The impetus that was given by the great endeavour for civil engineering works in the Netherlands in the time between the two world wars resulted also in the establishment of the Delft Hydraulics Laboratory.

At that time the hydraulic model as a tool in design had already proved its usefulness in various countries of Europe. Thus the general development in scope and size of the works to be designed was necessarily coupled with the development of scientific means, among which hydraulics got its workshop, viz. the laboratory.

This type of laboratory may primarily be looked upon as the place where the pure science of fluid mechanics and physics is adapted to engineering needs.

These needs, however, are always ahead of what science offers and is understood by engineers; moreover, there exists a difference in character (and perhaps also in alertness) between the scientific and the engineering approach to problems, so that this difference has to be bridged.

In engineering practice lack of basic understanding of natural processes is many times compensated by means of the more or less condensed experience in the past. The slow process of gaining experience does not meet the present-day requirements of the technique so that also this process has to be speeded up.
The position between science and technique is common for many laboratories in the world. The well-developed international exchange of knowledge and experience gives the opportunity to profit from the results of research of one another, so that differences between the laboratories arise mainly from the kind of problems submitted for solution.

The main task of a hydraulic laboratory, established for practical purposes, lies in the adaptation of the existing achievements of science to the requirements of engineering and to build up a completeness by means of theoretical and experimental research as far as a sound scientific background of engineering requires.

Where basic knowledge fails the laboratory has to provide the means of gaining experience in a short time.

In the Netherlands the task is also accomplished in connection with the graduate and post-graduate engineering education; the main emphasis remains on the consultative aspect in connection with the hydraulics in projects typical for the country.

These projects range from the largest for land reclamation, coastal protection and structures for inland and seagoing navigation to the smallest for industrial and domestic water circulation. Wherever hydraulic problems may be expected as such, or in connection with questions of material transport, constant or transient loads on structures, the hydraulics laboratory has a task. Of course, in special cases which involve also problems of another kind than those arising in hydrodynamics, co-operation is arranged with institutes specialized in the pertaining fields.

The task already mentioned covers the field around the established technique of solving problems by means of scale models. As these models can never be designed, or give results, without an understanding of the dynamic background, the results of research in any branch of fluid mechanics is of importance.

In addition to the broad field of experience already gained in hydraulics itself, the mostly experimental knowledge in the heterogeneous collection of phenomena called turbulence is also available. Hydraulics thus profits from the achievements of aerodynamics and in some case, use is even made of airflow as analogous to the flow of water.

The main reason why the insight into the details of the flow structure
was mainly attained in aerodynamics lies in the great difficulties of constructing the necessary equipment for the instantaneous measurement of the spatially fluctuating velocities of flow in water. The counterpart of the hot wire anemometer is not yet available for routine measurements. Only the small propellor type current meter has been developed to such an extent that some aspects of turbulence in water can be analysed. But because of the dimension of the instrument, details of the structure still escape the observations. A great drawback in the study of internal details of flow in water is that other means of observation, e.g., visual and photographic, are too time-consuming for practical purposes.

Together with the achievements in aerodynamics the great advances in electronics are useful for hydraulics. Beside the present possibilities of constructing pickups for water level variations, pressure fluctuations, etc., the recording of observations in a reproduceable form is available so that the performing of one or another type of analysis of observations can be facilitated by means of computers or electronic devices.

The general outcome of the improvements in instrumentation is not that the experiments give results quicker than before but, on the contrary, require more time and attention. This seemingly paradoxal trend in hydraulic experimentation can be considered as an advance. The investigator can draw more and more information from the model and gets more and more insight into the possibilities and limitation of his experiments.

Experiments, where turbulence is the object of observation in its context with scour of stream beds or vibrations of structures, can only in rare cases be carried out by means of two dimensional models. The turbulence in its dynamical properties being essentially three dimensional is wrongly influenced by guiding walls existing in models and not in prototype. The distortion of the dynamical effects by walls in the model thus make conclusions drawn from such experiments unreliable. This fact was already known to experienced investigators before the measuring equipment for turbulence measurements was available, but now it gradually becomes possible to provide for the criteria to determine how far a model can be reduced and schematized.

The same holds good for the design of models in which, beside the turbulence, the patterns of secondary flow have an accumulative ef-
fect, in the course of time, on the bottom configuration in loose beds. The growing of understanding of the dynamics of these flow phenomena may be seen as a synthesis between experience in hydraulics and analyses of the dynamical relationships in boundary layers and wakes in fluid mechanics. Also here the limitations of the possible simplification of models become visible.

In the multiphase flows (grains of solid material or air bubbles in water) the investigation in hydraulics has to provide many of its own means and methods for analysis. The most difficult and most frequently encountered problem is the determination of sediment transportation in natural streams. The inhomogeneity and anisotropy of the moving mixtures pose problems in analysis which require special ways of attack. The available measuring instruments give only a general picture of the correlation of the stream characteristics and the amount of sediments transported. Because of the stochastic element in transport too many accurate observations, both in time and in location, are required. New methods of measurements, e.g., by means of coloured or radioactive tracers, require extensive research on techniques of application and interpretation of results.

Evidence has already been obtained that the empirical relationships between sediment load and flow characteristics are valid only in permanencies. Even slow fluctuations in flow, as almost always encountered in nature, are followed by the load of transported material with a non-negligible timelag. Although this problem is one of the oldest in hydraulic engineering, it cannot be considered as even approximately solved.

Of similar nature is the problem of local scour. As the time scale of the models in which the scour is reproduced is of importance for big projects, continued research is indispensable on its mechanism in connection with the perpetually changing flow characteristics with the details of turbulence and secondary currents.

This trend in hydraulic research to paying attention to the details has had its influence on the general set-up of models. Not only the choice of the scales but also of the location of both the up and downstream limits is made on gradually improving grounds.

The initial turbulence, for example, in wind tunnels, already well discerned as a disturbing factor in the proper interpretation of the measure-
ments, appears also in the hydraulics of turbulent agitation of structures and in experiments on local scour as a recognized disturbing factor.

Also the technique of using models of currents with density stratification requires a critical hydrodynamic analysis. The numerous problems connected with the intrusion of salt water in the Netherlands, both as a nuisance for agriculture and as one of the agents in silt deposition in harbours, led to a programme for the improvement of the model technique in which the density stratification is reproduced.

Both silt suspensions and actual salt solutions were used to simulate sea water. The former, being better tractable as a fluid in the model, had the great disadvantage that measurements of densities during the experiments by means of simple devices appeared to be cumbersome. Because of the necessity of many measurements, the salt solution is up till now the best means of reproducing the sea water.

For experiments with equal importance on the dynamics due to density stratification and the mixing process, a systematic research on the two interconnected aspects has been set up in order to determine the admissible range of scales for models.

In the study of current patterns near harbour entrances and in cooling-water circuits, of hawser forces in locks and of discharge coefficients the remarkable differences in the results obtained with homogeneous water and density difference were sufficient reason for a perfection of this model technique.

The experiments with both density stratification and transport of solid materials are still too cumbersome for routine purposes.

The items of research mentioned so far concern mainly the scale and boundary effects to be avoided or correctly estimated. Another point of interest is the proper reproduction of the circumstances in nature, including the effect of statistical variations.

In the design of structures exposed to wave attack it is already a traditional practice to simulate in the models the stochastic element of wind-generated waves because in most cases the estimate of risks in extreme circumstances is decisive for the final design.

Beside the aid received from meteorology and oceanography in the statis-
tics of occurrence of storms in strength, direction and fetch in combination with the phases of the tides, a detailed analysis of the waves is necessary.

The well-developed mathematical theory on the statistics of time series is widely used for the analysis of wave observations. Unfortunately the underlying hypotheses of statistical random processes and of ergodic properties show some lacunae which make estimates of risks in the extremes doubtful. Herein lies the necessary field of research concerning the hydrodynamic limits in waves of extreme magnitude and the evaluation of the elements of sequences and coincidences that are important for design.

The requirement of proper reproduction in the models of waves of the total variations of circumstances is again a stimulus for the improvement of the technique of observations in nature. As the statistical and dynamic evaluations require not only accurate observations but also observations covering sufficient intervals of time, the amount of material to be collected requires a well-organized system for the deduction of the characterising parameters.

Thus the present research on waves includes the techniques of observation, the basic mathematical theories and the numerical treatment in computers. This research going beyond the limitations of hydraulics is carried out thanks to the collaboration with mathematicians, designers of instruments and the services in charge with the observations in nature.

The main task of the laboratory remains the study of the possible mechanism of destruction and to provide quantitatively the loads of impact on structures, with the incoming wave being well reproduced.

Apart from the interests for research on structure design, knowledge of the regime of waves combined with current is the starting-point in investigations on the penetration of waves in harbours. Experiments with harbours are, moreover, used to study the layout of the entrance on the possible dangers for navigation under extreme circumstances.

In this aspect ship model technique and hydraulic design go together. The avoiding of possible scale effects in the steering devices of ship models, however, requires bigger models than is needed for pure hydraulic engineering, so that the trend in this model technique points toward special facilities.

It is self-evident that these model techniques, backed by the knowledge of waves and currents, are apt for the solution of special problems such
as loading and unloading in the open sea and for structures for construction and exploration work.

The use of mathematics and computers has already been mentioned as an indispensable aid. The rapid developments in this field give reason to investigate whether some hydraulic problems solved hitherto only by means of models can be solved entirely or partially by means of computer techniques. Unsteady flow in networks of canals and flow in two horizontal dimensions under the influence of the topography are already, in theory, fit for treatment in computers. It is only a matter of the training of the programmers and the availability of computers. The use of computers is already normal practice in statistical and analytical evaluation of data and the design of models with movable bed according to the optimal set of scales for dimensions and current velocities combined with the choice of material for the bed in the model.

In addition to the primary aim of proper hydraulic design the element of hydrodynamical research may be discerned in the foregoing remarks. An important group of investigations by means of models, however, is possible only with the elements of basic knowledge at hand, viz., the models used for the study of processes of formation of shores, estuaries and river beds. The complex of the circumstances in which these formations develop must be simulated schematically in order to know the course of the processes and to study the possibilities and the effects in the long run, of human interference by means of structures or dredging operations. A simulation of the varying circumstances of waves, tidal currents and river discharges in every detail is impracticable, moreover, as the hydrodynamics of simultaneous action of the many agents is only approximately known, in many cases the only means of obtaining models which reproduce on the average the processes in nature, is the reproduction of that part of the process known from successive hydrographic maps, completed with estimates of the relative importance of currents and waves. As the time scale of these processes has only a remote connection with the hydrodynamic time scale, the possible schematization of the variations in circumstances has to be sought by sound judgment. Once such a model works properly, it provides a means of gaining experience in a relatively short time with the various designs to be investigated.
The items of research mentioned in this outline have been chosen to demonstrate the technique of using models considered as a necessary supplement to the theoretical approach to the problems. Many see models as a kind of a complicated analogue computer, and want to have these computers as reliable as possible. The efforts of research thus become merely an effort to create better and more powerful computers.

In one aspect the hydraulic model has, indeed, something in common with a computer in the ordinary sense of the word: bad operation, poor programming and unreliable data can never give reliable results. For the hydraulic engineer, however, the model is just as real as the objects of his design: the efforts of research to improve the operation of models is for him basically the same as the improvement of his understanding of hydrodynamics.

INSTRUMENTAL AIDS FOR HYDRAULIC MODEL STUDIES

BY IR. J. V. D. WEL

Introduction

Since the start of the laboratory there has been a need for a variety of instruments for the measurement of several quantities, such as wave heights, water levels, velocities etc. At first the instruments were very simple, but when the need arose for greater reliability and accuracy and the possibility of recording the signals, better instruments and methods were developed or are in development. For example, the wave height metering started with the measurement of the water level with a scale. The next method used was a floating ping-pong ball with a needle which scratched the wave height on a blacked glass plate which was moved along the needle along a horizontal line. The improvements in the electronic measuring techniques then made it possible to design an electronic instrument which measures the variations in the electrical resistance between two parallel stretched wires. Nowadays, when sometimes two or more wave height meters are used simultaneously for the measurement
of correlation functions, it seems that this method again needs some improvement in order to get better stability in calibration and linearity. The development of new instruments, data handling systems and control systems design is done by the Instrumentation Department of the Laboratory which has gradually come into being and which is still expanding. To avoid an accumulation of developments in the Department some of them are put out to contractors, while at other times it is possible to work in co-operation with a contractor who develops that part of an instrument in the design of which he is an expert.

