DYNAMIC ANALYSIS OF A HINGED-LEAF MAIN REGULATION GATE

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Barrages are a significant group of hydraulic structures for actual open watercourse water management problems. Several types of barrages are known depending on the design of the main regulation gate structure ensuring water storage. A hinged-leaf main regulation gate one end suspended and anchored at three points has been designed for the 10 m wide dike opening at the 125 + 200 km section of the Ipoly river station.

In this paper, dynamic analysis of the gate leaf is presented, seen in perspective drawing in Fig. 1. The gate suspended one end is moved by a horizontally arranged, oil-pressure operated device.

Principal dimensions of the gate leaf are: *height* in extreme position (inclined at 10°) 2 m, *length:* 10 + 1 = 11 m, *spacing of the anchors*: 5.1 m. The general outlay of the main regulating gate is shown in Fig. 2, its structural framework in Fig. 3, geometry in Fig. 4, and characteristic cross sections in Fig. 5.

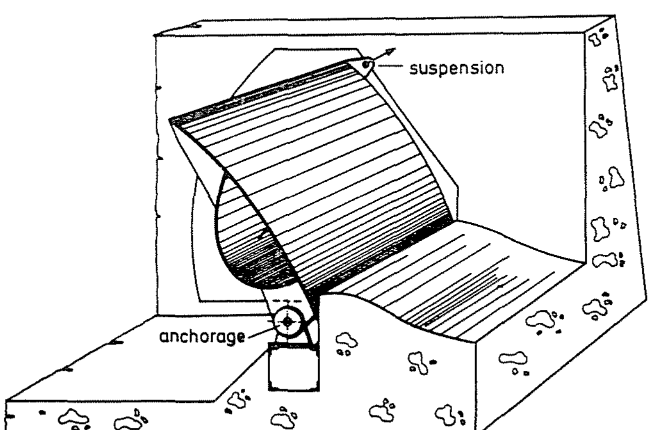

Fig. 1. The main regulation gate

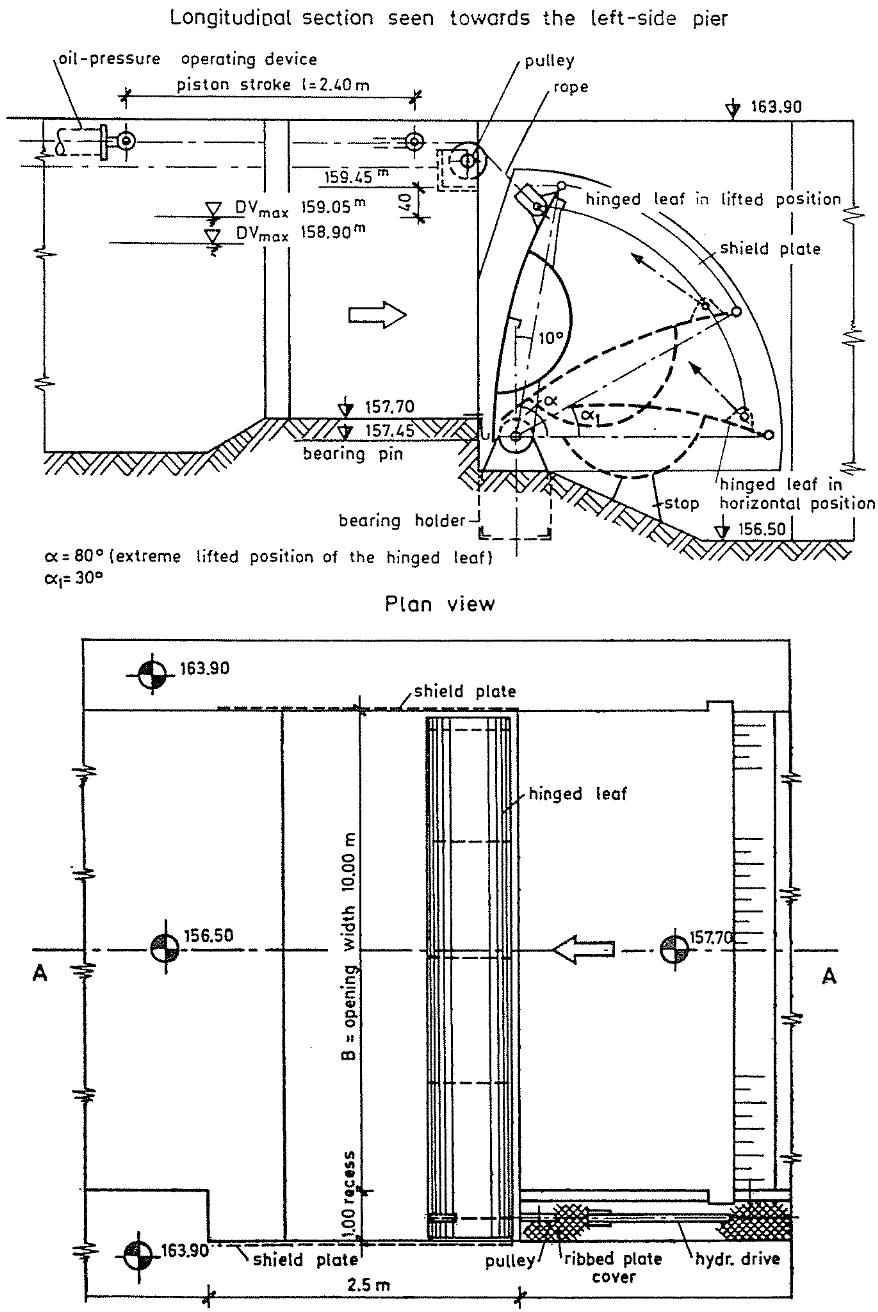

Fig. 2. General layout of the main regulation hinged leaf gate in the Ipoly river

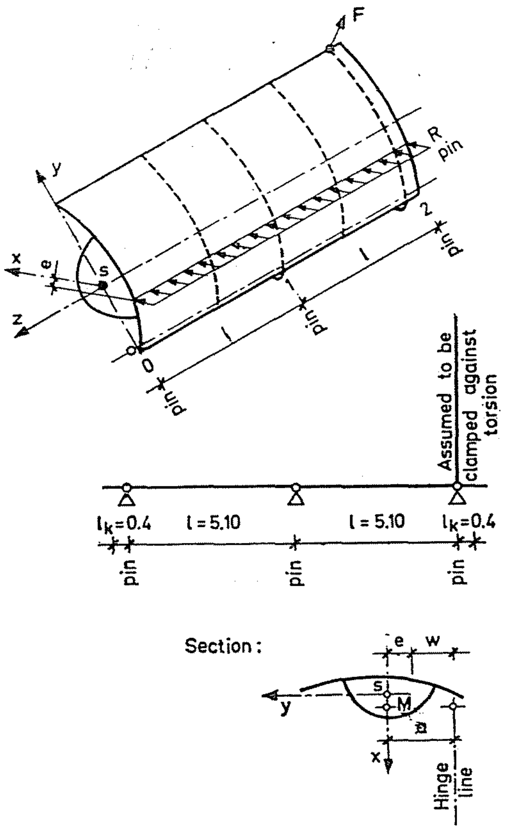

Fig. 3. Static frame of the main gate leaf

1. Calculation of loads and effects

The loads and effects have been taken into account according to the prescriptions of the Hungarian standard VMS 148—72 [3] for the different gate leaf positions.

