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Model Techniques for Determining Loads and Responses of Hydraulic Structures

Modèle pour la détermination des charges et du comportement d'ouvrages hydrauliques

Modelle zur Bestimmung von Lasten und Verhalten bei hydraulischen Anlagen

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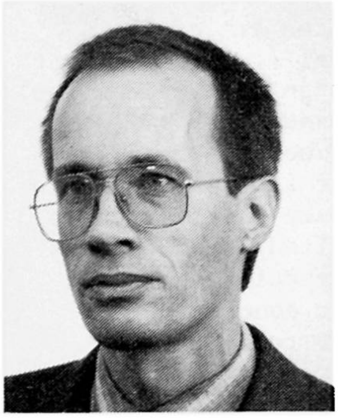

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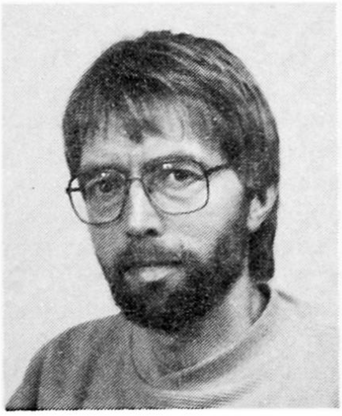
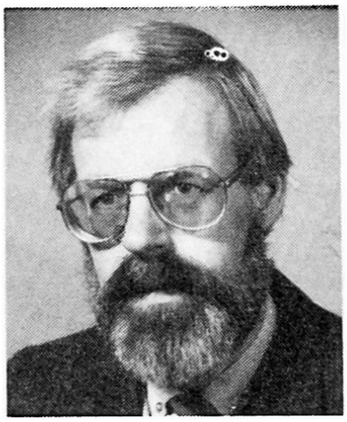


Tom Jongeling, born 1947, received his civil engineering degree at the Technical University Delft. Worked till 1976 at the National Physical Laboratory, since 1977 at Delft Hydraulics and involved in research on gates with special emphasis on mathematical models.



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SUMMARY
This paper outlines the use of scale models and numerical models to investigate the dynamic response and the resulting stresses in hydraulic structures caused by hydrodynamic loads e.g. flow and wave-induced forces. Numerical models provide additional analyzing techniques and it is stated that in the case of complex structures preferably both modelling techniques should be applied in a hybrid approach.

RÉSUMÉ
Cet article présente l'usage des modèles réduits et numériques pour l'étude du comportement dynamique et des tensions qui résultent des forces hydrauliques dues aux courants et vagues – sur les ouvrages. Les modèles numériques offrent des possibilités supplémentaires d'analyse. Dans le cas des ouvrages complexes, les deux techniques sont à utiliser d'une façon complémentaire.

ZUSAMMENFASSUNG
In diesem Artikel ist die Benutzung der Untersuchungen mit Modellen und numerischen Berechungen zu resultierenden Schwingungsformen und Spannungen hydraulischer Kräfte dargestellt. Numerische Berechnungen geben die Möglichkeit zusätzlicher Analysen. Es empfiehlt sich im Fall einer komplizierten hydraulischen Anlage die beiden Techniken zu kombinieren.

1. INTRODUCTION

The range of scale models that can be used in hydraulic engineering was greatly enlarged by the introduction of the elastic similarity models in about 1960. This development was stimulated by the Delta Project and the canalisation of the Rhine in the Netherlands, where large control gates were used. Economic considerations demanded a new approach to design procedures. The application of elastic similarity models in hydraulic engineering had been hampered prior to this by the lack of suitable modelling materials. These materials have to meet special elasticity requirements in addition to low internal damping and linear properties if they are to fulfil the scale laws, which are dictated by free surface flow. In addition the recent availability of computer simulation techniques has resulted in a wider application of dynamic models for hydraulic structures.