Birds-eye view of Control Systems and Instruments
Several specially-designed tidal control systems are in use now in the Laboratory. The simple ones are controlled by a feeler and a cam on which the tidal curve is cut, whilst the more complicated ones are multi-point control systems which are programmed by plug boards or punched tape. Special care had to be taken in order to avoid instability or interacting of the control systems. Especially in the Delta model instability of the control systems is difficult to be avoided completely in some situations. For the measurement and recording of water levels, velocities and discharges in open water flows in tidal models special instruments have been designed. The possibilities of speeding up the data handling of measurements in tidal models are now being studied.

For the measurements of wave heights the above-mentioned wave height-meter is used while an analyser for the automatic analysis of the amplitude distribution function with neglect of the small waves has just been developed.

For the measurement of waves in situ on a lake capacitive-type transducers have been developed for the evaluating of correlation functions, the wave heights being recorded on a multi-channel magnetic tape recorder. The measurements of sea waves can be done by an Ospos wave meter which measures the pressure fluctuations, caused by the wave motion, as close to the surface as possible. The signal is recorded in the instrument.

A contractor is developing a floating wave height meter for the measurement of sea wave heights. The floating buoy which is smoothly anchored contains an acceleration meter which detects only the vertical accelerations. This signal is converted in an FM signal, modulated on a carrier
Photo 1  Propeller current meter
radio wave and broadcast to the shore where it will be put on punched tape. The first item is under test now.

Velocity measurements are made by a propeller current meter with a diameter of 15 mm (see PHOTO 1). Because the meter is specially designed for the measurement of turbulent velocities, as many electrical impulses as possible have to be generated by the meter. This is done by a small ring with 60 holes mounted on the circumference of the propeller and two electrodes mounted in the holder, and giving signals with a 90° phase shift, recorded on magnetic tape. With these signals detection of the direction of rotation is possible. A special apparatus has been designed for evaluating the standard deviation of the turbulent fluctuations of the velocity.

For the measurement of velocity and direction of the current near the bottom under heavy conditions (sand in suspension) in situ, a current meter with a cuprotor and a vane has been constructed (see PHOTO 2).
The rotation of the rotor and the vane is coupled magnetically to a lamp and photo cell device and a low torque potentiometer. The instrument can be mounted on a support which is placed on the sea bottom. A pressure sensitive device is mounted in the underside of the instrument for the measurement of pressure fluctuations near the bottom. The signals are fed to a floating buoy with a modulator and a transmitter which broadcasts the signal to the shore.

For the study of the mixing process at the interface between salt and fresh water, a conductivity probe has been designed with a short response period (3 m/sec). The water of which the salinity must be measured is sucked by a siphon through a tube with an inner diameter of 0.5 mm and a length of 5 mm. The conductivity of the volume of this tube is measured with a conductivity meter. Due to the high velocity of the water in the tube (1.5 m/sec) the time of response is very short. For the measurement of salinity distributions the probe is moved up and down at a constant speed of 5 cm/sec, a speed at which the time lag is still acceptable.

INVESTIGATIONS ON STRUCTURES FOR FLOW CONTROL
BY IR. J. E. PRINS

In the design of structures for flow control two major aspects stand out: the structure must withstand the hydraulic forces, and the hydraulic effects on the surroundings must not interfere with the proper operation or stability of the structure.

In the hydraulic research much attention has been given from the very beginning to these aspects, viz., the determination of pressure distributions and total forces on gates or valves, and the study on downstream scour or culvert abrasion.

Both subjects are very complex.

First of all, the structures are very diverse in type (gates with underflow and overflow, submerged gates, high and low head valves, free surface and closed conduit systems) and the capacities vary widely in absolute values and in the range of operation.
Secondly, there is not a straightforward approach in relating the hydraulic conditions to the dynamic loads, nor to the scour or abrasion.

In considering the model investigations for the determination of the forces on gates and such-like, technical limitations have for a long time restricted the results to average values, leaving undefined the magnitude of vibrations in the prototype. Later on sensitive pressure pick-ups were able to give recordings of the pressure fluctuations along the periphery of the gate due to turbulence. Although this provided qualitative data enabling comparative studies, the interaction between turbulence and gate movements, i.e., vibrations, could not be predicted. Finally, the technique developed in the hydraulic research sector during the last decade, of constructing the model of the gate geometrically and elastically similar to the prototype structure according to Froude Law, has largely solved the problem, but still raises questions on the effects of scaling down the turbulence and the reproduction of damping.

Looking into the studies of scour and abrasion, generally the interpretation of the model results mainly relies on empiricism. For the process of scouring, the principal question is the ultimate state of the erosion. It has been established that average velocity, intensity of turbulence and applied bed material are important factors as to the form and development of the scour hole, and that due to the effect of vortices in the zone of separation of the main flow and the side eddies a three-dimensional model is indispensable. Fundamental research carried out in the last few years has refined the empirical approach in many respects; nevertheless, the urgent necessity remains to pursue a physically sound mathematical description of the scouring process using determinative parameters for the flow and the bed material. This will by no means replace model investigations, but will provide a basis for justified scale deduction and interpretation of the results.

In view of the far-reaching possibilities emanating from the use of dynamically similar models, this technique will be given further consideration later. The aspect of the local scour will be discussed more extensively in another contribution to this all-round review.

In its most simple form the dynamic behaviour of a gate structure can be considered as a mass-spring system, the gate and added water being
the mass and the lifting device being the spring. Assuming that the gate is exposed to flowing water, it will react on the exerted forces. When the model is dimensioned according to Froude Law, which is the practice in free surface problems, the mass-spring system in the model is bound to the following conditions:

- the mass of the gate has to be reduced by the length scale to the third power ($n_1^3$), and
- the natural frequency of the system has to be reduced inversely proportional to the square root of the length scale ($n_1^{-1/2}$).

The first condition satisfies the need for equal reduction of the mass of the gate and the virtual mass of water playing a part in the dynamics of the system. The second condition takes care of a similar location of the natural frequency of the system in the range of frequencies of the exciting forces in the flowing water. The conditions together lead to equal relative deflections for the prototype and the model.

For the exact prediction of the prototype movement from the model still two other factors are determinative, i.e., the reproduction of damping and turbulence.

The damping is a most troublesome matter, because rather undefined magnitudes are often introduced in the form of seals and guides or bearings of the lifting device. The magnitude of the internal damping of the prototype structure is generally very small, in contrast with the value obtained in the model. Moreover, the damping of the system by the surrounding water due to viscosity effects and surface waves is, for an otherwise freely suspended system, determinative in itself. On the latter factors experiments on scale effects have been carried out, but up to now no conclusive results have been obtained. On theoretical grounds the model may give too large a damping.

The reproduction of the frequency spectrum of the turbulence has in general been found satisfactory. The loss of the very high frequencies in the spectrum cannot be of any significance. What is important is the way of generation of the frequencies for which the structure shows resonance tendencies. In many cases violent vibrations are due to the interaction between the gate movement and the pulsating forces, imposing on the pulsation the natural frequency of the system (feed-back). For the low frequency range, i.e., macro-turbulence, viscosity effects and exactness of the model will be of minor importance; for the higher frequencies, how-
Examples of recordings of the vibration of the model of a sluice gate treated as a simple mass-spring system. Mass $34 \times 10^2$ kg. Spring constant $55 \times 10^6$ N/m. Natural frequency in dry 6.4 Hz.

a. Record with discharge of $0.7 \text{ m}^3/\text{secm}$ and waves that overtop the gate. Elevation of gate 0.06 m.
b. Record with discharge of $2.7 \text{ m}^3/\text{secm}$. No waves. Elevation of gate 0.50 m.

Examples of recordings of the vibration of the vizor-gate at Hagestein. Operational conditions: Elevation of gate in middle 1.10 m; water level upstream N.A.P. + 2.3 m, downstream N.A.P. + 0.7 m. Mass of gate approx. $200 \times 10^9$ kg.

a. Record of prototype, measured at point of suspension in horizontal direction perpendicular to the main flow direction. The record shows a voluntary movement of the gate, which by times is accompanied by two natural frequencies both due to flexural deformation (0.5 and 0.8 Hz). At this direction and location torsional deformation is nearly not noticeable.
b. Record of model, measured horizontally in radial direction in the middle of the upper side of the gate. The record shows a voluntary movement of the gate, which by times is accompanied by two natural frequencies, one due to flexural deformation (0.8 Hz) and one due to torsional deformation (1.2 Hz.). At this direction and location the flexural deformation with natural frequency of 0.5 Hz. is not noticeable.
Photo 3 Elastically similar model of the gates and supporting beam of Haringvliet Sluice. Scale of model $n_1 = 20$. The model is provided with strain gauges

Photo 4 Elastically similar model of the vizor-gate at Hagestein. Scale $n_1 = 20$. 
Photo 5  Water waves generated by plate vibrations during artificial excitation of the vizor-gate at Hagestein
ever, which are likely to be bound to small-sized parts of the structure, viscosity effects or a geometrically inaccurate reproduction of the part in question can suppress or prevent the spontaneous reaction of the system. It is evident, in view of this, that also the initial turbulence upstream of the gate requires an exact reproduction.

The simple mass-spring system as described above no longer suffices when the gate itself is subject to flexural and torsional vibrations, or when the construction is such that important parts may get in resonance by the pulsating forces of the flowing water. In this case, elastical similarity of the structure itself and the parts in question is required.

Next to the two conditions for the reduction of mass \( n_1^3 \) and natural frequency \( n_1^{(\ell/2)} \), now related to any natural frequency, axial, flexural and torsional, a third condition is necessary, holding that the mass has to be distributed correctly in view of the axial, flexural and torsional vibration characteristics.

Modern materials have facilitated the realization of the technique of elastically similar models. By the use of the hardened polyvinylchloride "trovidur", which has the practical advantage that it can be welded, the above given conditions for the model can be met at length scales \( n_1 > 11 \). The condition for the time scale of the natural frequency for the axial vibration gives \( n_E = n_1 \cdot n_0 \), in which \( n_E = E_{\text{steel}} / E_{\text{trovidur}} \approx 60 \) (\( E \) is modulus of elasticity), where \( n_1 \) can be chosen with the restriction that \( n_0 \leq 5.6 \), since \( E_{\text{steel}} / E_{\text{trovidur}} = 5.6 \) (\( E \) is density).

When \( n_0 < 5.6 \) – which is common practice as \( n_1 \) is generally larger than 11 – additional mass has to be introduced to the trovidur mass already present. This can be done locally under maintenance of the proper distribution as to the correct mass polar moment of inertia. Scale consideration also shows that the trovidur is strong enough to compete with prototype \((n_0 = n_E)\).

In cases where the study includes also the supporting structure of the gate, the elastical properties of this structure have to be reproduced as well. As the forces are those of the water, transmitted through the gate, the mass and natural frequencies of this structure again have to be reduced according to Froude Law. When reproducing a concrete structure with trovidur the length scale is bound to \( n_1 < 7 \), which does not conflict with the existing condition for the reproduction of the steel structure \((n_1 > 11)\).
When the assembly of the gate and its supporting structure is elastically similarly reproduced, the full response of this system to externally imposed loads can be detected. In this respect it may be of interest to recall that for models of this kind the unit elongation in a point of the model is equal to that in the same point of the prototype, i.e., with a straingauge exactly the same intensity of the signal is measured in model and prototype.

In the foregoing the erratically pulsating forces by the flowing water – at random excitation – have been taken to illustrate the need for a full dynamic performance of the model. A method to calculate from these pressure fluctuations the behaviour of the system, viz., the forced and resonance oscillations, is not feasible in hydrodynamics, since the repercussion of the gate movement on the nature of excitation is unpredictable: it may cause a change from a random excitation to a clear frequency-bound excitation!

There is another phenomenon asking for the use of elastical similarity, i.e., the response of a structure to impact forces of hydrodynamical origin. In this case calculation can be carried through only when the impact force can be actually handled for mathematical operation. For the cases thought of here, namely, impact forces caused by surface waves, this is hardly possible and a hydraulic model is needed. This is all the more true because the practical cases are those with wind waves, and the approach should be made statistically.

Summarizing, it can be said that the use of models with geometrical and dynamical similarity enables the designer to judge the ability of his design and provides the hydraulic engineer with a tool to approach the problems of vibrations and impact loads in a most extensive way. At the same time, it puts on the hydraulic engineer the responsibility of not applying a refined model technique without verifying the exactness of the hydraulic conditions to be fed into the model and the exactness of the interpretation that can be given to the results.
The development of river models during the past few decades is closely related to two important factors: on the one hand, the theoretical and the experimental building up of transport equations for sand by currents, and, on the other hand, the technique for measuring the transported quantities of sand in nature. It is clear that the stage of the river models will always lag behind the results in those two fields. In fact, the measuring technique in nature is the determining factor.

