PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

WAVES GENERATED BY LANDSLIDES.

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1. INTRODUCTION.

Landslides have occurred several places in the world through the years. Some of the slides that have entered or occurred in water, have caused disastrous water waves.

The size of the waves is governed by many factors, among others and probably the most significant the length, width and thickness of the slide, the slide velocity and the water depths. The wave pattern at a certain point will depend on the distance from the slide area, the water depth and bottom configuration.

The generation of slide waves has been studied by observation in nature, theoretically and by model tests. The problem is very complex. The theoretical work is usually based on great simplifications. However, the theoretical work is useful to understand the nature of the problem and as a guide to interpret observations in nature and model test results.

In Norway several slides that have occurred in narrow fjords and lakes have caused disastrous waves.

The Norwegian Geotechnical Institute has in one of their publications (1) given a review of the Norwegian slides causing disastrous waves.

Based on the data in this publication we have made a plot in Fig. 1 of some of the most disastrous wavegenerating slides in Norway. For each slide the slide volume is plotted against the height of the slide area above waterlevel. The maximum runup R_{max} is given

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for each slide.

Earth quakes have on many occasions triggered large slides causing disastrous waves. In July 1958 an earthquake triggered a large rock slide in Litua Bay, Alaska that caused a tremendous wave which ran up 524 metres on the side of the fjord opposite the slide area. (1), (2). During the Alaskan earthquake in March 1964 slides generated damaging waves at many places, among those being Valdez, Whittier and Seward. (3).

From an engineering point of view interest in slidegenerated waves has increased considerably after the rock slide into the reservoir behind the Vaiont Dam in Northern Italy in October 1963 generating a disastrous wave that killed approximately 2000 people.

It has become increasingly of interest to be able to predict a) the possibility of slides into a water body and b) the waves generated by the possible slide. Thus the problem of slide generated waves is a geological/geotechnical/hydraulic problem.

Allthough there are many descriptions of prototype slides and slide generated waves, the data are scanty regarding the relevant factors mentioned above on the size of the waves. It is therefore difficult to use data on prototype slides to predict slidegenerated waves at other areas.

Two case model studies regarding slidegenerated waves will be described in this paper. Allthough there are limitations in solving slide generated wave problems by model tests, such tests are nevertheless a valuable tool.

The tests were carried out at the River and Harbour Laboratory at the Technical University of Norway and delt with

1. Land slides in a future reservoir behind the Viddalsvatn rockfill dam, Aurland power plant. Sponsored by the Oslo Power Board.

2. Rock slides into the lake Årdalsvatn. Sponsored by the Governmental Committee on Evaluation of Slide Danger in the Årdal Area.

2. MODEL SCALES AND SCALE EFFECTS.

The forces relevant to model tests of this type are inertia forces, gravity forces, viscous forces, capillary forces and elastic forces. It is not possible to reproduce more than two forces in the same relation. When designing the model emphasize has to be given to the two most significant forces. When transforming the results from the model to the prototype scale effects due to other forces have to be taken into account.

The significant forces regarding waves are the gravity force and the inertia force. When considering these two forces the results from the model to the prototype is transformed according to Froude model law.

The model scales in the two studies were chosen as a compromise between as large a model as possible to avoid scale effects and economical considerations.

Calculations were made regarding scale effects from laminar and turbulent damping of the waves as they travelled away from the slide area. These calculations showed that laminar and turbulent effects would be of any significance only in very shallow water.

Scale effects due to the surface forces were observed. Through observations on the model and calculations the results were corrected for this scale effect and also for the scale effects from laminar and turbulent damping in shallow water.

Model effects from uncertainties in the input data in the models are discussed later.

3. LANDSLIDE IN VIDDALSVATN RESERVOIR, MODEL TESTS.

The Aurland water power scheme includes the construction of a rock fill dam at the end of the lake Viddalsvatn in Aurland, western Norway. On completion of this dam the water level will rise from el. 864.0 to el. 930.0. The reservoir will be about 8 km long and 0.4 - 0.7 km wide. The surrounding mountains rise steeply from both shores of the future reservoir, and at the foot of the mountains there are several conic piles of stone and gravel, one of them about 1300 m from the dam, Fig. 2.

There is a possibility that the varying water level in the reservoir will disturb the stability of these piles and cause a landslide into the reservoir. A slide may set up sizable waves which in turn may endanger the safety of the dam. A breakdown of the dam would no doubt have a disastrous effect on the built-up areas downstream.

Preliminary geological investigations have shown that the danger of starting a landslide is very small, but if a slide does occur its size is expected to be of the order of 150.000 m^3, most of this being below the water surface. Fig. 3 shows a cross-section through the possible slide area.

To determine the wave size to be expected and find means of protecting the dam, the builder decided to have model tests carried out.

The model was built to a scale of 1:500 and comprised the future reservoir and its surroundings.

Some preliminary tests were carried out using sand as sliding material in the model. However, the sand would not slide when placed in the model to form the prototype thickness and slope. In order to get the sand to slide it had to be placed on a plate with an exaggerated slope. The velocity of the slide was in this way uncontrolled. To have a better control on the model procedure a test arrangement was made as shown in Fig. 4. The test procedure was as follows:

The sand and gravel masses were replaced by one solid mass which was placed in position attached to a string which ran over two pulleys and carried an adjustable counterweight at the other end. When the slide was released, the counterweight controlled the slide velocity. The time/displacement curve of the slide was established by electrical measurements on one of the pulleys, and the resulting waves were recorded at the positions 2, 3 and 4 in Fig.2. Parameters for the tests were the slide velocity, the elevation of the starting point and the shape of the sliding masses.

