

## FLOW BASED VIBRATIONS OF SLUICE GATES – PHYSICAL AND NUMERICAL MODELLING

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**Abstract:** *The first part of the paper presents results from laboratory experiments simulating hydrodynamic load acting on the large model of sluice gate located on spillway. Vibrations of the gate as one of the key aspects of durability and reliability of sluice gates as outlet works were measured together with forces in operating mechanism and pressures in surroundings. The second part is focused on numerical modelling of the executed experiments and aims at possible approaches for reliability assessment of sluice gates. The influence of the shape of the gate bottom on induced vibrations and possible cavitation is discussed in both parts.*

**Keywords:** *Sluice gates, Physical modelling, Numerical modelling, Vibration*

### 1. Introduction

Reliability of flood gates installed on emergency spillways of hydraulic structures become widely discussed topic after major flood events struck Czech Republic in 1997 and 2002. Malfunction of flood gates followed by overtopping of the dam with all the related impacts is a primary cause in more than 25 % cases worldwide (Cassidy, 2000). Although no serious case of malfunction on important hydraulic structures during floods was reported in Czech Republic so far, increased probability of accidents can be expected despite regular maintenance as most of the gates are rapidly approaching the end of their designed service life.

The scope of the present contribution involves hydraulic and dynamic analysis of flow under the sluice gates. The importance of the issue of discharge under the sluice gate and possible vibration of the gate and foundation structure follows from operational grounds as well as from the reliability point of view. Hygienic standards also influence the necessity for deep understanding of this topic. Theoretical part of the paper is aimed at discharge under and over the sluice gate.

The experimental part focuses on description of principles used for measurement and evaluation of values on physical model constructed in the hydraulic laboratory at the CTU in Prague, Faculty of Civil Engineering. Pressures acting on the foundation structures and vertical forces acting on the gate structure under the steady state, gate lifting or lowering conditions measured on the physical model are presented in the experimental section.

The last section of this paper describes numerical model of sluice gate created in ANSYS Workbench environment while using ANSYS CFX code for modelling of flow and ANSYS Mechanical code for structural analysis. It comments the results obtained by applying one-way fluid-

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structure interaction where hydrodynamic forces calculated in fluid part are used as boundary condition for the structural part. First ten eigenfrequencies and corresponding shapes of the laboratory model were determined by modal analysis and are presented in the final part of the numerical section.

## 2. Theory

### 2.1. Overfall spillway discharge

Water flowing over obstruction or construction called spillway is generally regarded as overfall. The highest point of the spillway is called spillway crest or the edge of spillway. Flow over spillway results in changes in pressure and flow velocity. Upstream and downstream water surface level difference is of importance.

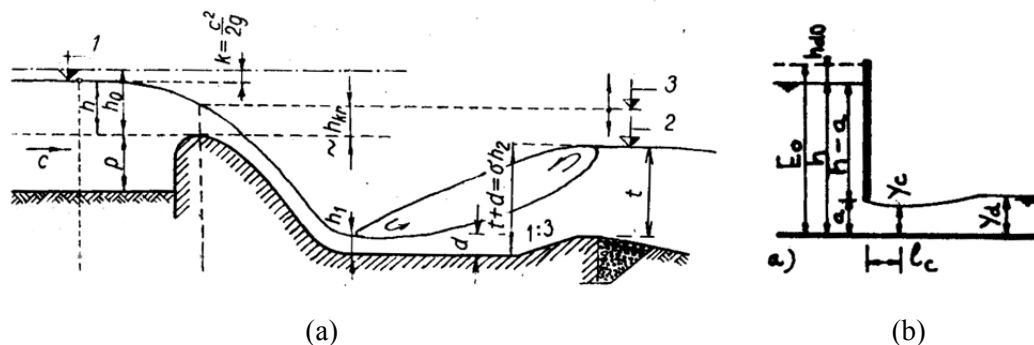


Fig. 1: Calculation schemes: (a) Overfall spillway, (b) Discharge under sluice gate

Bazin's equation can be used for calculation of spillway discharge under the conditions of steady flow which is not influenced by the tailwater level.:

$$Q = mb_0\sqrt{2gh}^{3/2} \quad (1)$$

Where  $Q$  stands for spillway discharge [ $\text{m}^3 \cdot \text{s}^{-1}$ ],  $m$  for coefficient of discharge [-],  $b_0$  for effective width of spillway [m],  $g$  for gravitational acceleration =  $9,81 \text{ m} \cdot \text{s}^{-2}$  and  $h$  for head [m].