Work on these three important factors in river-hydraulics-transport-formulae, transport instruments and transport models can be traced back in the history of the Laboratory. Of course, the work in these fields is closely related, and the solutions of practical problems at any time have to be based on the best knowledge available at that very moment. At present, there are still many questions waiting to be answered in order to obtain a better insight into the phenomena and greater accuracy in predictions.

Many river models have been built for the Rijkswaterstaat, and transport instruments have been developed in close co-operation with its special services.

The measurement of suspended load, rather simply compared with that of bed load, could be effected by the construction of the “Delft-Bottle”. The transport of sand close to the bed surface is difficult to measure with instruments. In the 1930's the “B.T.M. Arnhem” was developed and calibrated in Zürich. The later calibration some years ago, when the large high-discharge-flume of the de Voorst Laboratory was available, showed fair agreement with the Zürich data. The spread in the measurements, however, is still large, partly due to the phenomenon and partly due to this type of instrument of the basket type. New developments are under way to overcome the difficulties of the “B.T.M. Arnhem” and to study the statistics of the variations with time of the local bed load in order to get the optimal result in accuracy for the instruments.

The measurements of sand-transport with radioactive, and fluorescent tracers might be of great help. But it is clear that much work on the quantitative interpretation of these investigations will have to be done.
before answers along this quite different line can be obtained for the transport of sand in rivers. Those tracer techniques have already been carried out in the Netherlands for the coastal waters where the influence of tides and waves makes the transport problem much more complicated. Tracer experiments with a special view to quantitative results for rivers are under way.

The development of bed load formulae is being carried out by a great many investigators in different countries. The large number of formulae is already an indication about the small accuracy of sand transport calculations. In this connection, the work of FRIJLINK can be mentioned. By comparing the formulae of MEYER-PETER and MÜLLER with that of EINSTEIN and KALINSKE, he found that these formulae had basically the same form and that the differences were small compared with the measuring data. The difficult coupling of water-motion and sand transport by the bed roughness was part of the Laboratory research. Recently the non-steady character of the phenomenon in nature became a subject for theoretical and experimental studies. Similar to the flow on a fixed bed, where backwater-curves were studied even though roughness formulae still have small accuracy because of their nature, non-steady sand-motion is also being studied, although there are still many questions about the steady conditions.

The river models show the development of the measuring technique and the description of the transport formulae. The attitude remained the same: a mobile-bed model can never be used as a computer but only as a tool for the engineer to take conclusions out of tendencies noticed in prototype and model. The scale-rules were developed on “flow-parameter” and “transport-parameter” as soon it was noticed that the scales of water velocity and bed material had to be chosen in such a way that the transport scale was independent of time and place in the model. Gradually the concept of the “ideal velocity scale” was developed and up to now this basic concept has remained the same, although refinements due to the growing knowledge of the phenomenon have been made. Recently the determination of the optimal model-scales has led to a programme for a digital computer. It is clear that this does not give a solution for physical questions, but the method can be used to determine
the scales in such a way that experimental corrections during calibration tests can easily be carried out.

A special chapter is formed by the problems which are studied by river models. Mostly these are concerned with the demands of navigation. Wide entrances to river harbours, canals and locks ask for special arrangements in order to give enough guidance to the main stream. In different cases egg-shaped entrances were constructed to guide the main stream by the eddy in the entrance. The crossing of the Amsterdam-Rhine Canal and the River Lek got one “egg” on both sides, and special attention was given to the construction so as to get in the river at the crossing the same depth of water as in the canal, which was more than the depth in the undisturbed river.

Suitably constructed screens at the entrances make it possible to diminish the sanding-up of the entrance. This principle was carried out for different entrances.

A large group of river studies is connected with the canalization of the Lower Rhine. The bifurcation of the Rhine near Pannerden was studied in the Delft Laboratory and the bifurcation at Westervoort is under study in the De Voorst Laboratory. The difficulty of those bifurcation studies is that a compromise for the model scales has to be made as three different rivers, each with its own characteristics, have to be simulated by the model. The latter case forms a special study due to the combined use of a computer and a mobile-bed model.

A step-by-step procedure with a hydraulic model and a computer is used for the following reason. The artificial changes in the water distribution at the bifurcation will influence the bed of the three branches over a large distance. But the length of a river which can be simulated in any mobile-bed model is restricted. The influence of the river-bed outside the model area is taken into account in this case via the calculated boundary conditions of the model.

In addition to those studies of bifurcations several model investigations were carried out of parts of the River Rhine where new movable weirs have to be built. Again navigation was here the determining factor.

In regard to the scales of the river models, the following trend can be observed. The first river models were relatively small, having large scale-factors for the length. Later on, when the De Voorst open-air laboratory was established larger models could be constructed as more space was
available. Therefore more detail-information about phenomena could be obtained. The modern trend is that the scale-factors can become still larger, leading to smaller models with larger time-scales in order to obtain the model results quicker. The difference from the original models of some decades ago is that the experience and the knowledge obtained has led to the situation that nowadays much more detailed problems can be investigated and more accurate predictions can be made.

MODEL INVESTIGATIONS ON LOCAL SCOUR
by Ir. A. Paape

The application of movable bed models in studies on sediment transport has importance in many practical problems. The problems met in scaling down the bed materials have led to special model techniques, while extensive research has been carried out by many investigators on the problem of the interpretation of test results. The methods used for investigations into the various aspects of sediment transport show great differences, but this review will deal only with the investigations connected with the process of local scour downstream of structures (evacuating sluices, ship locks, weirs, structures for enclosing estuaries, etc.).

The difficulties which are met in scaling down the bed material need some further explanation. In many problems investigated only external forces (gravity) and inertia forces are considered. This leads to the Froude model law. The influence of friction forces caused by the viscosity of the water is then neglected. How far this is justified depends on the ratio between inertia forces and friction forces, which can be expressed as the Reynolds number $Re = vl/v$ in which $v$ and $l$ are respectively a characteristic velocity and length, and $v$ is the kinematic viscosity of the water. The influence of viscosity increases as the $Re$ number decreases.

Defining the length scale of a model

$$N_1 = \frac{\text{dimension in prototype}}{\text{dimension in model}},$$
and applying the Froude model law, the Reynolds number is in the model a factor \( N_1^{3/4} \) smaller than in prototype.

The behaviour of sediment grains on the bottom is determined by the flow conditions close to the wall. In this region the velocities decrease with decreasing distance to the wall, whereas the influence of the viscosity increases. With respect to the flow around the grains, the Reynolds number can be defined, for instance, by \( Re^* = \frac{\nu^*d}{\nu} \), in which \( d \) is the diameter of the grains and \( \nu^* \) is the shear stress velocity =

\[
\sqrt{\text{the bottom shear stress/density of the water}}.
\]

When the behaviour of gravel is considered, for instance with \( d = 4 \cdot 10^{-2} \) m, \( \nu^* = 0.25 \) m/sec and \( Re^* = 8000 \), in a model with \( N_1 = 25 \), the Reynolds number is \( Re^* = 64 \). Although there is an influence of viscosity, in this case a model in which the bed material is reproduced on length scale, can provide satisfactory results.

In many practical problems in the Netherlands, the conditions are:

\( d = 10^{-4} \) to \( 2 \cdot 10^{-3} \) m and \( \nu^* = 10^{-2} \) to \( 4 \cdot 10^{-2} \) m/sec.

So \( Re^* \) is of the order of magnitude: \( Re^* = 0.8 \) to 65.

The friction forces are now so important compared with the inertia forces that a reproduction of the bed material on length scale, thus decreasing \( Re \), is no more acceptable.

The application of the Froude model law is necessary for the reproduction of the characteristics of the main flow and only in some special cases can the velocities in the model be exaggerated. Hence for the reproduction of the scouring process in many cases other ways had to be found. A method which is generally applied, from the first tests that were carried out in this field, is the application of bed materials with densities smaller than those in prototype. The diameter of the grains in the model can be the same as or even greater than in prototype (thus increasing the \( Re^* \)-number), whereas the critical velocities are reduced because of the small effective weight of the grains.

In the Hydraulics Laboratory at Delft, for instance, as early as 1929 the scouring downstream of the evacuation sluices in the Afsluitdijk (Zuyder Sea Enclosing Dam) was investigated, applying in the model grains of pumice-stone. Another example, with grains of 1–2 mm, is shown on photo 6 (M185, 1940).
Although application of these materials has the advantage that the critical velocities (for initiation of motion) are reduced and that in the model the bed material can be transported, the difficulties encountered in the interpretation of the test results still exist. In practice the problem is to determine the required bottom protection in order to ensure the stability of the structure with minimum costs.

To consider these problems and the progress made in trying to solve them, the scouring process is characterized by:
- the geometrical shape of the scour hole;
- the ultimate depth, and
- the development of the erosion as a function of time.

For the moment it is assumed that the flow conditions are reproduced correctly. If in the model the velocities are great compared with the critical velocities for initiation of motion, it can be understood that the transport of sediment is distributed over the area considered in the same
way in model and in prototype. Consequently in this case it may be expected that the geometrical shape of the scouring hole is fairly well reproduced. This is the basis for a design procedure in which the required bottom protection is determined by means of comparative tests. The erosion that will occur for different bottom protections can be qualitatively compared. It is clear that when the ultimate depth or the development of the erosion as a function of time are not known, the solution which is chosen may be too expensive or may possibly provide insufficient safety.

Although new materials have become available (in the Hydraulics Laboratory, for instance, bakelite and polystyrene), the reproduction of fine sand in such a way that the scale of the critical shear stress velocity is the same as the scale of the actual shear stress velocities is in most cases still impossible. The procedure of performing comparative tests as described above has been applied in most of the investigations, but it is not necessary to deal with these tests separately here. The information obtained is useful, although the results have to be interpreted with due caution.

The ultimate depth of the scour hole can be derived from model investigations when the initiation of motion is reproduced correctly. As already stated, in case of fine sand in prototype this is mostly impossible, as the effective weight of the bed material in the model must be so small that for practical reasons the performance of the tests becomes too difficult. It is generally only applicable for rather coarse materials in nature. Sometimes a better approximation can be obtained by exaggerating the velocities in the model, which means that the velocities applied in the model are greater than those corresponding with the Froude model law. This, however, may introduce deviations in the reproduction of the flow characteristics (flow pattern), especially in three dimensional models. These problems need special attention.

When the ultimate depth is reached, the geometrical shape of the scour hole will be reasonably the same in model and in prototype. Deviations are possible when during the process a considerable suspended load occurs. In addition to the critical velocity, the settling velocity of the material also has to be taken into account.

The ultimate depth is not always a good criterion for the design of a
bottom protection, because the time which is required to reach this situa-
tion is unknown and may exceed that which is of interest to the designer.
In that case, actually only information about the development of the
scour hole with time can provide the required data. This is a very complex
problem, however, which in fact involves the determination of the time-
scale of the model.

In the Netherlands there are at present very important problems with
respect to erosion downstream of structures. Among these can be men-
tioned the erosion which occurs during the building of the enclosure dams
in the various estuaries and the erosion downstream of the Haringvliet
evacuation sluice. In all these cases the bottom consists of non-cohesive
fine sand with a mean diameter of 0.1 to 0.2 mm. The bottom protec-
tions for these works are very expensive. For an economical design a
better knowledge about the scouring process, including information about
the time-scale of a model, is imperative.

This made the Rijkswaterstaat initiate a fundamental study to be carried
out by the Delft Hydraulics Laboratory.

The general aim of this research work is:

a. To establish relationships between the flow conditions, the properties
   of the bed materials and the sediment transport. For practical prob-
   lems a model will always remain necessary due to the complex bound-
   ary conditions;

b. To verify in systematic tests the similarity of the scouring in model
   and in prototype, and to determine the time-scale of the model.

In practice these studies have to be carried out in close connection with
each other.

The study mentioned under a. implies that the flow conditions must be
known. For a complete description of the flow it is not sufficient to use
only mean values for the velocities. Especially in the region downstream
of structures the flow can be very turbulent and big eddies may occur
which certainly will have an influence on the erosion. Measurements of
turbulence characteristics in water, however, have always raised many
problems. With respect to this, important progress has been made with
the development of a small plastic propeller-type current meter used in
combination with recording on magnetic tape. From continuous records
of the velocities obtained in this way, the turbulence characteristics which
are of interest can be derived with the aid of a computer (see also the contribution in this book in “Instrumental aids for hydraulic model studies”).

