the inlet section of the embankment.

By way of example the case of the approach to the relief trough, as one among the great number of tests and optimisation analyses (with each alteration naturally having some effect on the other project features), will be demonstrated below:

On the assumption of the less favourable case of a reduced flow from the flood plain, the required discharge to the relief trough is no longer reached. So we had to alter the shape of the inflow section of the embankment (see Fig. 3) to meet two requirements: on the one hand, the discharge capacity (see Fig. 4) had to be high enough for the total discharge within the relief trough to reach the desired 240 m^3/s for different flood plain discharges; on the other hand, the embankment crest had to lowered as little as possible to ensure that overflow should take place only for major floods.

The optimum contour so found for the inlet section shows that the prototype had to be lowered by a maximum of not more than 40 cm against the original design. The configuration of the inlet section - designed as a descending side weir - follows the water lines. This ensures a more uniform inflow into the relief trough and in addition is better suited to ensure the required flow rate, as further sources of inflow are available in downstream reaches. For the extreme case studied, overflow over the embankment and, at the same time, inflow from the flood plain starts at a total discharge of about Q = 327 m^3/s. This approximately corresponds to a 1 in 5 year flood, which is greater than the flood of 1996 ($HQ_{"96"}$ = 315 m^3/s). Our optimisation tests were aimed at obtaining a relatively uniform overall discharge for the assumption of dif-

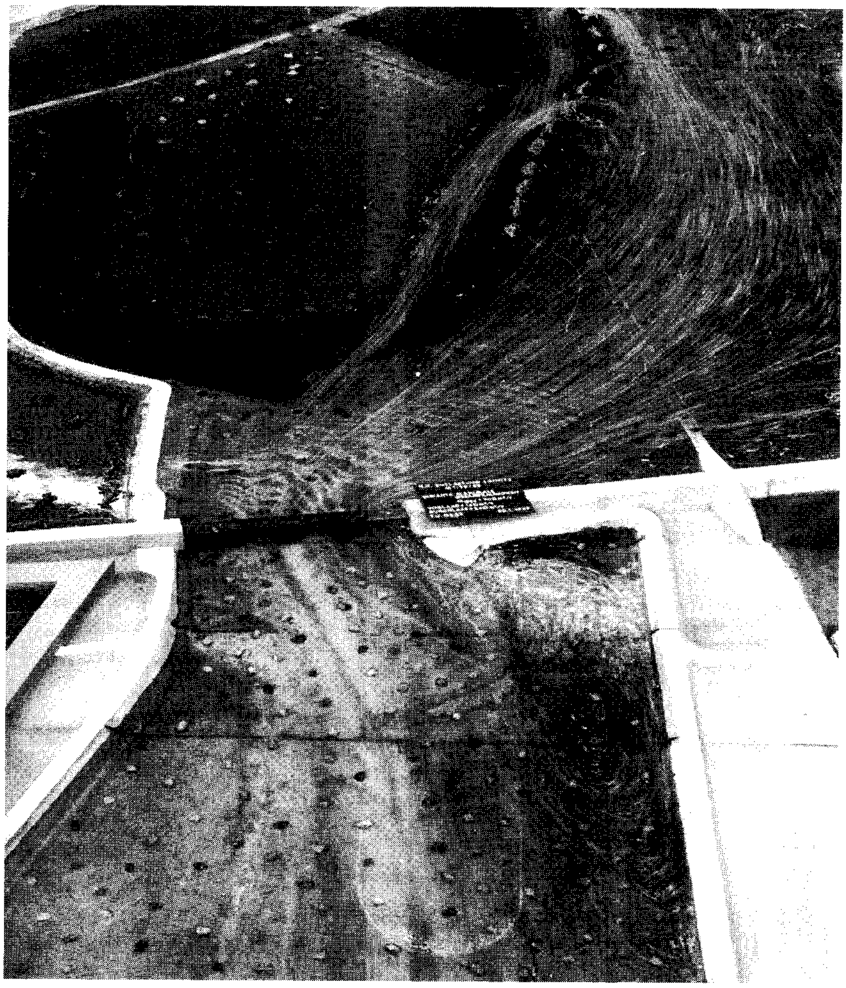

Fig. 5. Flow pattern of the final proposal for design flow HQ_{100} = 700 m^3/s

fering inflows from the flood plain. The discharge capacity curve of the inlet section shows that these requirements have been met very well. The flattening of the curve for the larger flood plain flows implies the advantage of a limitation of the total discharge. This means that the desired ratio of flow distribution for the case underlying the design has been accomplished.