### 2.2. Discharge under sluice gate

Discharge under the sluice gated which is not influenced by tailwater is regarded as free flow discharge or perfect discharge. For discharge calculation the tailwater level, the shape of the edge of sluice gate and channel bottom, the influence of side structures, the height of gate opening, the transition of outflow stream into the tailwater all have to be taken into consideration. Assumptions used for calculation of model discharge are as follows. Atmospheric pressure is acting on both head and tailwater and the gate opening has rectangular shape. The characteristic value is therefore flow rate calculated on one meter of width of sluice gate denoted as  $q$ . Under the assumption of free and steady flow following equation can be used to calculate the discharge:

$$Q = \mu_v ab\sqrt{2g(E_0 - \gamma_c)} \quad (2)$$

Where  $Q$  stands for discharge under the gate [ $\text{m}^3 \cdot \text{s}^{-1}$ ],  $\mu_v$  for discharge coefficient [-],  $b$  for width of gate opening [m],  $a$  for height of gate opening [m],  $g$  for gravitational acceleration =  $9,81 \text{ m} \cdot \text{s}^{-2}$ ,  $E_0$  for energy head and  $\gamma_c$  for smallest the flow depth [m].

### 2.3. Basic Static analysis – material for model

Basic static analysis using elastic theory was carried out for the purpose of material selection for laboratory model. Static scheme selected for skin plate and cross beam is clear from following figure. Material SIMOLUX was selected based on the calculated values of deflections. Table 1 presents results calculated from simple static and 3D numerical analysis for selected material under the hydrostatic conditions as well as measured value of deflection and deflection calculated using finite code ANSYS Mechanical, where loading was derived from fluid dynamic calculations (more in Section 4.3.), for the hydrodynamic load with 30 mm gate opening.

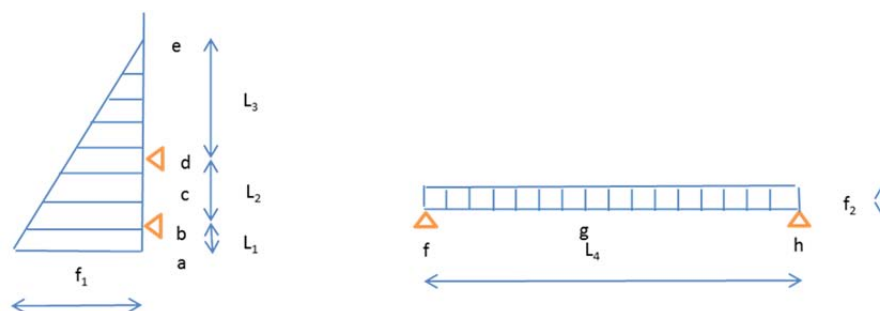


Fig. 2: Static scheme for basic 2D calculations of skin plate and cross beam

Tab. 1: Stress and deformation of laboratory model of sluice gate made of SIMOLUX

Source	Hydrostatic load	Hydrodynamic load
Deflection at point e – top middle (mm)		
Simple 2D analysis	2.9	----
FEM 3D analysis	2.8	1.10
Measured	----	1.45

### 3. Physical modelling

Physical model can faithfully represent the structure, under the certain conditions, and thus provide answers to numerous hydraulic, static and dynamic conditions. In order to obtain valid results from hydraulic research it is necessary to follow restrictions based on the type of the problem. In this case Froud's Law of Comparison was used. Several similar models, which complement and extend each other's range of interest, have to be built, so that obtained results can be generalized. The models should cover whole range of possible topologies, hydraulic conditions and loading cases.