From these investigations an important influence of the turbulence intensity on the scouring process was found.
A unique relationship between the flow characteristics and the sediment transport could up till now not be established. The phenomenon is very complex, and analogous processes in physics could not yet be found.
Systematic tests with variable bed materials and flow conditions confirmed the statement that when there is a considerable transport in the model, the development of the scouring hole is similar for different materials and different values of the length scale and velocity scale of the model. Under these conditions for a given situation a time-scale can be defined which is constant during the process.
The time scale \( N_t \) is a function of the length scale \( N_1 \) (already defined) the velocity scale \( N_v \) and the properties of the bed material in prototype and in model, for simplicity expressed as \( N_{mat} \). This function is of the form:

\[
N_t = \frac{N_1^m N_{mat}^n}{N_v^p}
\]

The values of \( m, n \) and \( p \) depend on certain properties of the bed material and the turbulence intensity of the flow. The determination of these exponents is one of the main items being investigated at present.

Consideration may now be given to the progress made in respect of the present practical problems.
The Veersche Gat estuary was closed in April 1961. The investigations on the scour to be expected were carried out in three-dimensional models in the open air department De Voorst and a two-dimensional model in the laboratory at Delft.
The great advantage of the models in De Voorst is that large areas in prototype can be reproduced on a reasonable scale. The importance of a large scale has been amply explained. These possibilities and the use of bakelite as a bed material have increased the applicability of the test results considerably. A better insight into the scouring process has im-
proved the interpretation of the test results, while a well-founded use of distorted and undistorted models can also be made. Although for the scouring models of the Veersche Gat the determination of the time-scale of the model was still questionable, the tests, in combination with investigations in a two-dimensional model applying bakelite and polystyrene, led to satisfactory results.

The remarks on current investigations will be restricted to the tests concerning the erosion downstream of the Haringvliet evacuation sluice. Although this structure is intended to have a long lifetime, also in this case the erosion as a function of time must be known. The final depth of the scour hole, if it can be defined, depends on large discharges with a relative small frequency of occurrence.

Besides the depth of the erosion the angle of inclination of the upstream slope of the scour hole is also important, especially as layers of loose sand occur.

Also in this case the investigations are being carried out in both a three-dimensional and two-dimensional model.

![Photo 7](image)

**Photo 7**
Two-dimensional model of Haringvliet evacuation sluice. Bed material: polystyrene

It has been found that because of the great width of the sluice, the results of the two-dimensional model are representative for a great part of the total width. The bed materials applied are bakelite and polystyrene. One of the first problems investigated was the determination of the optimum shape of the bottom protection in respect of the stability of the
In addition to the main shape, also the influence of the length and roughness of the protection was investigated, and it has been found that the latter has a considerable influence on the erosion. For the various solutions measurements of velocities and turbulence intensities were made, and these sustained the conclusions drawn from the scouring tests.

It is expected that with the current systematic tests the time-scale can be estimated within reasonable limits.

To summarise: from these models and investigations important data required for an economical design have already been obtained.

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**PROBLEMS CONNECTED WITH FLOWS DUE TO DIFFERENCES IN DENSITY**

**by Ir. G. Abraham**

Fluid motions in a gravitational field which are originated or influenced by variations in density within the fluid or by differences in density of the fluids involved are characterized by the term flows due to differences in density. Examples are given in Table 1.

The present activities of the Delft Hydraulics Laboratory are concerned with the following problems mentioned in this table:
1. intrusion of salt water through navigation locks;
2. siltation of harbours, situated along tidal rivers; and
3. jet diffusion in connection with waste disposal.

These phenomena will be discussed here.

Salt water intrusion is one of the major problems of the water management of the Netherlands. This intrusion is primarily caused by the intrusion of salt water into tidal rivers, the seepage of salt ground water, and the salt intrusion through navigation locks situated along the coast. The problem of the increasing salinity of ground water and surface water in the Netherlands is described in the summaries of the papers presented.
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in the Sixth Technical Meeting of the Committee for Hydrological Research T.N.O., January 18, 1950, and at the 18th International Navigation Congress, Rome, 1953, Section II, Communication 3, pp. 185–218. The construction of the Zuiderzee Works brought important advantages for the water management, as described by Prof. THIJSSÊ (Tijdschrift Koninklijk Nederlands Aardrijkskundig Genootschap, Tweede reeks, 52, 1935, pp. 481–507 in Dutch). On one side, it was possible to create a fresh water reservoir to supply fresh water to the Northern part of the country in seasons of drought; on the other side, the sea water was
kept from penetrating far inland. The Delta Works will bring similar advantages for the South Western part of the country.

Advantages of a different order of magnitude, but nevertheless important ones, can be obtained by controlling the intrusion of salt water through navigation locks, which is caused by the fact that during each locking cycle a volume of sea water is exchanged with a volume of fresh water. The sea water which has entered into the body of fresh water on the inland side of the locks must be expelled from it. The present desalting processes (such as flushing with fresh water) cause a loss of fresh water, which may not be available in periods of drought. Therefore research has been concentrated on the following subjects:
1. hindering the intrusion of salt water in the lock chamber;
2. improving the efficiency of the de-salting processes.

The most significant results of these studies are those of the investigation about pneumatic barriers, obtained by releasing bubbles of air from perforated pipes placed on the bottom of the lock in a direction perpendicular to its axis. An extensive study both in a hydraulic model and in the field showed that pneumatic barriers are an economically feasible method of reducing the intrusion of salt water through navigation locks. It is intended to apply pneumatic barriers in different locks situated along the coast of the Netherlands. Some results of the pneumatic barrier-study, carried out by the Service for Water Management and the Arrondissement "het Noordzeekanaal" of Rijkswaterstaat and by the Delft Hydraulics Laboratory are presented in Publication No. 28 of the Delft Hydraulics Laboratory, August, 1962.

At present the possibility is being studied of reducing salt intrusion in canals by deepening a part of the bottom adjacent to the navigation locks and providing a drainage culvert. The deep section is intended to act as a reservoir to trap salt water penetrating from the locks, while the culvert is intended as a means of sluicing out the salt water at a small steady discharge. This study is performed in models of different scales, so as to obtain an insight into the scale rules which have to be applied. The largest flume used for this study has the following dimensions: length 100 m, width 3 m, water depth 1 m. The conductivity probes especially designed for this study make it possible to study the mixing processes which are brought about when salt water is intruding into a stagnant
A considerable amount of money is spent each year on the maintenance dredging of the harbours of the city of Rotterdam, which are situated along the Rotterdamse Waterweg (or New Waterway), a tidal river which connects Rotterdam with the North Sea. In this tidal river fresh and salt water come in contact with each other, and due to tidal action the salinity of the river water varies with time at the entrances of the harbours. The salinity of the water varies less rapidly in the harbours than it does in the river, as the variation of the salinity of the water in the harbour is brought about by exchange of water between the harbours and the river. Such an exchange of water may be a result of:

1. exchange flows, due to differences in density between the water in the harbours and the river;
2. variation of the water level in the harbour due to tidal action; and
3. horizontal exchange of momentum between the water of the harbour and the water of the river.

For most of the harbours along the Rotterdamse Waterweg the quantity of water exchanged due to differences in density exceeds the quantities exchanged as a result of the other phenomena. As the exchange flows are a mechanism by which solid matter can be brought into the harbours, the effect of the flows induced by differences in density must be considered in studying the siltation problem.

The main questions to be answered in studying the siltation are:

1. what maintenance dredging will be required for new harbours?, and
2. what reduction of the maintenance dredging will be obtained by application of technical means, as, *e.g.*, pneumatic barriers at the entrance of the harbours?

If on one side the relationship between the variation of the salinity of the river water at the entrance of the (projected) harbour and the exchange flows induced is known, and on the other side the relationship between the rate of siltation and the quantity of water exchanged between river and harbour, then it seems possible to predict the maintenance dredging for new harbours. An extensive programme of field measurements is being carried out by the Service of Public Works, City of Rotter-
dam in order to find these relationships and to obtain an insight into the complex siltation mechanism.

The field data collected will provide a basis to calibrate hydraulic models to study how the exchange flows due to differences in density (and thus the rate of siltation) can be influenced by technical means at the entrance of the harbours. Until now the effect of such technical means has been studied only in hydraulic models under schematized conditions. One of these studies was concerned with the application of pneumatic barriers to reduce siltation. The results obtained by this model investigation gave a stimulus to investigate the application of pneumatic barriers in navigation locks on a prototype scale. Within a short time a field study of the effect of pneumatic barriers on the siltation of harbours will be initiated by the city of Rotterdam.

Submarine outfall disposal of domestic and industrial sewage is a method of disposal of steadily growing importance. The submarine outfall at Scheveningen, one of the earliest major submarine outfalls along the coast of the Netherlands, was constructed in 1934 on the advice of a committee of which Prof. Thijsse was Chairman.

In the direct surroundings of the outlet the flow from an ocean outfall is essentially that of a submerged jet. Therefore a study of the hydrodynamics of such jets is needed to evaluate the dilution of the sewage flow. A theoretical study of this kind was recently made at the Delft Hydraulics Laboratory under the direct guidance of Prof. Thijsse and Prof. Van Spiegele (Publication No. 29 of the Delft Hydraulics Laboratory, July, 1963). The study gives the relationship between the dilution and the determinative circumstances for jets issuing vertically upwards into lighter or heavier ambient fluid, whose density varies arbitrarily with height and for jets issuing horizontally into homogeneous ambient fluid of different density.

This study is restricted to the case of stagnant ambient fluid, while the influence of the free water surface is not considered. For this reason a model study about the influence of the free water surface in case of stagnant ambient fluid was initiated recently at the Delft Hydraulics Laboratory. It is hoped to expand this experimental study to the case of jets issuing into flowing water.
For many foreign people the struggle of the Dutch population against the sea is concentrated in the story of the little boy who pushed his thumb in the hole of a dike and in that way saved many lives. Although this story is legendary and has no historical background, it can be taken as certain that the Dutch have had to close bursts in the dikes from the very beginning of their construction. From pictures and descriptions it is known that during the floods earth, reeds, stones and even straw and hay were used to prevent further scouring when a hole in the dike was made.

It is also well known that already before the Middle Ages many disasters occurred as a result of breached dikes along the rivers as well as along the coasts. And those disasters have continued to occur even in very recent times.

On a number of occasions the inhabitants have had to withdraw in order to close the bursts, but they never abandoned the struggle. One only can have a great admiration for the efforts made in the past, and the successes of which have been the preparations for the enclosures executed at the present time.

Without the aid of mechanical equipment and a scientific basis it would be impossible to consider the present-day enclosures of bursts and estuaries, but now could they be undertaken without the spirit and experience gained in those earlier times.

Restricting this review to the enclosures which were preceded by investigations in hydraulic small-scale models, the following groups can be mentioned chronologically:

- the Zuider Zee (1930);
- the bombed dikes of Walcheren (1945);
- the dikes destroyed in the south-western part of the Netherlands by the flood of February 1, 1953; and
- the estuaries in the Delta area of the Rhine and the Meuse (under execution).

Part of the model investigations on the closing of the Afsluitdijk (Zuider Zee) was carried out in a foreign laboratory, viz., at Karlsruhe, but the
In the small-scale models many phenomena can be studied in connection with enclosures, the scale of the model being determined by the problem to be investigated. They can be separated according to the following classification:

- horizontal scale some thousands: investigation into the changes of water level and currents in adjacent area caused by the enclosure works;
- horizontal scale some hundreds: investigation into velocity distribution, flow pattern, and scouring in the near vicinity of the works; and
- horizontal scale some tens: investigation on bottom revetment, stability of parts of the construction, and manoeuvring of enclosing elements.

The first group of models provides the data on changes of currents and water levels during and after the execution of the works.

The discharge in an opening is mainly determined by its dimensions and the head of the water levels. As most of the enclosure works are situated in a tidal area, the water level on one side is given by the natural tide.

Photo 8
The water level on the other side is mostly dependent on the capacity of the enclosure itself, and hence the boundary conditions are changing during the execution of the works. Storage area and resistance should be adjusted in the right scale in such models and, moreover, the current must be turbulent.

This leads to model scales which may be greatly distorted; a distortion of about 50 is quite normal. The fitting out of the large model of the Delta of the Meuse and Rhine (M 284, M 600) developed during many years until it has reached the stage in which nearly all operations are now carried out automatically by electronic instruments (Photo 8).

After the disaster in 1953, however, some models with a very simple outfit could provide very valuable information at very short notice (Photo 9). The second group of models gives an insight into the currents and their scouring effects, and hence the shape of the works in a horizontal as well as in a vertical sense are investigated in this type. In many cases they have a movable bed. A slight distortion of the scales is mostly allowed for vertical water movements and is nearly always needed to get a corresponding flow pattern in a horizontal sense.

Photo 9
In the third group the detail problems are investigated. They give an insight into the stability of bottom revetment and bigger elements as pontoons, etc., into the manoeuvring of the enclosing elements, and into the forces caused by the currents. Mostly the scales of these models have to be undistorted.