2. INVESTIGATION STRATEGY FOR THE DYNAMIC BEHAVIOUR OF THE GATES OF THE OOSTERSCHELDE STORM SURGE BARRIER

Hydraulic loads and the dynamic behaviour of hydraulic structures are often strongly related to the shape of the structure. In a scale model study this might necessitate reshaping of the model in order to improve the design. Vibrations due to feed back phenomena can be dangerous and are not always reproduced satisfactorily using simple dynamic models. Elastic similarity models are a better research tool. However, because modifications to elastic similarity models are cumbersome, these models are usually preceeded by more simple models such as single mass spring models. This investigation strategy was applied for the gates of the Oosterschelde storm surge barrier (Figure 1), but because of the complex fundamental modes and the interaction with the adjacent elastic concrete beams (see Figure 1) the initial, simple, models could not contribute to an understanding of the dynamic behaviour as they normally do. Early in the design process, therefore, the possibility of using elastic similarity models for two gates (with different heights) to finalize the design, rather than to check it had to be considered. The progress made on scale modelling techniques and on numerical modelling techniques made it possible to got for such an approach. The elastic models were therefore designed in such a way that the fundamental mode frequencies (in the vertical and horizontal bending and torsion directions) could be changed without drastic reconstruction of the models (e.g. diagonals were initially fixed by screws). The effects of schematizing details of the model gates could also be predicted by using FEM models of the steel gates and the model gates. In this approach mathematical models of the gates proved to be indispensible and the need for scale models to check the validity of the mathematical models was essential.

3. SCALING TECHNIQUES

3.1 Scaling laws for elastic similarity models of hydraulic structures

Scaling techniques for elastic models of hydraulic structures are described in literature [1,5]. The most important scaling laws are summarized briefly below. Elastic similarity models with free surface flow must reproduce both the Cauchy and Froude numbers and when the length scale of the model is n_L, this produces the following scale factors:

Fluid:

(1) $n_a = n_g = 1$ (a=acceleration; g= gravitational acceleration)

(2) $n_v = n_L^{0.5}$ (v=flow velocity)

(3) $n_t = n_L^{0.5}$ (t=time)

(4) $n_p = n_\rho \cdot n_v^2$ (p=pressure; ρ=specific density)

Elastic structure:

(5) $n_\omega = 1/n_t = n_L^{-0.5}$ (ω=angular frequency)

(6) $n_\varepsilon = n_\sigma / n_E = 1$ (ε=relative deformation, σ=stress) (E=modulus of elasticity)

(7) $n_m = n_\rho . n_L^3$ (m=mass)
(8) $n_\gamma = 1$ (γ =ratio of damping to critical damping)

In general the vibration of a structure in water produces pressure variations on the structure which can be broken down into components which are in phase, out of phase or in opposite phase with the structure displacements. These pressures (or interaction forces) appear as rigidity, damping or mass components in the equation of motion and are referred to as "added terms". In general this effect is always present to some extent.
This means for instance that the scaling law for the mass (7) holds for the total mass, i.e. $m_{struct.} + m_{water}$. In the case of geometrical reproduction the added forces will be reproduced correctly by the water and it is only necessary to pay special attention to the reproduction of the structural mass, rigidity and damping.

The scaling laws given above are used when modelling structures. For instance if $n_E=n_\rho=1$ is selected, it follows that $n_\varepsilon=n_v^2=1$, which means that a geometrical model, which is tested in the same fluid and with the flow velocity values which occur in reality will correctly reproduce deformations of the structure. This, however, is in general not possible in hydraulic models.
Combination of (4) and (6) with n_ρ =1 gives an additional condition:

(9) $n_L/n_E= 1$

In practice there is no material which satisfies all conditions, but often a solution can be found by adapting the material thickness in the model. DELFT HYDRAULICS has gained a considerable amount of experience with Trovidur (R), a kind of PVC, which has low damping and a fairly linear elasticity.

3.2 Oosterschelde models [3,4]

A scale factor n_L = 40 was chosen for the Oosterschelde storm surge barrier scale models. The PVC material has an n_E value of 60, and therefore the plate thicknesses were increased by a factor of 1.5. The low weight of the plastic material was compensated for by attaching concentrated lead blocks to the plates in such a way that moments of inertia were correctly reproduced without significantly influencing the fluid flow.

Since the gate structure had a low torsional stiffness to prevent it from jamming in situ, the retaining plate structure, the vertical support system (trusses) and connections were important details of the design. FEM models of the two model gates were made to facilitate correct schematization of the scale models. Comparison of results obtained with the scale and numerical models led first to a refining of the numerical models and then to an adaptation of the scale models. It was possible to simulate the bending stiffness within a few percent and the torsional stiffness to within 10 percent of the values indicated by the FEM models.