During the physical modelling all sorts of variables are measured and logged. For example, both static and dynamic action of water on the foundation structure, on the sluice gate structure, on the operating rod and their response and also hydraulic conditions in front and behind the gate. Typically, water pressure, force in operating rod and water levels are measured for selected flow or discharge rate. Thomson's spillway was used to measure flow rate, pressure probes to gather pressure distribution along the spillway, cylindrical gauges to measure deformations of the sluice gate and position of the water surface and force transducers to gain the force in time distribution in the operating rods. Table 2 shows typical result of measured and derived hydraulic variables on models with different shape of a spillway crest.

Tab. 2: Stress and deformation of laboratory model of sluice gate made of SIMOLUX

Variable	Spillway no. 1	Spillway no. 2	Spillway no. 3	Spillway no. 4
Description	Negative pressure overfall shape	Negative pressure overfall shape	Jambor sill	Jambor sill
$h / h_a$ (-)	2.2	1.3	-	-
$s$ (m)	-	-	0.03	0.1
$h_a$ (m)	0.05	0.085	-	-
$h$ (m)	0.12	0.12	0.12	0.5
$b$ (m)	0.53	0.53	0.53	0.5
$m$ (-)	0.53	0.52	0.52	0.55

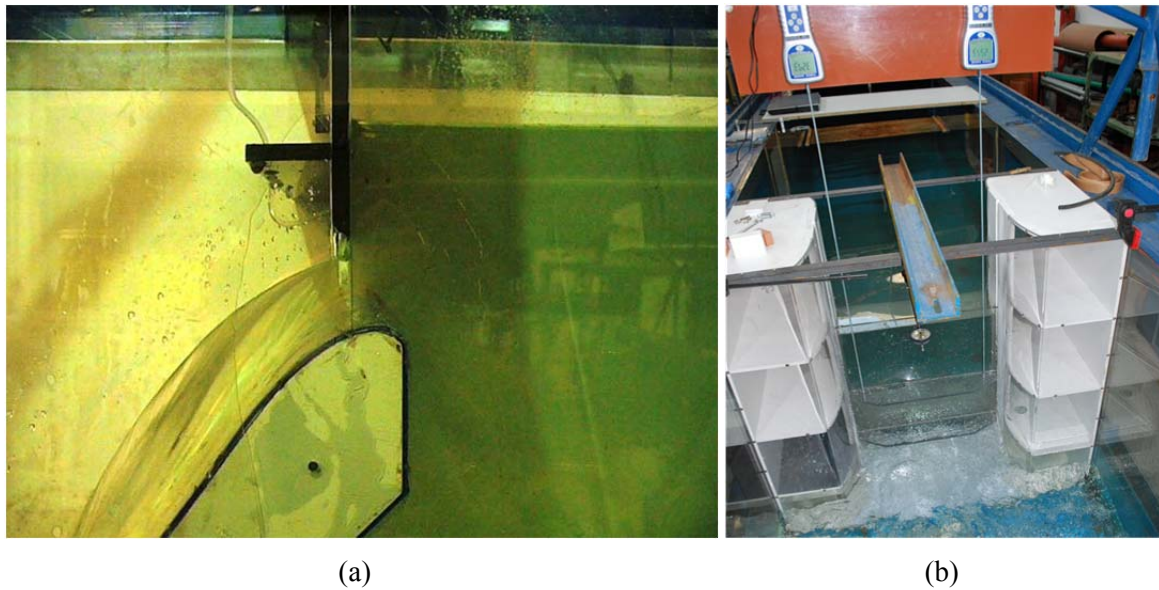


Fig. 3: Laboratory models: (a) Spillway no. 1 – set-up 9, (b) Spillway no. 5 – set-up 2

Coefficient of discharge  $m$  derived from measured values on spillway no. 3 varies in range 0.51 to 0.54 and discharge coefficient  $\mu_v$  varies between 0.782 and 0.87 both depending on the head. These values are different from usually used and published (e.g. Gabriel et. al., 1989; Kolář, Patočka and Bém, 1983) as the standard range for  $m$  is 0.43 to 0.5 and for  $\mu_v$  it is 0.7 to 0.75. All these differences obtained by physical modelling will be subjected to future detailed research and the influence of tailwater will be included. Left part of the following figure presents measured values of pressure variations acting on foundation structure Fig. 4 (a) while on the right side the force in the operating rod is plotted against time during lifting the gate. Both figures contain data for different shape of the spillway model (i.e. spillway no. 1, no. 2 and no. 3)