Permanent load: dead load of the gate and the weight of the silt deposited on the underwater fish-bellied part of the gate.
Specific dead load of the hinged gate leaf: 2.5 kN/m^2.
Weight of a hinged gate leaf: $G_t = 55$ kN.
Weight of the silt deposit assumed to be 5 cm thick in the fish-bellied part of the leaf ($\gamma = 18$ kN/m^3):

$$G_{silt} = 18.7 \text{ kN}$$

$$G = 55 + 18.7 = 73.7 \text{ kN}$$

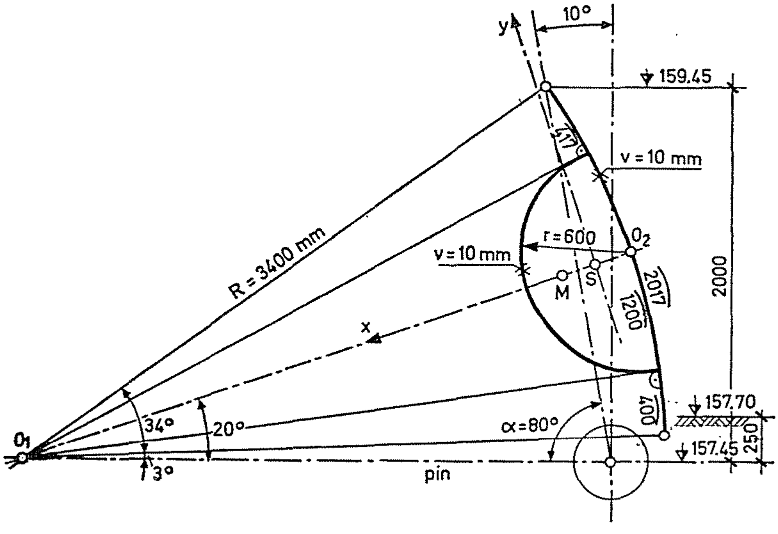

Fig. 4. Hinged leaf geometry

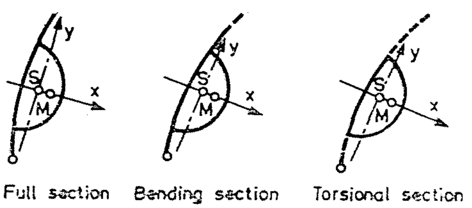

Fig. 5. Typical sections

$$g = \frac{73.7 \text{ kN}}{11 \text{ m}} = 6.7 \text{ kN/m} .$$

Dead load will be assumed concentrated at the actual cross section centroid.

The effect of dead load will be expressed by the moment about the hinge line:

$$M_{\ddot{o}} = gk \text{ (kN/m)}$$

where k is the lever of the weight for different positions of the leaf.

Incidental loads:

Hydrostatic and hydrodynamic water load

I. Water load in operation

Calculation of the hydrostatic water load with the gate lifted:

$$\alpha = 80° \text{ (Fig 6).}$$

$$\text{Impounding head} = 159.05 \ (IH \text{ max})$$

$$\text{Tailwater level} \simeq 0 \text{ (assumed)}$$

$$H = 12.8 \text{ kN/M}$$

$$V = 3.1 \text{ kN/m}$$

$$R = \sqrt{H^2 + V^2} = 13.2 \text{ kN/m}$$

$$\text{tg}\,\vartheta = \frac{3.1}{12.8} = 0.242; \qquad \vartheta = 13.6^\circ$$

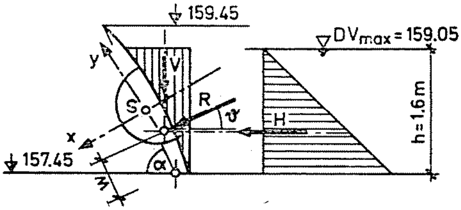

Fig. 6. Hydrostatic water load

$$w = 0.55 \text{ m (Fig. 7)}$$

$$Rx = R\cos\varepsilon = 13.1 \text{ kN/m}$$

$$Ry = R\sin\varepsilon = 1.5 \text{ kN/m}$$

$$Gx = G\cos 70^\circ = 2.3 \text{ kN/m}$$

$$Gy = G\sin 70^\circ = 6.3 \text{ kN/m.}$$

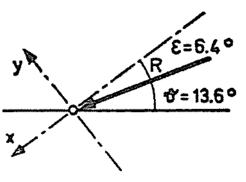

Fig. 7. Direction of the resultant

The moment about the line through the hinges is

$$M_R = Rw \text{ (kNm)}$$

where w = distance of the influence line of the resultant force from the line of hinges.