4. USE OF MODELS IN THE DESIGN PROCESS

Important hydraulic phenomena in the design of the gates were vibrations, quasi-static wave loads and above all wave shocks. These wave shocks could easily occur on the plate girders, which were designed on the sea side of the vertical retaining plate, and were thus exposed to sea waves. The research on these wave shocks is discussed in detail below in connection with the use of hydraulic models. Reference should also be made to [2,3,4].
A hybrid investigation program was set up to determine design wave shock loads using:

A) stiff models equipped with pressure transducers to measure local pressures and to enable the type of wave shock to be identified, wich was important in view of the choice of the scaling rules, see Figure 2.

B) elastic similarity models to obtain information about the shock momentum in all fundamental response modes, see Photograph 1.

C) FEM models of the steel gates to investigate the overall response and the local steel stresses due to wave shocks.

The wave shock loads on the steel gates (in a time domain) were deduced from A and B. In order to use the numerical models of the steel gates added mass components had to be incorporated. Because the added mass phenomenon is related to modes of the structure, it could not be simulated as an invariable mass. A computer program, based on potential flow was used to establish the three-dimensional added mass matrix for the gate structure (see Figure 3). The method was already in existence but had not been used for thin walled structures with water on both sides of the gate. In this case the scale model results could be used to check the validity of the added mass computer program. The response of the gate to wave shocks could then be computed in various vibration modes, see Figure 4.

The study enabled two concepts to be compared for the main support system of the gates: one with easy to manufacture flat steel plates but inviting heavy shock loads, and therefore needing too heavy gates (see Figure 1), the second with truss girders but with greatly reduced shock loads (see Figure 5). Because of this aspect the girder design with a truss on the seaward side was chosen.

5. CONCLUDING REMARKS

- Elastic similarity models can be used as a final check on the dynamic behaviour of slender or thin-plated hydraulic structures. If stiff models are used to obtain information about local pressures caused by wave shocks, elastic similarity models can be used to measure the shock momentum on the main support system.

- FEM models can be used to analyse the local dynamic stresses which result from hydraulic shock loads and with these models the design of complicated hydraulic elastic similarity models can be refined. Results of scale models can also be understood more easily by analysing vibration modes with FEM calculations. Comparison with scale model tests may be necessary in order to refine FEM models of complicated structures.

- Fluid-structure interaction effects should be incorporated into numerical models. DELFT HYDRAULICS is collaborating with the National Physical Laboratory (TNO) in the implementation of a fluid module in the FEM DIANA package, which will enable a full dynamic analysis to be made of structures including interaction effects.

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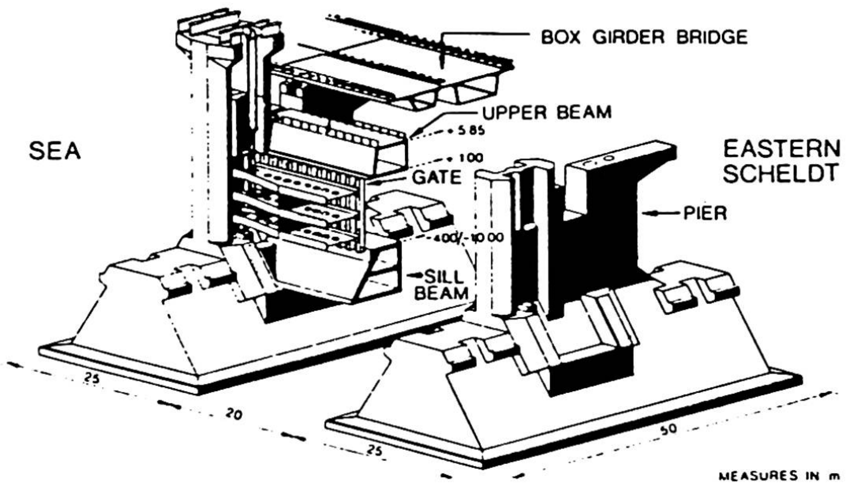


Figure 1

Elements of the Oosterschelde Storm surge barrier. In three channels 66 piers, forming 63 apertures, have been placed on 45 m center to center line distances.