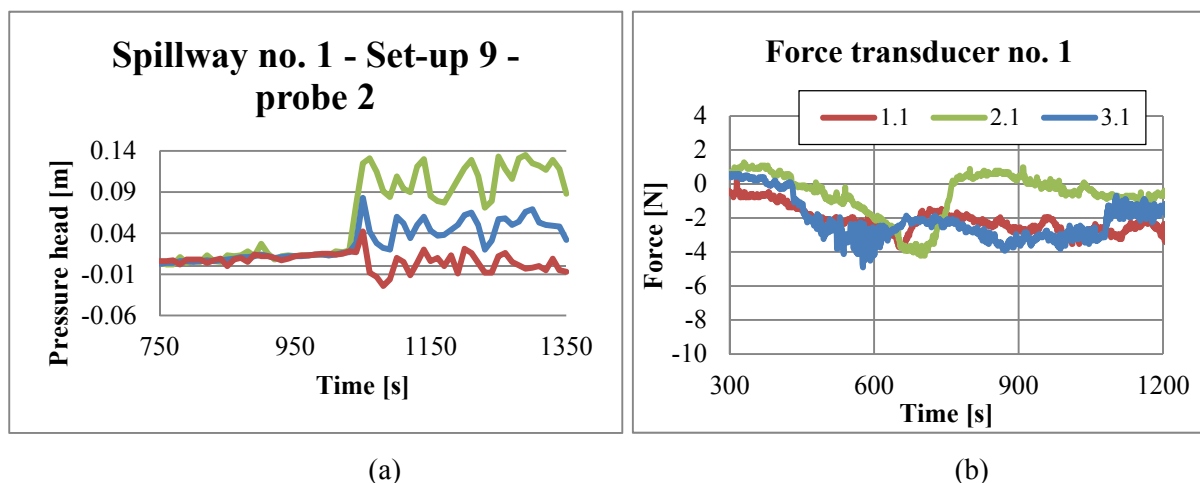


Fig. 4: Measured values during gate lifting for different spillway models: (a) Pressure acting on the foundation structure, (b) Force in operating rod

Presented results clearly demonstrate the differences in pressure and force fluctuations and the time where bottom part of the gate loses contact with the water surface and free overfall state is reached. Fig. 5 (a) shows force fluctuation in operating rod measured on the spillway no. 5 under the steady conditions. The position of the gate opening (20 mm) was kept constant as well as the flow rate. The tailwater was not influencing the discharge under the gate and so all the observed vibration are only induced by the water flowing under the gate. Force magnitude is related to the net self-weight of the gate, which was used to set 0 on transducers. Fig. 5 (b) on the other hand presents absolute values

of forces in case of 30 mm gate opening but influenced by the tailwater, i.e. with submerged hydraulic jump that affects the downstream part (beams) of the gate structure.

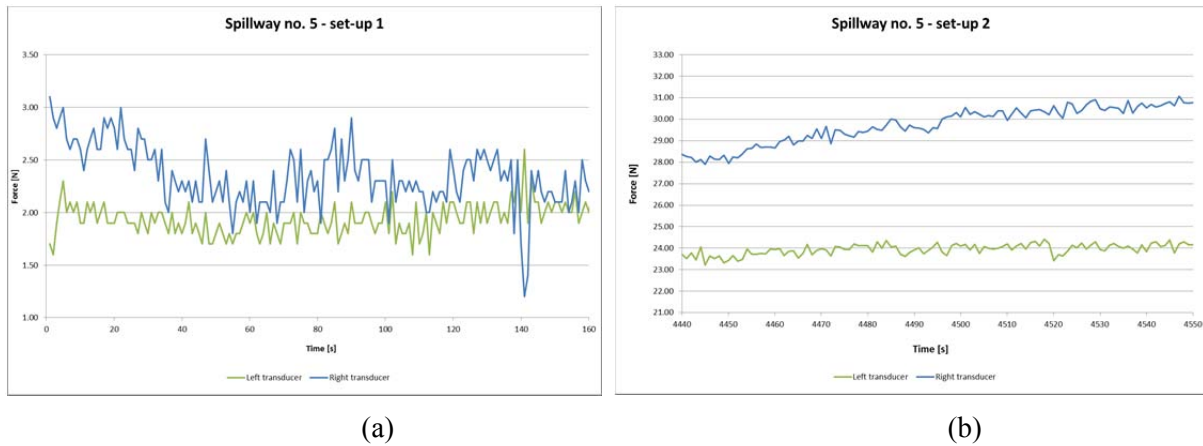


Fig. 5: Measured forces: (a) Without the influence of tailwater, (b) Tailwater influenced