Calculation of the most unfavourable hydrodynamic water load

The hydrodynamic water load acting on the hinged gate leaves is produced by the effect of the water flow. The hydraulic water load is simplest determined graphically in knowledge of the pressure diagrams, determined either in a model test or by calculation.

In a model test, the pressure distribution on the surface of the gate leaves is determined by measurements in different leaf positions and plotted in pressure diagrams.

Exact calculation methods for pressure distribution are found in [1].

Some examples will be presented below for approximate calculation of hydraulic water loads according to [2].

For approximate calculations, the maximum hydrodynamic water load on one meter of leaf may be estimated as follows:

in the case of an arched gate leaf:

$$W_{hydr} = 0.4\ \gamma\ s h_{max}$$

$$M_{hydr} = 0.135\ \gamma\ s^2 h_{max}$$

in the case of a flat gate leaf:

$$W_{hydr} = 0.7\ \gamma\ s h_{max}$$

$$M_{hydr} = 0.35\ \gamma\ s^2 h_{max}$$

where s = width of gate leaf (m),
h_{max} = hydrostatic head in case of maximum storage (m).

The hydrodynamic water load for different load positions is expressed by the resultant force W_{hydr} and the moment about the hinge line M_{hydr}:

$$M_{hydr} = W_{hydr} w \text{ [kNm]}$$

where w = distance of the influence line of the resultant from the hinge line.

According to small-scale and full-scale model test results, maximum hydrodynamic loads on hinged gate leaves act at the leaf position $\simeq 30°$, to be started from in presenting the calculation of the hydrodynamic water load.

i. *Calculation of the hydrodynamic water load at a leaf position $\alpha = 30°$ (Fig. 8)*

Impounding head: 159.05 (IH_{max})

$$s = 2.017 \text{ m}$$

$$h_{max} = 1.6 \text{ m}$$

$$W_{hydr} = 0.4 \cdot 10 \cdot 2.017 \cdot 1.6 = 12.9 \text{ kN/m}$$

$$M_{hydr} = 0.133 \cdot 10 \cdot 2.017^2 \cdot 1.6 = 8.65 \text{ kNm} = 8.65/12.9 = 0.66 \text{ m}$$

$$W_{x_{hydr}} \sim 12.9 \text{ kN/m}$$

$$W_{y_{hydr}} \sim 0$$

$$G_x = G \cos 30° = 5.8 \text{ kN/m}$$

$$G_y = G \sin 30° = 3.35 \text{ kN/m}$$

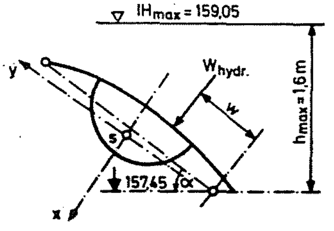

Fig. 8. Hydraulic water load point

ii. *Short-time water load*

Impounding head: *IH* max 159.05 + 0.30 (excess head) = 159.35 m.
Tailwater level: according to the discharge rating curve.

iii. *Extraordinary water load*

Impounding head: *IH* max 159.05 + 0.50 (excess head) = 159.55 m.
Tailwater level: according to the discharge rating curve.

Critical load grouping

I. *In operating condition, without ice load* (safety factor: 1.2).

In the case of upright (extreme) leaf position ($\alpha = 80°$), from the hydrostatic water load:

$$X_M = 1.2(G_x + W_x) = 1.2(2.3 + 13.1) = 18.5 \text{ kN/m}$$

$$Y_M = 1.2(G_y + W_y) = 1.2(6.3 + 1.5) = 9.3 \text{ kN/m}.$$

In the case of critical ($\alpha = 30°$) hydrodynamic load

$$X_M = 1.2(G_x + W_{x_{hydr}}) = 1.2(5.8 + 12.9) = 22.4 \text{ kN/m}$$

$$Y_M = 1.2(G_y + W_{y_{hydr}}) = 1.2(3.35) = 4.0 \text{ kN/m}.$$

Critical load pattern!