In the Netherlands the first enclosures were investigated in small-scale models in the 1930's. The Hydraulics Laboratory at Karlsruhe had then already carried out some model experiments in connection with the enclosing of the Zuider Zee. Cross-sections of dike foundations at different water levels, their resulting water movements and scouring effects were investigated. Young engineers of the "Dienst der Zuiderzeewerken" (Zuyder Sea Works Service) gained experience on model investigations and when in 1927 the Delft Hydraulics Laboratory was founded, one of them, J. Th. Thijsse, became the first Director.

The openings in the enclosing dike of the Zuider Zee were closed step-by-step. In a vertical sense they were constructed of layers of willow mattresses covered with heavy stones, at some spots even with anchor-chains. In a horizontal direction boulder-clay and sand were built out. In one of the first models of the young laboratory (M 13) the so-called "beteugelings dammen" were investigated, dams constructed of boulder-clay which by their special shape protected the sand-body of the dike against scouring. In other models alignments and cross-sections of dike-parts were investigated on flow-pattern, velocities, scouring and stability of revetments. The confidence in model tests grew strongly when some of the model reproductions of hydraulic works gave reliable results.

The changes in the tide caused by the enclosing dike were in previous years calculated under the guidance of Prof. Lorentz. Nowadays such a study would probably be done either in a tidal model or by calculation with an electronic digital computer.

Just after the second world war the bombed dikes of Walcheren had to be closed. As equipment, personnel and materials were very scarce and the dikes had to be closed at short notice, a new method was developed, viz., the use of big elements, which were placed on the revetments in the dike breach.
There was no time to make careful preparations, but here again the tests in small-scale models showed their importance even under such circumstances. Models were constructed of the enclosures at de Nolle, Ramme-kens, Westkapelle and Veere, while investigations into special problems were also carried out in order to forecast the consequences of unknown methods.

Concrete caissons which in wartime were used for the construction of temporary harbours had to be floated to the right spot, and when they were sunk and filled they had to withstand the forces caused by differences in water level. Hence in the models not only were flow pattern, scouring effects, lengths of revetments and the stability of stones on willow mattresses investigated but the results also gave very valuable information on the movements of the pontoons, the forces in the wires by which they were kept in position, and the friction forces of concrete on the stone revetment.

Again in 1953 several hydraulic problems had to be solved after the February flood disaster when the dikes burst at many places. They had to be repaired before the next winter, a matter of only a few months. Experience gained at Walcheren therefore proved very useful.

To study the effects of the enclosing works on the changes of discharges in the openings caused by the tide two models were constructed, one of Schouwen on a scale 3000/50, and another of Duiveland on a scale 2000/50. Resistances were adjusted by small-mesh wire-netting; tides were simulated by hand-operated valves. The models had a very simple outfit but in a short time gave the wanted information.

There is no need to mention here every model which was then in operation. Some of them were used for general information, such as the investigations on revetments in which the critical velocity for the stability of stones and concrete blocks, the overlapping of willow mattresses, the water movements, and the scouring effects downstream of the revetment were investigated. Quite a number of models were constructed in which the special problems of every enclosure were studied.

In close contact with the engineers in charge of the operation, methods and alignments of the closing works were investigated. During the operations with vessels and caissons there was continuous telephonic contact between field operation and model in order to reproduce all new situa-
tions in the model and then to pass on the data obtained for the following step in operation.
Such models were available for the enclosures of Hellevoetsluis, Zierikzee, Kruiningen, Schelphock, Stevensluis and Ouwerkerk.
In spite of the tremendous difficulties there were only a few failures in the work of closing the dikes, while as a result of all the information provided by the small-scale models the dikes were closed before the next winter storms arrived.
Then there is the group of models in connection with the present Delta Plan. Already before the disaster of 1953 the investigations had been started and the first hydraulic works instituted with the enclosures of the Brielsche Maas and the Braakman. Both were closed by the use of concrete caissons, those in the latter project even being provided with gates which were open until the last caisson had been placed and then closed during slack tide. The flow patterns, the scouring effects and the manoeuvring of the caissons were in both cases investigated in small-scale models. M 359, the model of the Braakman, was the first to be executed in the open air laboratory at De Voorst in the North-East Polder.
Long before that time, however, the large model covering the greater part of the south-western area of the Netherlands was already in operation in order to study the effects on water levels and discharges. The scale of this model is 2400/64. Although it has since been extended and the equipment changed from hand-operated to electronic instruments, the principle has remained the same: highly distorted scales in combination with artificial roughness which permit a large area to be investigated in a rather small space. In this model the whole programme of the Delta Scheme during and after its execution is being studied under all possible circumstances of tide and river discharge.
New methods on bottom revetments have been developed. Asphalt, emulsions with sand, and synthetic canvas were introduced in many ways, and their resistance against wave attack and currents investigated in combination with thorough studies on resistances of many kinds of stones and gravel.
Again, the method of closing with big elements was compared with that of a gradual closing. Both methods were investigated in models as well as under natural conditions; the first one has been applied for the Veersche Gat and South Grevelingen; and the second for North Grevelingen.
For the Veersche Gat an extensive study was made for the building up of the sill on which the caissons have been placed, for the shape of the opening, for the scouring effects, for the wave attack on dikes and caissons, and for the manoeuvring of the caissons. The scouring effects in nature have been compared with those of the model, which will give more accuracy in the prediction of model results in future.

The works in the Haringvliet have a special character as in the enclosing dike a sluice with a width of 1000 m is being constructed. Apart from all the items already mentioned, the scouring around the building pit and the constructions themselves had also to be investigated in small-scale models. The description of these, however, goes beyond the scope of this article.

In the present stage of model experience it seems to be very important to pay great attention to velocity distribution and flow-pattern on the sill of the openings in order to predict reliable results as to the scouring of the bottom. In the models of Veersche Gat and Grevelingen it was found that the scouring effects are very dependent on this flow pattern and velocity distribution.

For the great future works of the Brouwershavense Gat and Oosterschelde it may be indispensable to use tidal models instead of models with a permanent water circulation in order to get sufficient information on the scourings to be expected.

HYDRAULIC REFINEMENT OF ENGINEERING STRUCTURES

by Ir. J. Wijdeks

Under this title there are brought together a number of model investigations, although their only common denominator is the fact that they are restricted in scope and investigation time. For this type of investigation particularly the hydraulic sense and experience of the testing engineer is very important. A clear developmental history cannot be given, except for the model studies on locks. Very often, it is possible to give advice
from the early beginning of a project, which provides certain freedom in hydraulic designing and model testing.

For the models of ship locks, which are mainly investigated to minimize mooring forces and lock-filling times, progress has for some years been made in measuring technique and now it is possible to use models with very compact measuring systems. For the steady flow state comparative model studies of the stream pattern on the downstream side of the ship lock have been undertaken. As there are in prototype other factors, such as the nonsteady character of the lock-emptying discharge and the influence of density differences for sea locks, a further refinement of measuring technique was necessary. The freedom in design which was given to the examiner then led to the construction of door-filling and emptying systems for ship locks up to a difference of level of more than 8 m, in this way constructing a cheap lock. In the 1960's a further expansion of research in ship locks arose by the application of tug pushing and the development of the Delta plan: Ship lock in the Hartelkanaal (entrance to Europoort), ship lock in Volkerakdam (shipping route Antwerp–Rhine), and the inland ship lock at Terneuzen.

Now in study is the sea lock at Terneuzen (connection Ghent–W. Schelde), a lock almost as big as the Ymuiden sea lock. Special provisions have been made to minimize the entering of salt water into the Canal, thus producing the first big model in which mooring forces and stream patterns were studied with salt water as dense material. The scale effects of this model motivated investigation into what have already been called by Abraham more specialized studies in flows induced by difference in density.

Most of the foregoing model studies on locks were commissioned by the Netherlands Government Waterways Department (Rijkswaterstaat). This, however, has not generally been the case for the other objects, and as there is great variety in these studies some of them will be described briefly.

The water Companies have been regularly commissioning the Hydraulics Laboratory, and recently the Rotterdam Waterworks asked for advice from the first stage of design of its installation at Berenplaat. This advice extended from the inlet pumping-house up to regulating the water to the
freshwater storage. The design of the reservoir (2–3 months’ storage) has been based on model tests undertaken in 1943 for a storage reservoir of the Amsterdam City Water Department, bearing in mind that wind was stated to be of prior influence on the water motion in the reservoir. The chosen design (FIG. 1) also has the advantage of small fetches, which made light protections of the earth dams possible.

![Diagram](image)

**FIG. 1** Storage reservoir at the Berenplaat Waterworks

The inlet pumping-house is of a hydraulically attractive shape: pump with syphon. It is possible to use the low pressure area of the syphon for sucking air into the water, and special design of the syphon, tested in model, gives the opportunity of dissolving oxygen in the water in an economical way. The various parts of the chemical dosing building and the filtering building, such as overflower with minimum turbulence mixers, distributors, etc., were tested with rather simple detail models schematized calculations. In connection with the growth of the population, more studies like these are expected.

The Hydraulics Laboratory gave its first advice on the filling and emptying of a dry dock in 1951. In recent years the shipbuilding industry has
been carrying out more and more repairs, and especially the construction of repair docks for tankers of over 100,000 tons is now increasing in the Netherlands as well as in foreign countries. For some of them it was sufficient to estimate the filling and emptying time and to make some hydraulic changes. A system often used is filling the dock with equilibrium cylindrical valves and pumping it dry with syphon protected pumps. As the same requirements remain for larger docks (filling time 1 hour, emptying time 2–3 hours) bigger pumps must be installed. This needs special attention for the last period of pumping dry: the main pumps must be used as long as possible without inserting air entraining vortices.

Also in recent years there has been more interest in the formation of pumps in cold water channels and pumping-houses, but from literature and in practice many badly working pumps are known. Very often the axial flow pump is used because of its simple mounting and insensitivity to dirty water, but it is very sensible to the stream pattern on the upstream side. Small construction heights of pump cellars and channels also produce problems to overcome the sucking of air into the suction bell of the pump. The Delft Laboratory is now testing a problem like this for a cold water channel with a free surface and two axial flow pumps in line. In a pilot model scale 16 air was sucked in under normal conditions (Photo 10).

As the surface tension has an important influence on this type of investigation, the advised changes will be tested in a larger model on scale 4. In models like this not the whole pump is scaled down but only the suction bell and the discharge pipe are built in.

As already shown for the inlet pumping-house for the water works at Berenplaat the economical dissolving of oxygen in both drinking water and sewage is of interest. Model tests here made self-suction of air possible for the cylindrical valve of the Amerongen Weir (Lek). Another example investigated for air entraining in sewage water was a model with a type of Kessener brushes developed by T.N.O. and Passavant Werke.

An interesting problem mainly solved by calculation was the estimate of the forces on the emergency valve of the metro tunnel in Rotterdam in case of damage to the underwater part of the tunnel. It was possible to estimate the forces for the different situations of the valve (valve closed or valve closing in streaming water). The model, scale 110/160, had to
Photo 10 Air entraining vortex in the suction bell of a pump
be corrected on friction for the laminar boundary layer. While there was also a scale effect on the compression of air a part of the investigation had to be calculated.

The foregoing descriptions, it should be mentioned in conclusion, are intended to give only an impression of the work done by the Laboratory on this part of hydraulics.

WAVE ACTION ON STRUCTURES

BY IR. A. PAAPE

In hydraulic engineering there are many problems related to the occurrence of surface waves in water. Great progress has been made in the development of a mathematical description of wave motion in a water mass with geometrically simple boundaries. Most of the problems with practical applications (wave motion in the vicinity of structures, beaches, etc.) are still too complex for theoretical solutions. Moreover, the theories cover only part of the properties of irregular natural wind waves. Therefore the studies on wave action on structures are mainly carried out by means of small-scale models.

To evaluate the progress made until now and to call attention to present developments it should be noticed that in the design of a structure exposed to wave action there are two main questions to be answered:
- how can wave motion in nature be described, and what are the wave characteristics for a certain location?, and
- for given wave conditions what are the effects of the waves on the structures?

As the wave characteristics which must be known to solve a technical problem depend on the character of the problem, it is necessary to deal with these items in close connection one to another. In practice, however, there has been a tendency to work in different ways in the studies on wave motion in nature and the application in model investigations. The main reasons for this were the difficulties which were met in collecting
detailed observational data from nature and the application of a strongly schematized wave motion in the models. This led to a design procedure in which generally the wave conditions were characterized by a significant wave height and period which were applied as design conditions in model investigations with regular paddle generated waves.

The studies on waves occurring in nature as far as applied in civil engineering practice mainly concerned the generation of waves by wind. It was tried to establish relationship between wave dimensions and wind velocities duration and fetch. With these relationships a prediction of waves on the base of meteorological data was made possible. Important work in this field has been carried out by SVERDRUP, MUNK, THIJSSE (see below) and BRETSCHNEIDER.