All the measured sets of data were carefully analysed using FFT. The logging frequency of the transducers was 1 Hz. Vibrations induced without the influence of tailwater did not show any significant differences from vibrations induced only by water flowing under the gate.

#### 4. Numerical modelling

Numerical model of sluice gate was created in ANSYS Workbench environment while using ANSYS CFX code for solving the flow based problem (CFD) and ANSYS Mechanical for structural analysis.

##### 4.1. Model description for CFD

Axis symmetry of the problem was applied in order to decrease the computation time. Sufficient length of the intake and outlet channel was incorporated into the model geometry to stabilize the flow conditions around the gate and also to exclude the direct influence of boundary conditions. Otherwise all the dimensions were taken from the physical model in laboratory. The CFD model topology was created in the Rhinoceros 4.0. software and consequently imported and modified in the ANSYS Geometry. Mesh was created in the ANSYS Meshing tool using the automatic mesh generator. The mesh consists of tetrahedron elements with significant refinement in the area around the bottom edge of the gate. The model consists of total three million elements.

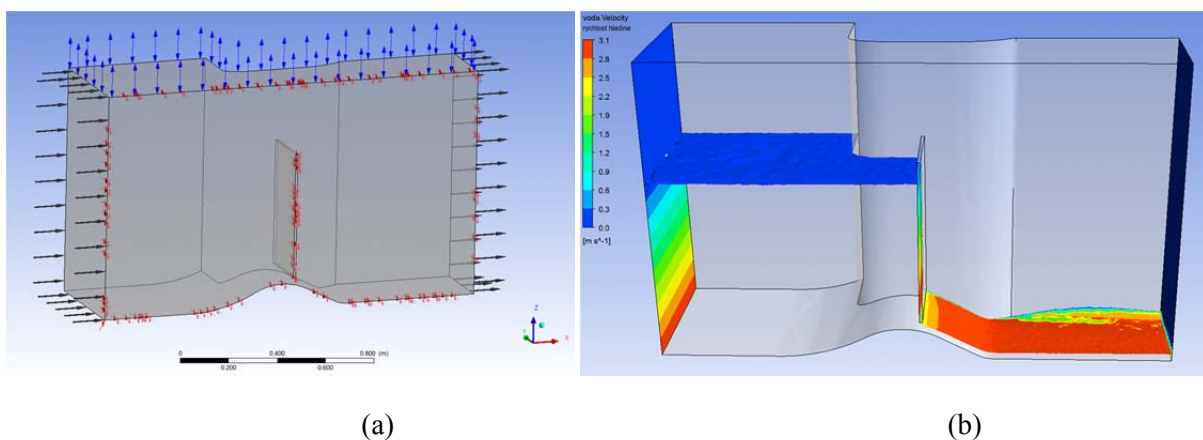


Fig. 6: CFD model: (a) Topology with boundary conditions, (b) Velocities distribution in  $m.s^{-1}$

## 4.2. Fluid flow modelling

The flow problem was calculated in ANSYS CFX code using following boundary conditions: ontake channel edge – constant water surface level; outlet channel edge – free flow with zero hydrostatic pressure for set-up no. 1 and raising tailwater level so the hydraulic jump will be positioned just under the gate for set-up no. 2. Top of the model was opened to the air pressure while the rest of the surfaces are considered impermeable. The model setup is clear from Fig. 6 (a).

The initialization of the steady computation of the free discharge under the sluice gate without the influence of the tailwater was executed employing homogenous multiphase water-air model with time step 0.1 s and a standard k- $\epsilon$  model of turbulence. Subsequently, the time step was increased to 0.5 s and the multiphase model was set to “mixture”. Figures 6 (b) and 7 (a) present calculated velocity distribution and pressure acting on the gate respectively.