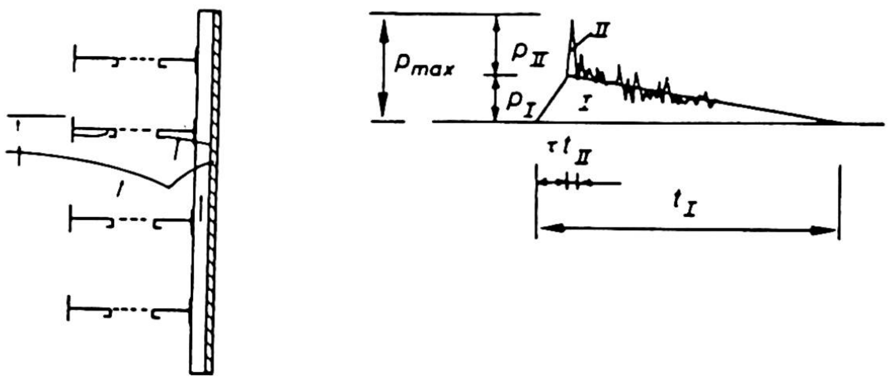


Figure 2

Wave impact and schematization as decided with the scale model studies.

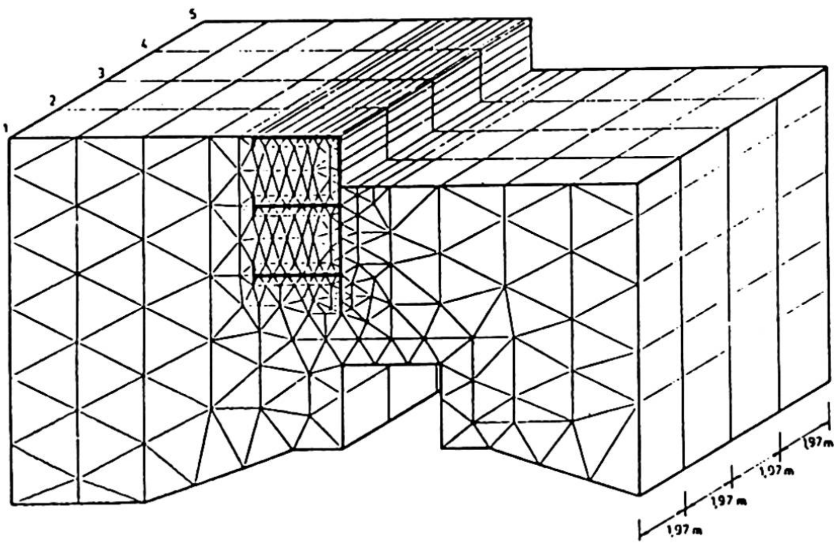


Figure 3

Four segment FEM model for computing the added mass mabrix of a gate with plate girders.