Although these relationships need further improvements and supplementary data are necessary, it is justifiable to stress once more the importance of this work, as at present it is in many cases a starting-point for the design of maritime structures.

A better insight into the properties of natural wave motion was obtained by theoretical studies and especially in the last few years by the establishment of wave recording stations, thus making a comparison between model and prototype waves possible.

In the models attention was paid to improvements of the wave machines and measuring equipment. For a long time, however, the principle of generating waves remained the same (regular series by means of a wave board). Although the deviations between model and prototype in various phenomena, introduced by the schematization of irregular wind waves to regular waves, are still not exactly known, it can be said generally that this simplification of wave motion is only justified when:

- the total energy of the waves during a long period is determinative for the effects which are investigated, or
- the phenomena which are investigated depend only on the characteristics of one individual wave, whereas the influence of the geometrical shape of the wave is small.

To obtain a better reproduction of wave motion in nature, in 1935/1936 a wind flume was built in the Hydraulics Laboratory at Delft on a suggestion by Professor THIJSSE. The idea to build this equipment was realised
when the Laboratory was requested by the Zuyder Sea Works Service to investigate the wave run-up on seawalls. This was done by applying waves under direct influence of the wind. The flume had a length of about 25 m, a width of 4 m and a height of 1 m. The waves were generated by wind blowing over the entire length of the flume, while in addition a combination of wind and a wave board could be used. For irregular waves with various significant wave heights, statistical distributions of the wave run-up on seawalls were obtained. Of course, the waves generated in this way might be different in some respects from those in nature, but a better approximation was obtained than with regular waves, whereas the very important procedure was introduced of dealing with the action of waves in models in terms of statistical quantities. The equipment was also used to obtain additional data on the generation of waves by wind. Especially the influence of limited depth was studied. The results were published in: “Gravity waves” U.S. Department of Commerce, N.B.S. circular 521. (J. Th. Thijss: Growth of wind Generated waves and Energy Transfer. pp. 281–287.)

The importance of applying irregular waves in many investigations and the increase in work to be done led to an extension of the flume to a length of 55 m and the building of a wind flume with a length of 100 m in the Laboratory’s open air department De Voorst in the North-East Polder.

It is not too pessimistic to say that the knowledge about waves is still very inadequate. Extensive research is necessary for which observations in nature have to provide the required data. The development of new methods for wave recording and the statistical processing with the aid of computers makes the performance of these studies possible. The reproduction of wave motion in models leads at present for many technical problems already to results which are satisfactory. With detailed information on natural wave motion it can be tried to improve this reproduction where necessary.

Starting from the general tendencies outlined above, some remarks will now be made on the testing procedure for some types of investigations. The investigations on seawalls concern generally the wave run-up and overtopping as a part of the determination of the most economical cross-section, and the wave forces exerted on the sea side facing. Instead of
the relationship between the wave run-up, the wave characteristics and
the geometrical shape of the exposed side, at present the overtopping is,
generally, considered. The main reasons for this are:
- the statistical behaviour of wave run-up by irregular waves, which
  implies that for an economical design some overtopping has to be
  accepted, and
- that in many cases the rate of overtopping is determinative for the
damage caused to the seawall itself or to the protected area (many
examples were found after the flood of February 1953).
A significant influence of the irregularity of the waves was found in
systematic tests. Especially the distribution of wave heights appeared to
be important. The wave-height distribution curves for the wind flumes
are in good agreement with those from Katwijk (a wave recording station
near the Dutch coast) when in the flumes only wind is used for the
generation of the waves.

The determination of the rate of overtopping does not in itself provide a
design criterion for the structure. It must be known what is acceptable.
In respect of the critical values of the overtopping for the stability of the
seawall itself, there is still very little known. For grass-grown slopes this
led to a preliminary criterion for the overtopping of a few litres per
second per m$^2$, corresponding with the former criterion of 2\% of the
waves overtopping the crest. Very probably some seawalls in 1953 with­
stood a rate of overtopping which was considerably greater.
It may be expected that for impermeable revetments like asphalt a rather
great overtopping is acceptable. However, also in this case the effect of
high current velocities on the material is not exactly known. Research in
this field has to be continued.
The forces exerted by waves on the exposed facing of seawalls have in­
cidentally been investigated. A special category is formed by the impact
forces of breaking waves which have a short duration but can reach very
high peak values of the pressures. Measurement of these forces can only
be made by means of pressure cells or force meters with high natural
frequencies. Already 1953 the distribution of local pressures along a sea­
wall with horizontal berm was measured, but important progress in the
application of force measurements for the design of seawalls has, however,
not yet been made. It is still difficult to measure with sufficient accuracy
the impact pressures and the overall force on areas of various dimensions. A far more complex problem is the response of the structure on the forces. At present it is not clear in what way damage is caused to the various types of structures. This is not only a matter of the covering materials (stone revetments, asphalt, grass-grown slopes) but also the stability of the core may be influenced. Efforts are being made to develop the methods for research on these problems in close collaboration between specialists on structural materials, soil mechanics, hydraulics and instrumentation for measurements.

An important part of the studies on wave action concern the stability of rubble mound breakwaters. In the Netherlands this type of structure is generally not applied, as no natural rock is available in the country itself. The arrangement of models for these investigations is in principle simple: the various categories of blocks are reproduced on length scale (sometimes with corrections for the density) and the behaviour of the structure under certain wave conditions is studied. For the required block weights on the sea side slope, various formulas have been established. It is not possible to deal with these formulas in details here, but there are two points which must be mentioned:
- the wave height to be applied in the formula is defined by IRIBARREN as the height of the breaking wave on the slope. The other formulas were derived from model tests, applying the mean or significant height of more or less regular waves;
- only in the formula given by HUDSON is the rate of damage considered. The main difficulties in the design procedure are encountered in these two points. The structure will be in nature exposed to a whole spectrum of wave heights. As the stability is not governed by one individual wave, but depends on a series of waves, both the occurrence of significant wave heights as well as the wave height distribution for constant significant height have to be considered. With well-chosen values for the probabilities with which certain damage is accepted, the conditions for the model investigations can then be determined. Unfortunately the available data on waves are generally insufficient. A frequency distribution of significant wave heights requires observations over a long period. An approximation is possible on the base of meteoro-
logical data. It is also of interest to get more information about the extreme values that may occur in a series of waves. With respect to this, research is being done on the statistical properties of waves recorded in nature.

When the wave heights considered are not limited by the water depth, it is necessary for an economical design to investigate the damage which is caused under different conditions. Hudson has expressed the damage as the percentage of blocks that were removed. This has the advantage that it is an objective criterion. It is investigated whether such a criterion is generally applicable to describe the necessity and possibility of repairing.

Investigations have shown that special attention has to be paid to the stability of the crest, the harbour side slope, and particular sections like the head of the structure. The most suitable crest height is often determined by the cost of providing a cover layer that can withstand considerable over-topping or of increasing the cross-sectional area by heightening the crest level.

With regard to the stability of the head, it should be noticed that with the present knowledge it is not possible to base the design of this part with sufficient reliability on the results obtained for the normal section. Already for many years attention has been paid to the development of specially-shaped concrete blocks for protective cover layers. It is clear that the decision on the type of blocks to be applied is only a matter of economy. Comparative tests carried out for one of the preliminary designs for the extension of the breakwaters at Ymuiden provided data for various types of blocks. In the ultimate design for Ymuiden a cover layer of stone asphalt is used. The application of this material can be stimulated by research on wave action as mentioned above for seawalls.

In respect of wave action on various other types of structures, only the occurrence of impact forces will be mentioned. When for the structure, or parts of it, natural frequencies can be defined, a force is called an impact force when the time of increment is short compared with the natural period or is of the same order of magnitude. For other problems like the sliding stability of a caisson the impact force is the component of the wave force with a duration which is short compared with the wave period. It is noticed that these forces are not only exerted by breaking waves, but also by non-breaking irregular waves.
The occurrence of the type of force has already been known for many years, and they have been recorded both in nature and in models. But only recently has the practical use of such investigations been made possible. As already mentioned, this is due to the difficulties which are met in:

- measuring the overall forces and local pressures on the structure; and
- calculating the response of the structure on the forces.

The devices for the measurement of pressures or forces in models are practically all based on the principle that the deformations of a membrane or spring are recorded. This implies that the measuring devices have natural periods in which they can oscillate. To measure the actual forces or pressures, the models or measuring devices must have natural periods which are small compared with the duration of the impact force. Only in that case is the force "felt" and recorded as a static load.

The first devices with high natural frequencies were pressure pick-ups with which the local pressures could be recorded. This information can be important for the design of parts of the structure, like skin plates, etc. There is generally also interest in the overall force on areas which are large compared with areas covered by one pressure pick-up. A superposition of pressures recorded simultaneously on a number of pressure pick-ups provides mostly no reliable data, as the variations in pressures from one point to another are very great. High peak values can occur very locally. Hence the models have to be suitable for measurements of overall forces in the structure or sections of it. The principle is simple: the model is fixed to force meters. However, the deformations or displacements which are recorded must be large enough to obtain sufficient accuracy, whereas the mass-spring system formed by model and force meters must have a high natural frequency. It is extremely difficult to meet these contradictory requirements. Based on this principle, investigations were carried out on wave forces on piles and caissons with various angles of inclination of the exposed front. In the latter case three components of the forces were recorded on magnetic tape and worked out with an analogue computer.

The forces can be dealt with only as statistical quantities. This is one of the problems involved in determining the response of the structure, as the calculation can only be carried out for some cases which are assumed
to cover the design loads. Moreover, the time force history has to be schematized in such a way that the calculations can be carried through. This method has the advantage that the properties of the structure can, within certain limits, be varied. Another approach is possible by using models which are elastically similar to the prototype. An example of this are the investigations concerning the Haringvliet evacuation sluice. For information on this type of investigation, reference is made to another contribution in this book: “Structures for water control”.

Probably the reproduction of wave motion as it occurs in nature is in no model investigations so important as in the tests on wave impacts, but in this respect improvements of laboratory facilities will probably be necessary. Only field measurements will enable the hydraulic engineer to evaluate the reliability of the model technique and to improve the testing procedures.

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**THE COLLECTING OF FIELD DATA**

*by Ir. J. G. H. R. Diephuis*

The early architects of hydraulic engineering works had only one expedient: experience, based upon observations and common sense. Today they have esoteric small-scale model techniques and intricate electronic computers at their disposal, but the basis is virtually the same: observation and common sense.

In the Netherlands hydraulic, hydrologic and geo-morphologic data have been collected during centuries, but only in recent times – generally after the 18th century – this has been done in a systematic and co-ordinated way by particularly the Rijkswaterstaat, a Department of the Ministry of Communications and Works. The Delft Hydraulics Laboratory is thus favourably circumstanced, having as a rule adequate and reliable data at its disposal to serve as boundary conditions for model investigations of hydraulic problems in the Nether-
lands. Because of the close co-operation for many years between the Rijkswaterstaat and the Laboratory the one has taught the other what is needed and what is possible.

But not all data are available. For instance, when in 1933 the Petroleum Harbour at Pernis was being investigated, tidal data and figures on river discharges were available, but no data on siltation. This holds even more for the wave action and sand displacement along the coast: only in recent years are accurate measurements being carried out.

Too concise data from the field have, indeed, in the past caused the failure of a model study: it is impossible to conduct a justified model investigation without having available full and accurate data from the field. To quote an example: the flow pattern of a large river estuary, governed by river discharge, tide, coastal currents and currents caused by meteorologic influences, cannot be characterized by the results of a few measurements. If the variables have a cyclic character the measurements have to cover a full cycle, while afterwards the variations between the cycles have still to be taken into account.

The same is true for measurements of, e.g., sediment transport. As a rule this will happen by means of waves or ripples, so these have to be reckoned with in the first place. Then there is generally a seasonal variation, thus a year cycle. But there may be a cycle that lasts even longer, causing waves or banks a score or more of miles in length having a period of a great number of years. Figure 2 gives an illustration; the sounding was done in 1961. Such data seem to be simple and uncomplicated, but there is always the danger of periodicity, and then they can be very misleading if the character of the bottom configuration is not known and fully understood. This is particularly the case when extremes have to be assessed and risks are to be determined.

It is clear that an annually exponentially increasing quantity of data cannot be collected without developing the measuring devices and particularly without being able to process this avalanche of data into graphs or conveniently arranged tables. Together with many other institutions, the Laboratory is contributing to this development. In this respect most attention is paid to current meters and wave meters.