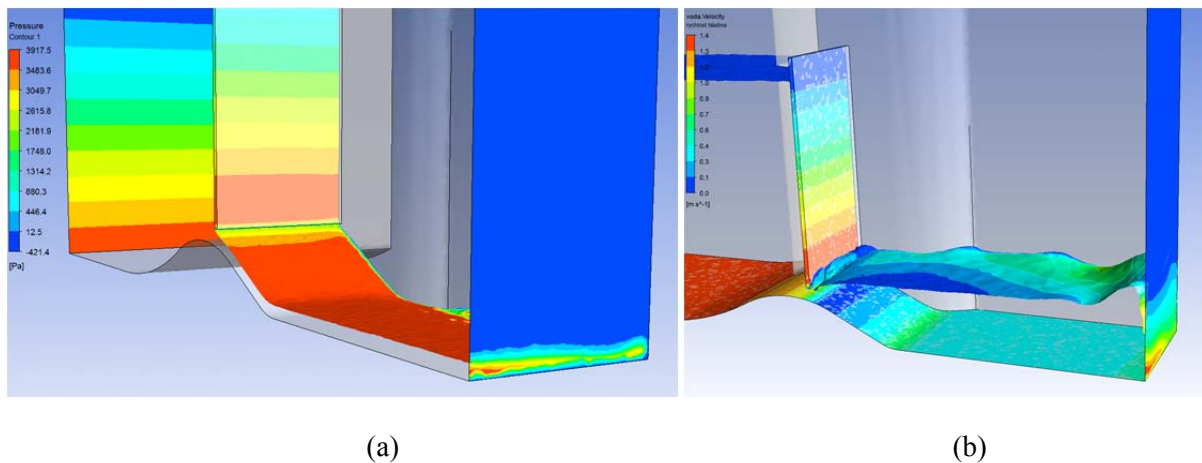


Fig. 7: CFD model: (a) Pressure acting on the gate without the tailwater influence, (b) hydrostatic pressure (water surface) with the rising tailwater level

Unsteady solver with a time step 0.01 s and 5 iterations in each step was used to calculate the discharge influenced by the tailwater. Example of the results can be seen in Fig. 7 (b). Rising tailwater changes nature of the hydraulic jump and shifts into the close proximity of the bottom edge of the gate. The stream interacts with the bottom part of the gate and together with small wave action on the upstream face causes vibration of the entire gate construction. Time dependent forces with dynamic part having frequency approximately 2.1 s were obtained by the integration of pressures along the surface of the gate. Figure 8 shows fluctuation of forces acting on the bottom and downstream side.

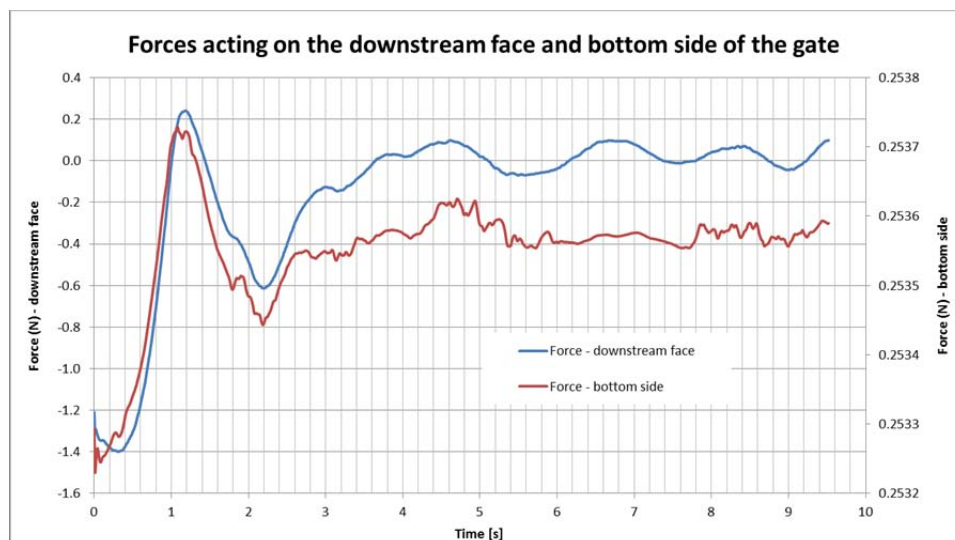


Fig. 8: Fluctuation of forces in numerical model obtained by pressures integration