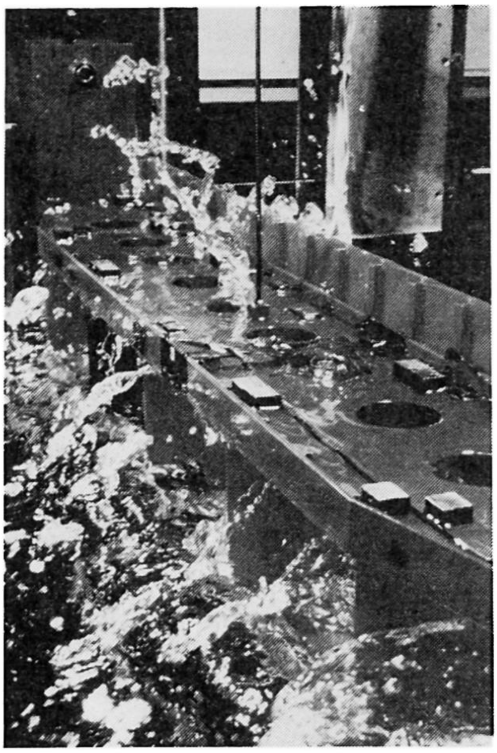


Photo 1

Wave impact of the elastic scale model

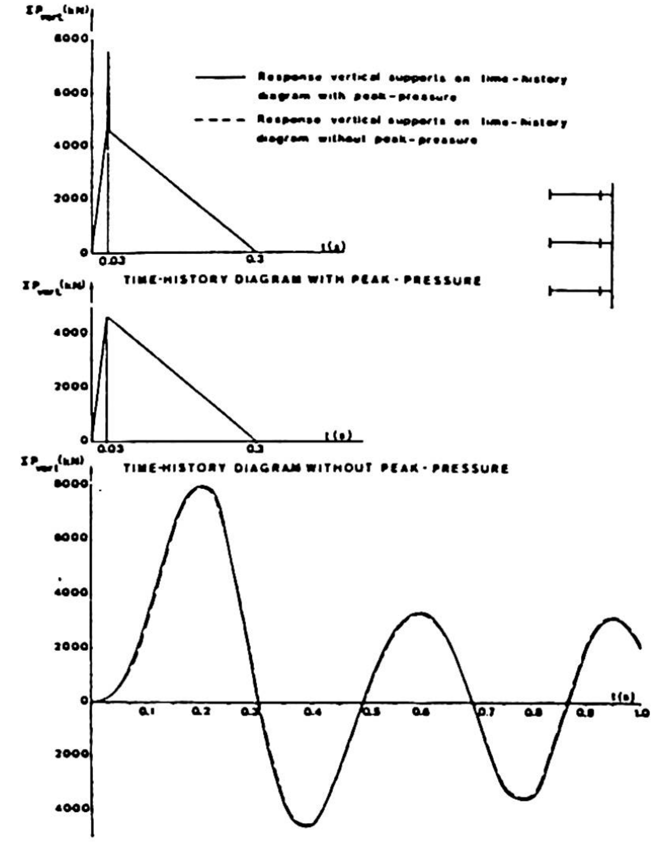
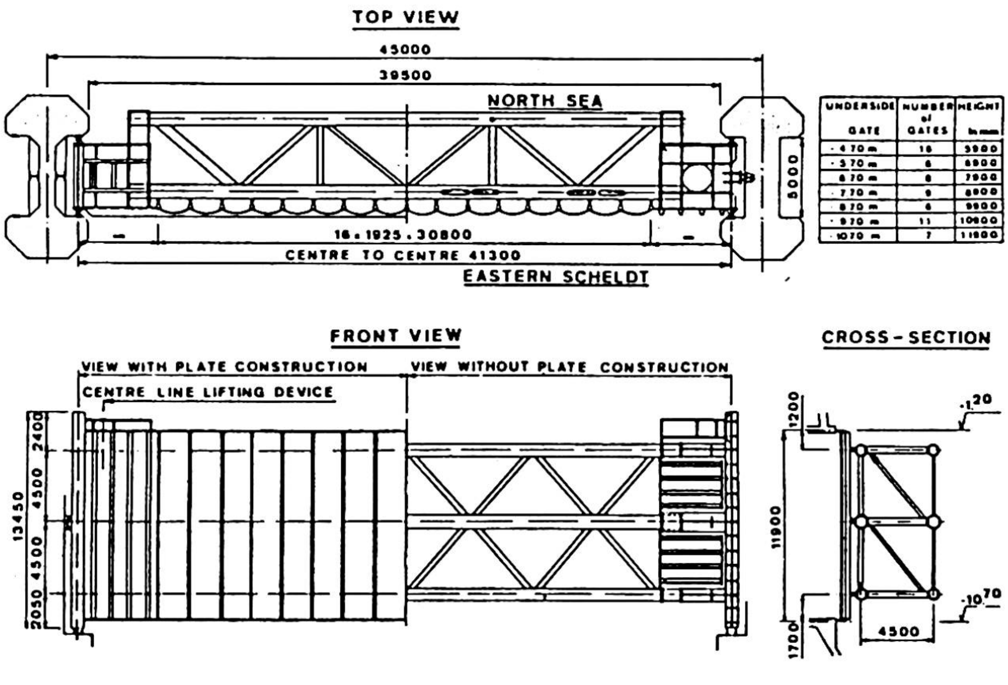


Figure 4

Response vertical supports (loading and response for a half FEM model).

Figure 5

Construction of gates



UNDERSIDE GATE	NUMBER of GATES	HEIGHT in mm
- 4.70 m	16	5900
- 5.70 m	6	6900
- 6.70 m	8	7900
- 7.70 m	8	8900
- 8.70 m	6	9900
- 9.70 m	11	10900
- 10.70 m	7	11900