The manual elaboration of a graphic wave record is a job of which the trouble and the time are in complete disproportion to the results, for a
subjective frequency distribution of the wave heights and a similar determination of the average wave period is generally the limit of what can be obtained. In this connection the present electronic computing machines are a real boon, and it may be expected that the graphically registering wave recorder will have only secondhand value before long. With the current measurements the elaboration as well as the method of collection is being simplified, and already the costs are leading towards autonomic transducers. However engaging a large simultaneous measurement with, e.g., eight vessels and 100 men may be, such a method cannot be maintained for the sake of accuracy and economy. Moreover, in some areas it is physically impossible to conduct such large measurements. Thus the feasibility of the measurements has the Laboratory's full attention, and it tries in particular to anticipate problems and to avoid being caught by facts and the need to improve.

![Diagram of Giant or mega ripples along a coast](image)

The conditions abroad differ generally from those obtaining in the Netherlands. In many cases the data required for a satisfactory model study are lacking and the study has to manage with concise data. In 1946 a foreign river board provided the Laboratory with extensive discharge data, levels, etc.; but in 1953 when investigating a harbour mole, an accidental picture postcard gave the only information about the existing conditions of spray.
For the design of a harbour of another country, investigated in the same year, part of the data originated from a local schoolmaster who was only an amateur yachtsman. With all due deference to the merits of this observer, the report had to mention that “however, with the available data, it is not possible to estimate accurately the risk of damage or failure”. When in 1958 a scour investigation had to be carried out only insufficient flow data were available and the discharges and velocities had to be estimated.

Data on waves are generally lacking. As a substitute, they have been and are often computed by the Laboratory from meteorological data which are, as a rule, available on a larger scale. Aviation has in this respect been a powerful ally.

The first measurements in the field having fair proportions were carried out by the Laboratory in 1934 and 1936; these referred to translatory waves on canals in Twente and in Limburg. The latter (1936) was of a rather large scope. No doubt the participants, very junior at that time, and very senior at present, remember the happenings with pleasure. Since then the Laboratory workers have set out many times to measure waves, hawser forces, currents, movements of vessels, and many other phenomena. In the Netherlands these measurements were generally related to a model study, and only in rare cases did they serve exclusively as a base for an advice.

However, the advices given by the Laboratory are not founded exclusively on model studies but can as well be based on an investigation of the phenomena on a scale 1 : 1 as on a scale 1 : 10, 1 : 100 or 1 : 1000. This depends on the character of the phenomena and the nature of the engineering works. A harmonic approach can be obtained when the hydraulic consultant collects the field data himself, having right from the beginning the possibility of a model study in mind.

This kind of consulting work started in 1950 with an investigation in situ into a harbour of the United State of Saurashtra. Current, silt, density and tide observations were done and soundings and an aerial survey carried out, but no model studies were made. A similar investigation was carried out one year later, 1951, in South Africa.

This work has been continued and extended during the following years,
and large investigations in situ, taking more than a year in some cases, have been carried out since in Africa, America, Asia and Australia. Often these site investigations have been made by the Laboratory in co-operation with other organisations, notably when more complex subjects were involved which extended beyond the specialisation of the Hydraulics Laboratory.
Much has changed during the past forty years: the instruments; the methods; the processing of the data; the scope of the work. Much, however, has remained: the preparedness of an institution to disseminate and transfer its experience and the need to augment its own knowledge and that of others by solving ever new problems.

NAVIGATION TESTS IN SMALL-SCALE MODELS

by Ir. R. Reinalda

For many centuries the Netherlands has been regarded as a maritime nation, a title which applies not only to the ocean navigation but also to inland water traffic. This entails that in the design of various hydraulic engineering works the demands made by navigation have to be taken into account. In this respect mention can be made of important activities like the construction and extension of harbours, the regulation and can- alization of rivers and the laying-out of ship canals.

Although many of these projects have been investigated in the Hydraulics Laboratory by means of small-scale models, navigation tests were omitted in former years. Usually the opinion of nautical experts was asked, or use was made of some general rules which have developed in the course of time. However, the big problems which have arisen by the development of the navigation have changed the situation. On the great rivers and canals larger and faster ships have appeared, which cause such a severe water attack on the embankments that in many cases the existing bank revet- ments have shown they are not proof against it. Then, too, the push-towing is developing very quickly and several canals and ship-locks have to be made suitable for this type of navigation. As for the ocean navigation, enormous tankers have been built in the past few years which are making high demands upon the ports called by them.

Because of these developments the nautical requirements often play such a prominent part in the design of hydraulic engineering works that it is not justified to rely only upon the opinion of nautical experts. In these cases navigation tests on a small scale are desirable.
In connection with the XVIIIth International Navigation Congress at Rome in 1953, where Prof. Ir. P. Ph. Jansen and Ir. J. B. Schijf reported on the water motion in canals caused by ships, comprehensive model tests on this subject were carried out in the Delft Hydraulics Laboratory in 1952. These experiments had the aim of checking the results of the simplified theory developed by Ir. J. B. Schijf, on which he had already reported at the International Navigation Congress at Lisbon in 1949.

The investigation was carried out with self-propelled cargo vessels on a scale 1 : 25, sailing through a straight canal. The ships were provided with electromotors moving the propellers, the velocity of rotation of which could be controlled. Since the main purpose was to study the water motion, the model ships were guided by a tightened cable over the length of the canal.

The model results confirmed the existence of a limited speed for a self-propelled vessel in a canal. It was found that whilst the depression of the water level caused by a towed ship tallies reasonably well with the calculated value, for self-propelled ships this depression is larger, because of the influence of the propeller on the flow pattern. Near the stern of the ship the depression of the water level is strong and consequently the settling of the stern of the ship is greater than the theory indicates.

Further, it appeared that overtaking is not possible if the difference between the speeds of both ships is too small, for then the faster ship is not able to leave the area of the depression of the water level caused by both ships, and they sail alongside each other with the same velocity.

Recently tests with free-sailing ships have also been made in order to check the navigability of harbour entrances, river bends, etc. Usually the plan of these investigations is the same. The model ships are equipped with electromotors operating the propellers and the rudders. The steering and the control of the propeller speed are done from the waterside via an electric cable, which also supplies the power for the electromotors. This cable is supported by a rod, the end of which is kept over the ship, so that no force is exerted on it. Accordingly the ship's manoeuvres are governed only by the propeller(s), the rudder(s) and possible currents. The manoeuvres are recorded by photos taken at certain time-intervals.
This system has been considerably developed during the years. At first the rudder could be moved to starboard or to port by making a contact in the steering case. As long as the electric circuit was closed, the rudder moved till it reached its maximum deflection, an indicator astern of the ship showing the position of the rudder. Nowadays the rudder position is controlled proportionally by a wheel on the steering case. Moreover, the actual velocity of rotation of the propeller is counted electronically and indicated on the steering case.

Because the model ships must be rather large to contain the electrical apparatus, the investigations have to be carried out on a large scale. Accordingly the models usually cover a wide area, and therefore most of these investigations are done in the De Voorst open air Laboratory in the North-East Polder.

A great number of investigations has been carried out according to the method described above. In this respect mention can be made of the study of the problems connected with the sailing into St. Anna Bay at Curaçao in 1954 and 1955. The scale of the model was 1:64, and the tests were performed with three model ships, representing tankers of different sizes. In 1956 similar tests were carried out for the entrance to the Botlek and the 3rd Oil Harbour in Rotterdam on a scale 1:75 with a tanker of 40,000 dwt. Another example is the study of the approach of a ferry boat to the landing-place in the port of Den Helder on a scale 1:50 in 1959. In the next year the proposed harbour of Terneuzen was investigated for tankers of 30,000 dwt and 50,000 dwt.

In 1960 the bifurcation of the rivers Beneden Merwede–Noord–Oude Maas near the town of Dordrecht was studied with a push-tow on a scale 1:60. After the completion of the Delta Works the flow conditions here will change, necessitating a modification of the lay-out. In the prototype the sailing-line of push-tows, when passing the bifurcation, was measured by taking photos of the radar screen on board a moored vessel. It appeared that a fair agreement existed between the manoeuvres in the prototype and in the model.

At this moment the bifurcation of the rivers Oude Maas–Dordtse Kil, likewise near the town of Dordrecht, is being studied for push-tows on a scale 1:40. The navigability of the rapids in the River Niger near the village of Bajibo is also under study for push-towing.
Photo 12  Navigation tests with a push-tow. Scale 1 : 60

Photo 13  Navigation tests for the North Sea Canal. Scale 1 : 50
In all these tests the electric cable necessary for the feeding of the electro-motors, the steering and the control of the propeller speed appears to have been troublesome. Therefore attempts have been made to construct radio-controlled model ships, although up to now the control of the rudders and the propellers has been defective, mainly as a result of the light and cheap construction. For these ships a small weight of the apparatus is very important, because also accumulators have to be placed in the ship. It seems, however, that the technicians have advanced so far that in the near future tests with radio-controlled model ships will be common practice.

Nevertheless several tests have already been carried out with radio-controlled ships. In 1959 the entrance of a proposed harbour at Suru near Bandar Abbas on the Persian Gulf was examined on a scale 1 : 175 with such a model ship, representing a tanker of 40,000 dwt. In the same year some possible lay-outs of the new moles at IJmuiden were studied with a tanker of 65,000 dwt on a scale 1 : 120. Also in 1959 the manoeuvring of ships for inland navigation when entering the ship-lock at Ravenswaay was examined on a scale 1 : 50.

Besides these, many other projects have been investigated in connection with their navigability with free-sailing model ships, but they need not be mentioned here separately.

Although these tests may be very helpful for the design of many hydraulic engineering works, some factors exist which cause discrepancies between the ship manoeuvres in the prototype and in the model. Some of these scale-effects will be discussed here.

It is well known that the resistance of a sailing model ship is relatively too big. Consequently the force exerted on the ship by the propeller must be higher than the theoretical value to obtain a certain speed. Therefore by changing the rotation velocity of the propeller, the speeding-up or slowing-down of the ship is not reproduced correctly.

Moreover, the force on the rudder caused by the propeller jet is also too large so that it may be possible for the rudder of a model ship to be more effective than in reality. Although the magnitude of this scale-effect is unknown, caution should be exercised.

Another problem is caused by the time-scale, based on the fact that the reaction of the helmsman of the model ship would be much faster than
in the prototype. Since the helmsman is not on board the ship, he does not observe a change in the course of the ship fast enough and consequently his reactions come too late.

Finally, it may be remarked that usually the helmsman of the model ship lacks navigation experience. It has appeared that much exercise is needed before his skill can be compared with that of his colleague in the prototype. Experience has shown that because of the scale-effects, navigating with a ship in a model is somewhat more difficult than in the prototype. Nevertheless, the results of navigation tests have a qualitative value in the respect that an opinion can be passed on the mutual effectiveness of different solutions. Moreover, an impression can be obtained of the difficulties to be encountered in reality.

Notwithstanding these problems, the Hydraulics Laboratory started in 1961 on a comprehensive study of the North Sea Canal which has to be deepened and widened because of the increase of the number and of the sizes of vessels calling at the ports of Amsterdam.

It may be pointed out that this model investigation will yield quantitative results, because the dimensions of the canal have to be determined. Therefore the influence of the scale-effects on the ship’s manoeuvres has to be eliminated as far as possible. On the basis of the results of model tests concerning the performance of ships in restricted waterways at the David Taylor Model Basin, and after consultation with the Netherlands Ship Model Basin at Wageningen, the scale of the model has been fixed at 1 : 50.

The experiments are being carried out with four model ships corresponding to a cargo vessel of 10,450 dwt, a tanker of 47,600 dwt and two tankers of 70,000 dwt. The ships are self-propelled and the three tankers are so big that the helmsman can sit in them.

In order to get some insight into the ship’s manoeuvres in the prototype, measurements have been carried out on board sea-going vessels passing through the canal. The position of the ship was recorded by photos from the ship’s radar screen every minute, or by using a range-finder and the ship’s compass. Further, the position of the rudder and the rotation velocity of the propeller were noted. Moreover, the encounter of two vessels in the canal has been measured by taking photos from a helicopter. Though attempts have failed to reproduce exactly some of the manoeu-
vres which have been measured in the prototype, the impression has been obtained that the manoeuvres of the ships in the model correspond very well to those in the prototype. Measurements have been made to assess the relation between the rudder angle and the distance of the ship’s centre from the axis of the canal, and the results already give an impression of the effect of a certain widening of the canal in respect of its navigability. Moreover, tests of the encounter of vessels have been executed, which have been recorded by photos. Though the investigation is still in progress at present and the results have not yet been fully elaborated, it is already sure that the width of the canal can be smaller than foreseen in most of the designs.