### 4.3. Structural analysis – stress, strain and modal analysis

ANSYS Mechanical was used to perform structural analysis of the sluice gate model. Hydrodynamic load calculated using CFD as described in the section above was used as the loading boundary condition. The used method corresponds with the one-way fluid-structure interaction analysis.

The model topology was, as in the case of CFD, prepared in Rhinoceros 4.0 code and meshing was done in ANSYS Meshing code using automatic mesh generator. Hexahedral elements with nodes in the middle of sides of the elements were used. The structural model consists of approximately twenty thousand elements. Isotropic elastic material model with SIMOLUX parameters, i.e.  $1270 \text{ kg}\cdot\text{m}^{-3}$  density, Young's modulus equals 1900 MPa and 0.2 for Poisson ratio.

The boundary conditions for structural analysis were set as follows: axes of symmetry – frictionless support; operating rod – vertical displacement constrain; wheels – horizontal displacement constrain; whole domain – self weight; skin plate – hydrodynamic load calculated by CFD for discharge uninfluenced by tailwater. All the applied boundary conditions are clear from Fig. 9.

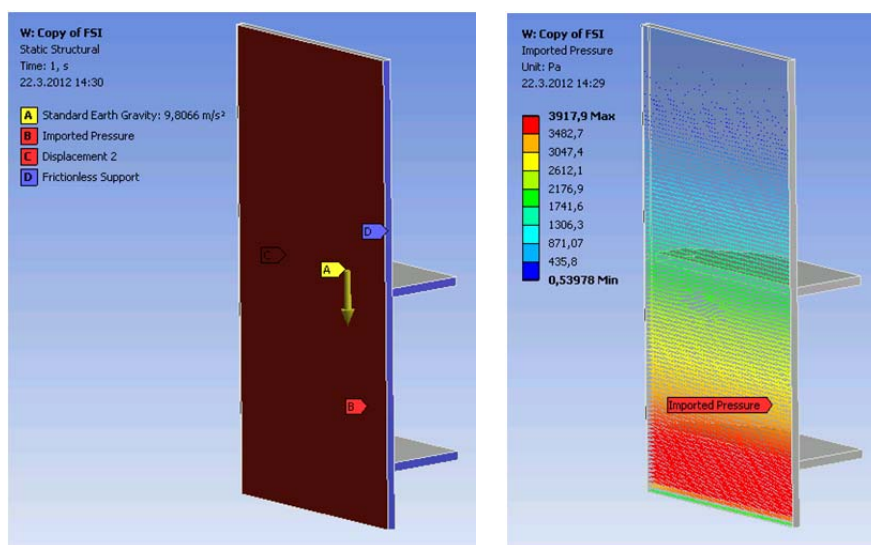


Fig. 9: Boundary conditions applied in stress-strain analysis (pressures in Pa)

Calculated deflection of the middle top of the sluice gate under the conditions described above was 1.1 mm. Maximal principal stress in wheels was 10 MPa while in cross beams 0.5 MPa. Typical results are shown in the following figure.