As the discharge capacity of the relief trough is dependent not only on the configuration of the above mentioned approach area, but is a result of the interaction among all the project features, the contour of the inlet sill above the road culvert has been optimised at the same time by lowering the crest by a maximum 35 cm as compared with the original design. But it has not been necessary to alter the planned dimensions of the excavation.

Further.major alterations have been required only over the upper reach of the low-water channel to improve the relatively unfavourable flow patterns downstream of the road culvert. The S-curve of the original design will receive a somewhat flattened configuration. This results in a better distribution of flow over the whole width of the relief trough.

Additional studies related to the optimisation of structural measures to protect the stream bed from erosion. By measuring flow velocities and determining the magnitude of shear stresses, we identified the areas calling for special protective measures. This mainly concerned the reach between ground sill and culvert and the toes of the slopes near the culvert as well as the reach downstream of the culvert, where higher velocities and partly turbulent flow conditions may occur.

A point of particular interest is the complex flow pattern directly at the culvert, where flow transition from subcritical to supercritical occurs as an undulating hydraulic jump. As we did not know the exact design of the bridge piers, accurate study of the culvert itself has not been possible. In addition, the increased height scale used did not permit the appropriate reproduction of the contraction effects. However, it has been possible to derive the energy line from the measured maximum velocities and upstream and downstream water levels and to verify flow patterns and shear stresses with a sufficient amount of accuracy. The flow depths approximately correspond to the analytically determined limiting depth H_{MIN} = 1.31 m, the mean flow velocities are 2.3 m/s. In one of the four sections of the bridge downstream, the occurrence of a hydraulic jump can actually be observed, in the other zones an undulating hydraulic jump develops. Further downstream, over a length of 100 m, the flow pattern is still severely undulating. The maximum velocities are 4.05 m/s. the shear stresses reach a maximum 145

the shear stresses reach a maximum 145 N/m^2. This means that this reach calls for extraordinary stabilisation measures (e.g. mortared middle-sized stone)

4. CONCLUDING REMARKS

The substantial flood risk in the Lafnitz basin between Heiligenkreuz in Austria and Szengottghard in Hungary has called for the preparation of a detailed project providing for the discharge of part of the flood flow to the Lahnbach, a tributary stream. As analysis of the extremely complex flow pattern within the approach by means of one-dimensional calculation methods did not appear satisfactory and had to rely on a number of assumptions, checking by means of a hydraulic scale model test was needed. The tests were carried out at the hydraulic laboratory of the Technical University of Graz. The Szentgottgard Flood Protection Project was developed by Werner Consult for the Republic of Austria, Hydraulic Engineering Department for the province of Burgenland.

The purpose of the hydraulic scale model test has been to obtain detailed information on the assumptions underlying the design and to optimise the structural features covered by the model. The results of the hydraulic tests, while largely confirming the assumptions made in the design, have led to improvements for a great number of details. In this way, they have formed part of the basis needed for obtaining the construction permit from the water-right authorities and, in addition, have led to reductions in construction cost, as it has been possible to better define, and thus reduce, the reaches needing special bed stabilisation.

Work on Austrian territory commenced in

February 2000. The project is scheduled for completion by July 2002. The work comprises construction of the flood relief trough, about 1,800 m long and up to 220 m wide, including the about 560 m long inlet sill as well as the approx. 700 m long embankment section near Neuheiligenkreuz including appurtenant structures, such as shut-off units, connections to field paths, etc. The project covers more than 300,000 m^3 of earth movements, concrete works, stabilisation works, special civil engineering works, and more than 400,000 m^2 of land restoration works. The total cost of the Austrian part of the project amounts to ATS 110 million (US $ 7.4 million), of which ATS 28 million (US $ 1.9 million) accounts for land purchase and damages. Financing is largely based on funds from the federal and provincial governments, but it has been possible to obtain ATS 20 million (US $ 1.3 million) in EU funds.

The economy of the project has been established by a cost-benefit analysis. Realisation of the planned measures will provide permanent protection from floods for areas assigned to high-quality uses. On Hungarian territory, the town of Szentgotthard will for the first time enjoy reliable protection from floods. Reconstruction of the railway station, which would otherwise have been necessary, can be omitted for the time being. Also, the project will afford increased protection to the road and railway nets in this area. Above all, however, it will now become possible to continue the realisation of the Industrial Park extending across the Austro-Hungarian border, so as to create the basis needed for the continued development of this region.