Consideration of the ice load effect

Gates exposed to stationary or floating ice should be calculated by allowing for the effect of ice load [3].

Ice loads acting on gates have to be assumed according to the following:

- gate leaves and bracings should in each case be designed for a uniform basic load of at least 30 kN/m^2;
- in designing the main supporting structures, the effect of expanding and running ice should be assumed as a uniform linear load acting at the winter operation water level.

	Permanent kN/m	Short-time kN/m	Extreme kN/m
Expanding ice	20.0	40.0	70.0
Running ice	7.0	15.0	20.0

The effect of ice load needs not be involved in the excess head. *Load on the hinged gate leaf in lifted position allowing for ice load* ($\alpha = 80°$, Fig. 9):

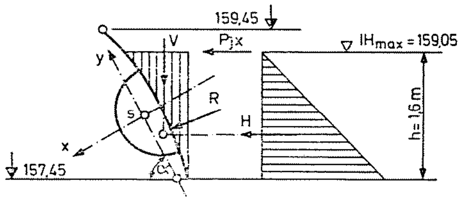

Fig. 9. Water and ice load

Hydrostatic water load:

$$H = 12.8 \text{ kN/m}$$
$$V = 3.1 \text{ kN/m}$$
$$R = 13.2 \text{ kN/m}$$
$$R_x = 13.1 \text{ kN/m}$$
$$R_y = 1.5 \text{ kN/m.}$$

Ice load on the main girder:

$$P_{jx} = 20.0 \text{ kN/m.}$$

Dead load:

$$A_x = 2.3 \text{ kN/m}$$
$$A_y = 6.3 \text{ kN/m.}$$

Critical load grouping in the case of ice load:

$$X_M = 1.2(G_x + R_x + P_{jx}) = 1.2(2.3 + 13.1 + 20) = 42.6 \text{ kN/m}$$
$$Y_M = 1.2(G_y + R_y) = 1.2(6.3 + 1.5) = 4.3 \text{ kN/m.}$$

2. Determination of hinged gate leaf stresses

(Note: The calculation presented below will refer only to operating condition without allowing for the ice load.)

Basic assumptions

The hinged gate leaf is a continuous girder (over three supports). In calculating the stresses only the forces acting in direction x are taken into account, considering that the forces in direction y buth slightly affect the stresses. The driven end (the cross section fastened to the driven equipment) is assumed to be restrained from torsion.

Assumption of the primary beam system: The structure is hyperstatic with three redundancies.

The primary beam is best assumed by making it discontinuous, inserting hinges above the supports unable to transfer moments and shear but transferring torque undisturbed towards the moving end assumed to be restrained from torsion.

The torque transferred to the moved end (at the end cross-brace) is balanced on the end cross-brace by a moment in the direction of the hoist force and by another moment passing through the end bearing.

Primary beam stresses

Stresses due to external loads:

$$X_M = p_x = p_{\max} = 22.4 \text{ kN/m}$$

$$Y_M = p_y \sim 0$$

Moments (—):

$$M_0 = \frac{22.4 \ 0.4^2}{2} = -1.8 \text{ kN/m}$$

$$M_0 = \frac{22.4 \ 5.1^2}{8} = 72.8 \text{ kN/m}$$

Reactions:

$$A_0 = 0.4 \ 22.4 + \frac{5.1}{2} 22.4 = 66.1 \text{ kN}$$

$$A_1 = \frac{5.1}{2} 22.4 \cdot 2 = 114.2 \text{ kN}$$

$$A_2 = \frac{5.1}{2} 22.4 = 57.1 \text{ kN}$$

Shears:

$$T_0^b = -0.4 \cdot 22.4 = -9.0 \text{ kN}$$

$$T_0^j = -9.0 + 66.1 = 57.1 \text{ kN}$$

$$T_1^b = 57.1 - 5.1 \cdot 2.24 = 57.1 \text{ kN}$$

$$T_1^j = -57.1 + 114.2 = 57.0 \text{ kN}$$

Torque (Fig. 10):