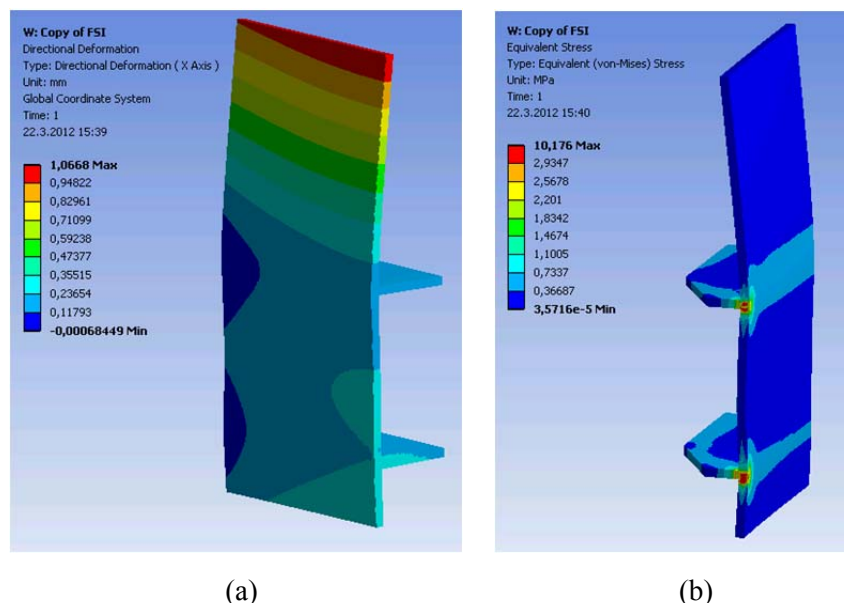
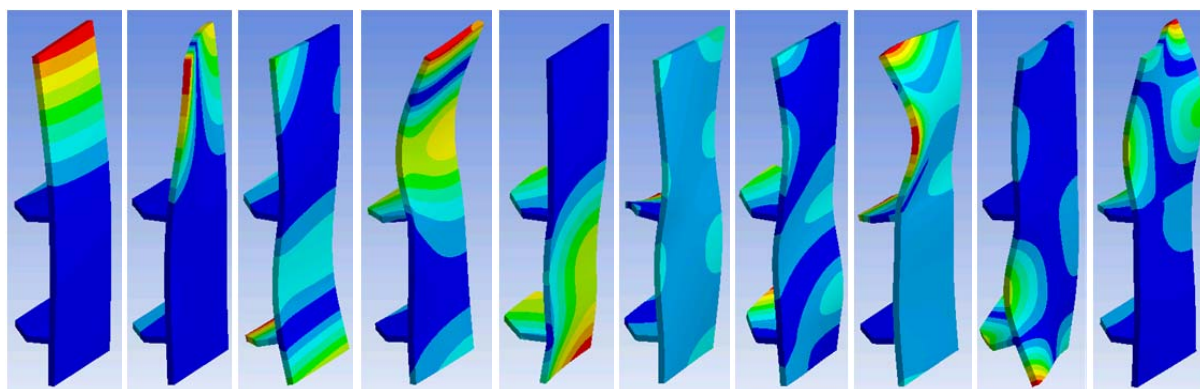


Fig. 10: Stress-strain analysis (a) horizontal deflection (mm), (b) Von-Mises stress (MPa)

First ten eigenfrequencies and corresponding shapes were obtained by modal analysis and are presented in Fig 11.



1	2	3	4	5	6	7	8	9	10
22.8	83.9	98.4	128.4	139.4	176.8	221.9	240.7	245.5	276.4

Fig. 10: Eigenfrequencies (Hz) and corresponding shapes

Although agreement between calculated discharge 30.4 l/s and measured discharge 29.9 l/s present suitability of CFD for numerical modelling of discharge under the sluice gate mounted on the Jambor sill, the difference in deflection calculated in the structural analysis part and measured is, however, larger than expected.

## 5. Conclusions

An extensive experimental program was started in order to properly evaluate vibration of sluice gates induced during discharge and their influence on the safety and reliability of the gates. As a part of this program CFD simulations and one-way fluid structure interaction calculations were carried out to verify the possibility of substituting numerical modelling for demanding physical modelling. Even with no calibrating procedure employed the hydraulic results are in reasonably good agreement with measured values of discharge and pressures. The results obtained from structural analysis show, however, the necessity of calibration of the material characteristics and model topology.

Hydrodynamic loading acting in the horizontal direction on the gate structure is mainly caused by the upstream water surface wave action and tailwater influence which shifts the hydraulic jump backwards to contact with the gate. Oscillations of the pressure in the hydraulic jump are then transferred to the gate structure. Hydraulically sharp or unsuitably shaped bottom edge of the gate can be the source of vibration even without the tailwater influence.

## Acknowledgement

The financial support of the project No. VG20102014056 provided by the Ministry of the Interior of the Czech Republic is gratefully acknowledged.

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