Similar tests will be carried out for canals for inland navigation on a scale 1 : 25. A model has been built with a length of 600 feet in which the encountering and overtaking of push-tows, hawser-towed vessels and self-propelled cargo vessels will be studied in order to ascertain the most economical depth and width of canals with a certain intensity of traffic. As a part of this investigation, experiments on different scales are carried out to determine the influence of the scale-effects on the manoeuvring of model ships. These tests are being done in co-operation with the Netherlands Ship Model Basin at Wageningen and the Laboratory of Shipbuilding of the Technological University at Delft. Measurements on board a push-tow in a canal will also be made.

It has appeared that in many cases the results of navigation tests are strongly influenced by the individual factor. To get detached results this factor has to be eliminated, which can be realized by an automatic pilot. A prototype of such an apparatus has already been tested, and probably will be used for the investigation mentioned above. The principle is that the model ship follows an electric cable lying on the bottom of the canal, so that the sailing-line is fixed. Manoeuvres can be performed by using a set of cables and switching over from one cable to another according to a certain programme. The steering of the ship is done automatically. It may be further reported that, besides navigation tests, other types of experiments with model ships are also carried out by the Hydraulics Laboratory. In this respect mention may be made of the measurement of mooring-forces on ships in locks, the study of the motions of moored and sailing vessels by waves and tests on the launching of ships.
In recent years the digital computer in hydraulics research has become a more and more important factor in hydraulic engineering. The possibility of fast numerical calculations is now becoming decisive as to whether a problem has to be solved by calculation or by hydraulic model investigation.

The advantage of the computer is that quite different geometrical but topologically similar situations with a certain type of problems can be covered by the same programme. After use the mathematical model can very easily be "stored" for later use in similar cases. On the other hand, however, the hydraulic model does not need a complete mathematical description of the problem, but it uses in fact only the knowledge about hydraulic similarity-laws for the special problem.

Though the computer can solve the problem only if a fair "mathematical model" can be formulated, its large capacity will be of great help for the formulation and testing of new mathematical descriptions of phenomena. A good example of a problem for which a good mathematical model can be formulated is provided by open channel flow on a fixed bed. For tidal movement the calculations based on the linearisation of the resistance after Lorentz have already been carried out during the latest decades. Tidal models became important as the area to be covered was too large for calculations by simple means. The modern development will be that more tidal problems can be solved by calculations. Calculations of the water movement on flood-plains of rivers at high discharges were carried out for a long time in the Netherlands by the Research Section for the Upper Rivers of Rijkswaterstaat. Also in this case a switch-over to the computer has been made.

Another type of problem of open channel flow is formed by hydraulic networks. In many cases this flow can be considered to be steady, and in these cases the relaxation of discharges and water levels following the two "Kirchhoff" Laws can be carried out very quickly. Complicated systems of open channel networks, very common in the Netherlands, can be studied on discharge of large rainfalls in the wet season or for economic water supply in the dry season. In quite a few cases the phenomenon is
non-steady, as a certain area has to be discharged by sluices or pumping-stations into the sea. This calculation problem for the computer, the non-steady flow in open-channel networks, is under study.

In the above-mentioned cases the hydraulic problem is wholly solved by a computer. The combined use of a hydraulic model and a mathematical model is also possible. Two different examples can be given. For the design of the Haringvliet sluices the hydraulic model in the wind flume is used to determine the load on the structure, the stresses in the gates and the supporting "Nabla beam" are calculated. Besides that, direct control measurements of stresses on an elastic similar model were possible. On the other hand, the river model of the bifurcation at Westervoort is treated in the opposite way. The computer calculations give the boundary conditions for the model and the hydraulic model gives the changes in the bottom at the bifurcation.

Another group of calculations is found by the very important treatment of measuring data from model and prototype. Measurements of tides, waves and vibrations of structures are analysed to obtain information about the phenomena observed and about the reproduction in the model. In all these cases large amounts of data have to be analysed to obtain significant results.

The use of the computer may also lead to better understanding of hydraulic phenomena. Mathematical models about phenomena, i.e., diffusion of effluent waters, density currents and tracer experiments for sand-transport studies, form examples in this field. Measurements of data can be correlated with theoretical models in order to find the important parameters.

Much of this basic research work is done in co-operation with the special services of Rijkswaterstaat (Ministry of Waterways) and the Delft Technological University.

Summarizing, it can be stated that the use of a computer in hydraulics research will lead to changes in the treatment of hydraulic problems directly by the speedy treatment of wellknown phenomena and indirectly by the better understanding of complicated phenomena for which much research work has still to be carried out.
When writing the history of investigations of coastal models in recent decades it becomes clear that the principal approach to the problem has not changed a great deal. Although the knowledge of the phenomena and the experience in interpretation have increased considerably, the most important task of the model is to be a tool in judging and comparing different possible solutions rather than to provide exact data of shoaling and developments of bottom configuration.

It is neither possible nor necessary to review here all investigations concerning harbours and coasts which have been executed by the Laboratory. Only those studies will be mentioned which will give a better insight into the development of this part of the work of the Laboratory. In this respect it is a favourable circumstance that several models have been investigated twice at Delft, so that it is possible to see the progress which has been made in the approach to the study, then and now.

The first investigation of a harbour entrance, viz., the entrance to the “Rotterdam New Waterway” at “the Hook of Holland” was made even before the establishment of the present Hydraulics Laboratory. It was carried out by “the Rijkswaterstaat” (Ministry of Waterways) and aimed only at a better insight into the phenomena occurring at the entrance of the Waterway.

It was this problem again which was one of the first coastal engineering problems studied by the newly-erected Hydraulics Laboratory. In the report of this study it was stated once more that it would not be possible to obtain exact and definite results from the tests but that an increase and deepening of insight into the phenomena was one of the most important aims of the study.

Because of the small space available in the cellars of the building of Civil Engineering of the Technological University where the laboratory then was housed, the model could be only small. The scale factor for the horizontal dimensions had to be 1000 and for the vertical dimensions 150. Firstly, only current patterns were studied, and from the velocities possible shoaling due to silt depositions was predicted. Later also tests with
a movable bed were executed. As bottom material pumice sand with a density of 1500 kg/m³ and an average grain size of 2 to 3 mm was used. In the years from 1959 to 1962 further tests concerning this area have been carried out in the Delft section of the Hydraulics Laboratory. There was no major difference in the general set up, even the scales being in the same order of magnitude, viz., 800 vertically and 125 horizontally. Due to the bigger area to be investigated because of the large dimensions of the new entrance to be made, the model covers a much wider area, while now a bottom material with the same density but a grain size of only 0.2 to 0.3 mm, was available, viz., fine ground bakelite. With the aid of a wave generator to activate the movement, it was possible to obtain information about the development of the bottom configuration as result of bedload movement. For detailed information in the entrance itself a much bigger model on scales 250/80 in the De Voorst Laboratory has been used.
The most salient difference between the two studies is the fact that in the latest study a much greater accuracy in the comparison between the different solutions has been obtained.

A milestone in the development of this type of model studies was the investigation for the Port of Abidjan on the Ivory Coast. In this model, with scales 270/120, the entrance of the de Vridi Canal to the Port of Abidjan was studied. This canal had to be dredged in order to give access to the lagoon in which the new Port of Abidjan was to be built, sufficient depth being obtained by the tidal currents in and out of the lagoon. The relation between the cross-section of the canal and the tidal current was calculated by means of a tide calculation with linearized resistance as developed by Lorentz. The model was to give an answer to the question of possible shoaling of the entrance due to the littoral drift generated.

Photo 15
Model of harbour entrance of Abidjan (Ivory Coast) in the laboratory de Voorst
by the long waves approaching the coast under an angle almost constant all over the year and coming from the "roaring forties".

In this model the sand movement along the coast which would probably shoal the entrance of the canal was reproduced in such a way that reliable results could be obtained. The sand of the prototype, which had a grain diameter of about 0.5 mm, was reproduced by pumice sand with a grain diameter of about 2 to 3 mm, and a test was also made with fine sand with a mean grain size of 0.2 mm, which gave slightly different results. As no comparison was possible with tidal outlets protected by moles, it was very difficult to determine only from theoretical considerations which material would reproduce the details of the bottom configuration in the best way. The final tests were done with pumice sand and the development of the situation in nature since completion of the work agrees for the greater part with the tests. The shoal which was predicted by the Laboratory to be formed, and which, according to the tests, should for the greater part lie on the downdrift side of the entrance channel was formed, however, on the updrift side of the channel, and is likely to have the tendency to develop in a way which seemed to be less favourable for navigation. As there were some differences between the lay-out of the mole in the prototype and the alignment investigated in the model, and because during the construction some stone outcrops have come into being on the canal side of the updrift moles, in 1960 the Government asked the Laboratory to make another model investigation. By this model investigation the influence of the differences in alignment and of the stone outcrops should be determined, and the possible development of the shoal in the entrance should be studied. A model on scales 150/60 was built, and fine sand was used as bottom material. This time it was possible to calibrate the model with the development of the shoal in the entrance during the last few years.

It proved to be possible to predict with reasonable accuracy from this second model investigation the development of the shoal in front of the entrance: that it would not extend much more into the channel and that a safe solution could be obtained by a slight shift of the approach line, or by a limited volume of maintenance dredging. The fact that in the second model more accurate and definite results could be obtained is, apart from the better calibration possibilities, also
the result of the better understanding of the phenomena which determines the development of the bottom configuration under the combined influence of waves and currents.

After the first tests of Abidjan in 1930 a series of harbours on sandy coasts have been investigated. Among investigations for foreign countries, the Port of Lagos was one of the most important. In this model, with scales 500/180 and pumice sand as bottom material, the possible shoaling of the harbour entrance and the erosion of the downdrift beach were studied. Although the results obtained from this investigation were rather definite, another test was ordered within 5 years of the completion of the tests in the first model. The reason for the second model was the wish to have a model, not only of the entrance and coast, but also of the interior of the harbour permanently available. The second model had scales 200 and 50 and fine sand as bottom material. The results concerning the erosion of Victoria Beach – the downdrift beach – and the possible shoaling of the entrance obtained in the first model were completely proved by those of the new one. Of course, due to the smaller scale factors more detailed information could be obtained.

From these differences between the old and new versions of the above-mentioned models it should not be concluded that fine sand in the model always guarantees a better reproduction than a bottom material with smaller density. Also during the more recent years coastal models in which a material of small density was used as bottom material have been built. For instance, both the model of the harbour extension of IJmuiden, and of the tidal inlet to Limfjorden at Thyboron in Denmark have ground bakelite ($\rho = 1300$ kg/m$^3$) as bottom material. In these cases, however, the main point of the investigations was concentrated in relatively deep water under the combined influences of waves and currents.

From the above-mentioned investigations the Laboratory has gained so much experience that at this moment tests for coastal problems can be executed with great confidence. It is, however, still necessary to calibrate the model thoroughly by comparing it with a development in the prototype, the so-called historical method. Therefore a special study has been set up to determine the fundamentals upon which the choice of scales is based in such a way that even without the possibility of a comparison with a known development in the prototype the scales can be determined.
In main lines these scales concern:
a. the distortion of the model with regard to the reproduction of the
   beach slopes on the one hand and the resistance with regard to the
   reproduction of the current pattern on the other hand; and
b. the scales for the wave heights and lengths on the one hand and the
   scale for the current velocities on the other hand with regard to the
   combined effect of these phenomena on the bottom material move­
   ment and with regard to the stream refraction.

Another type of coastal problem is that of harbours in estuaries. In these
problems waves are mostly of only minor importance on the bed load
movement, so that in these models only currents have to be reproduced.
The choice of the scales is in this case somewhat simpler and, moreover,
based on the vast experience with river models.
The last group of model investigations for harbours concerns the investigation of the wave penetration into a harbour due to refraction and diffraction.

The principal approach has hardly changed during the existence of the Laboratory; the techniques of the wave recording, on the other hand, have changed a great deal. Originally the waves were registered by mechanical means, such as writing points mounted on light floats, but later on different electrical and electronical wave recording devices have been developed. The recording technique nowadays is the registration of a sufficiently large number of waves at a certain place in the model in order to obtain from this record the mean wave height. The next development will be a registration by which a wave height spectrum will immediately be obtained. This can probably be realized by means of registration on a tune band and plotting by electronic computer. It will remain necessary, however, to give the investigator an idea about the wave height on the spot.

Also for this type of investigation the decrease of the scale factor has led to a better insight into the phenomena occurring behind a breakwater. This resulted in the broad-headed breakwater which in some cases can give much lower wave heights in the harbour than a normal breakwater.

Summarizing, it can be said that although the principles according to which the model investigations for harbour and coastal problems are executed have remained the same, there has been a gradual development of knowledge and model techniques which makes it possible to obtain nowadays much more detailed information from the models.