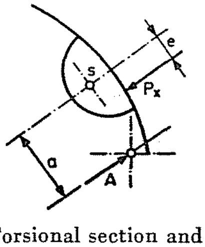

Fig. 10. Torsional section and force

$$M_{cs} = A \cdot a - P_x e$$
$$a = 1.00 \text{ m}$$
$$p_x = 22.4 \text{ kN/m}$$
$$M_0^b cs = p_x l_k e = 22.4 \cdot 0.4 \cdot 0.34 = 3.0 \text{ kNm}$$
$$M_0^j cs = A_0 \cdot a - M_0^b cs = 66.1 - 3.0 = 63.1 \text{ kNm}$$
$$M_1^b cs = M_0^j cs - p_x \cdot l \cdot e = 63.1 - 22.4 \cdot 5.1 = 24.2 \text{ kNm}$$
$$M_1^j \; cs = M_1^b cs - A_1 \cdot a = 24.2 + 114.2 = 138.4 \text{ kNm}$$
$$m_2^b cs = M_1^j cs - p_x \cdot l \cdot e = 22.4 \cdot 5.1 \cdot 0.34 = 99.5 \text{ kNm}$$

Primary beam stresses due to unit moment (1 kNm) arising at supports:

$$A_{10} = \frac{-1}{01} = -0.196 \text{ kN}$$
$$A_{11} = 2 \cdot A_{10} = 0.392 \text{ kN}$$
$$A_{12} = -0.196 \text{ kN}$$
$$M_{1cs} = \frac{a}{1.2} = 0.196 \text{ kNm}.$$

Primary beam loads and stresses due to external unit moments and to those arising at supports are represented in Fig. 11.

Unit and load factors are obtained from work equations:

$$a_{ik} = \int M_i M_k \, dl + \frac{J}{G \cdot J_{cs}} \int M_{ics} M_{kcs} \, dl + \int \frac{EJ}{GF} \int T_i T \, dl \tag{1}$$

where constants calculated from the cross-sectional and strength characteristics of the hinged gate leaves are:

$$\frac{EJ}{GJ_{cs}} = 0.54 ;$$
$$\varrho \frac{EJ}{GF} = 1.35 .$$

The *amplified* value of the unit factor:

$$a_{11} = \frac{5.1}{3} + \frac{5.1}{3} + 0.54 \cdot 1 \frac{1}{5.1} + \frac{1}{5.1} + 1.35 \frac{1}{5.1} + \frac{1}{5.1} = 4.14 .$$

The *amplified* value of the load factor:

$$a_{10} = -\frac{1.8 \cdot 5.1}{2} \frac{1}{3} + \frac{2}{3} 72.8 \cdot 5.1 \frac{1}{2} \cdot 2 + 0.54 \, 1 \frac{63.1 + 24.2}{2} - 1 \frac{138.4 + 99.5}{2} + $$
$$+ 0.4 \cdot 1.35 = 207.6 .$$

The solution of the conditional equation of junction:

$$x_1 \cdot a_{11} = a_{10} = 0$$
$$x_1 \cdot 4.14 - 207.6 = 0 \tag{2}$$

hence

$$x_1 = -50.14 \text{ kNm}.$$

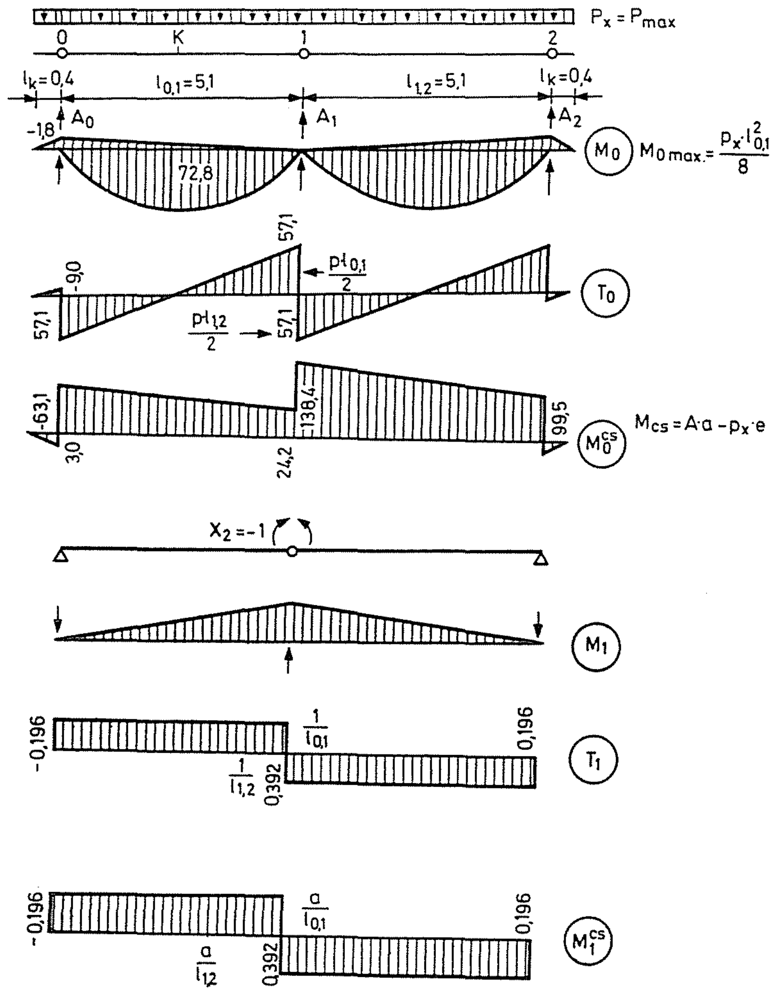

Fig. 11. Load and stress diagrams of the primary beam

Determination of the reactions:

$$A_0' = A_0 + x_1 \cdot A_{10} = 66.1 + 50.14 \cdot 0.196 = 78.1 \text{ kN}$$

$$A_1' = A_1 + x_1 \cdot A_{11} = 114.2 + 50.14 \cdot 0.392 = 134.2 \text{ kN}$$

Stresses in the structure are:

Bending moments:

$$M_1 = x_1 \cdot M_1 = 50.14 \cdot 1 = 50.1 \text{ kNm}$$

$$M_k'^{\max} = M_k + 50.14 = 72.8 + 25.0 = 97.8 \text{ kNm}$$

Shears:

$$T_0^{b\prime} = -9.0 \text{ kN}$$

$$T_0^{j\prime} = -9.0 + 78.1 = 69.1 \text{ kN}$$

$$T_1^{b\prime} = 69.1 - 114.2 = -45.1 \text{ kN}$$

$$T_1^{j\prime} = -45.1 + 134.2 = 89.1 \text{ kN}$$

Torque:

$$M_{0cs}^{b} = 3.0 \text{ kNm}$$

$$M_{0cs}^{j} = 63.1 + 50.14 \cdot 0.196 = 75.1 \text{ kNm}$$

$$M_{1cs}^{b} = 24.7 + 50.14 \cdot 0.196 = 36.2 \text{ kNm}$$

$$M_{1cs}^{j} = 138.4 - 50.14 \cdot 0.196 = 126.4 \text{ kNm}$$

$$M_{2cs}^{b} = 99.5 - 54.14 \cdot 0.196 = 87.5 \text{ kNm}$$

3. Checking the supporting structure, calculation of beam stresses

If cross-sectional and stress characteristics are known, members of the structure have to be designed in the following sequence:

— gate leaf,
— horizontal ribs,
— cross beams,

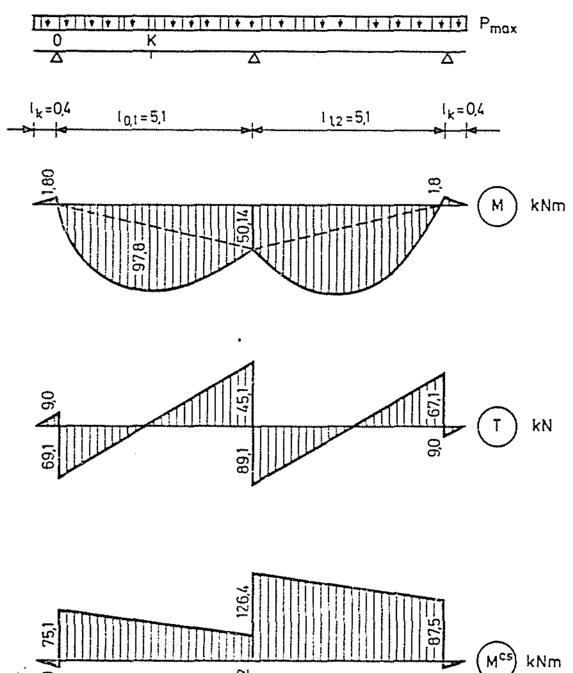

Fig. 12. Load and stress diagrams of the main girder

— fish-bellied main girder (Fig. 12).

— the resultant stress induced in the shutting-off slab has to be demonstrated to be less than the ultimate stress.

4. Calculation of the hoist force (unilateral hoist force)

The hoist force can be calculated from the hinge line moment equation (Fig. 13). Its variation with the gate leaf position is conveniently represented in a diagram (Fig. 14).

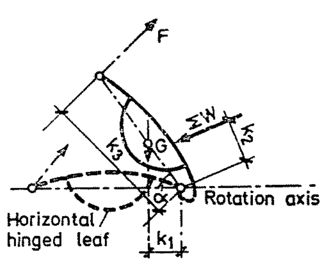

Fig. 13. Calculation of the hoisting force

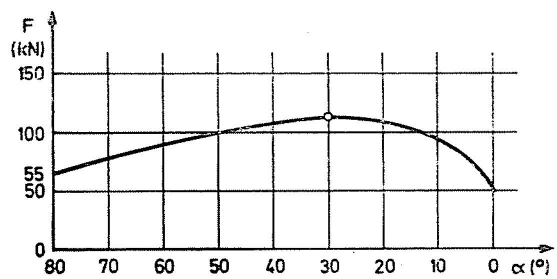

Fig. 14. Hoisting force F *vs.* leaf position

$$M_0 = G \cdot k_1 + M_{pin\ friction} + M_{seal\ friction} + \Sigma W \cdot k_2 - k_3 \cdot F = 0 \qquad (3)$$

where:

ΣW = resultant water load (kN)

G = dead load (kN)

F = hoist force (kN)

α = angle of inclination of the gate leaf, ranging from 80° to 0°.

In the case of $\alpha = 80°$ (upright gate leaf)

(Omitting pin friction and seal friction)

$$M_0 = 1.2k_1 \cdot G + k_2 \cdot W - k_3 \cdot F = 0;$$

$$F = 55 \text{ kN}.$$

In the case of $\alpha = 30°$

$$F = 105 \text{ kN}$$

The hoist force for designing the hoisting device:

$$F_M = 1.25; \qquad F = 131 \text{ kN}.$$

Summary

Dynamic analysis of the main regulating hinged leaf gate suspended at one end and anchored at several points to be built into the 10 m dike opening of the Ipoly river station at section 125 + 200 km is presented. The main girder, of closed fish-belly cross section, is subject to combined bending, torsion and shear because of the one-end suspension. The rather novel design of the main regulation gate especially suits 2—6 m barrages, in particular, those with wide, low dike openings.

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