Preliminary tests showed that only slides in the position 1300 m from the dam could cause waves of a size that might endanger the dam stability. Slides in this position tended to generate a train of waves that lasted for 4 - 4.5 minutes (prototype values) and comprised 6 - 9 major waves.

Three types of slide configurations were used as shown in Fig. 5.

Fig. 6 shows samples of a wave recording and a position-time curve for the slide.

In Fig. 7 and 8 results from two test series are shown. The diagrams show observed wave heights at points 2 and 4 as a function of slide velocity and with starting elevation and slide shape as parameters.

The model results can be summarized as follows:

1. The wave heights attain a maximum value for a certain slide velocity. If the slide velocity increases beyond this value the wave heights decrease. The explanation of this fact is probably that increased slide velocities cause more splash and shorter and steeper waves which break more easily, so that a greater part of the slide energy is converted into heat through turbulence instead of being transmitted in the form of waves.

2. An increase in thickness of the slide tends to increase the wave heights, even if the mass of the slide is unchanged.

3. The wave heights are higher for starting elevation + 990 than for starting elevation + 930 for the same maximum slide velocity. This is apparently due to differences in the time - displacement curves for the slide.

So far the model tests results. How then to interpret the model results to apply them to prototype conditions? The model results show that the slide form and the slide velocity are significant parameters. However, can we from present knowledge on geology and soil mechanics tell anything about slide velocities and which forms slides attain? In our opinion it is very difficult to give an exact answer on this. We feel that in order to be able to predict slide-generated waves better, more research is needed on the dynamics of slides.

In the case study for Viddalsvatn the free fall velocity of the slide was calculated to be 20 m/sec when the top of the slide was on elevation + 930.0 and 38 m/sec when the top of the slide was on elevation + 930.0 and 38 m/sec when the top of the slide was on elevation + 990.0 m. The slide was assumed to travel to the bottom of the reservoir.

A prototype slide will certainly not reach these velocities. Nevertheless it was preliminarily decided to investigate the stability of the dam against the train of maximum waves that was recorded in the model. The stability investigations were carried out in a two dimensional model on scale 1:30. The results of the stability investigations showed that the problem can be engineered. But there will be a final decision later on based on economical considerations when more investigations have been carried out on the slide area. Possibly part of the slide masses will be removed rather than taking necessary measures against failure of the dam from possible slide generated waves.

4. ROCK SLIDES INTO THE LAKE ÅRDALSVATN - MODEL TESTS.

4.1. Introduction.

Årdalsvatn is a narrow lake located in the western part of Norway. The lake is about 8 km long, and has a maximum depth of about 200 m. The mean water level is 2,4 m above sea level. Fig. 9 shows a map of the lake. The Ministry of Agriculture appointed in 1968 a committee to evaluate the danger of slides along the lake and what measures should possibly be taken against slides and slidegenerated waves to protect the large industrial settlements at the ends of the lake.

Preliminary geological investigations showed that the most dangerous areas were possibly at Stedjeberget, an almost vertical cliff adjacent to the lake. The largest possible slide at this point was estimated to have a volume of 120.000 m^3 with an extension from elevation - 20 m to + 175 m. Fig. 10 shows a cross section through the slide.

Most of the tests were concerned with the waves caused by the fall of this piece of rock into the water. However, during the tests it was also discussed to what extent the falling piece of rock could trigger an underwater slide in possible sand masses under water. Echosoundings of the bottom were made and the underwater masses that possibly could slide was preliminarily estimated to 4 mill m^3. The preliminary estimated underwater slide area is shown in Fig. 11. Some preliminary tests were also made regarding the waves from such an underwater slide.

4.2. The model of Årdalsvatn.

The model was built on scale 1:250. Tests with slides at different places were carried out. However, only the most important one at Stedjeberget is referred to in this paper. The estimated sliding piece of rock was simulated in the model by a piece of concrete which was suddenly released and fell by gravity into the water. Fig. 12 shows a photograph from the model just after the slide had been released.

For the underwater slide a technique similar to the one used in the Viddalsvatn slide tests was used, Fig. 13.

4.3. Test results.

4.3.1. Waves from the 120.000 m^3 piece of rock.

Several test runs were made and waves and runup were measured at several places along the lake. The maximum wave height (trough to crest) in the vicinity of the slide area was 8.8 m. Close to Årdalstangen the maximum wave height was about 1.0 m and at Øvre Årdal 3.2 m.

The wave height and runup varied and were partly irregular depending on the distance from the slide, depth conditions, reflections and possibly resonance oscillations in parts of the lake basin.

Fig. 14 shows samples of wave recordings at different places. These samples show that the character of the wave train changed as the waves travelled along the lake.

In the vicinity of the slide area the periods of the maximum waves were 13 - 14 sec, Fig. 14. At Rausnes the period of the maximum waves were about the same or slightly higher. At Øvre Årdal the period of the highest waves were 35 - 40 sec and at Årdalstangen the period of the maximum waves were of the same magnitude, 35 - 50 sec.

The reason for the increased period of the maximum waves at the shallow areas at Årdalstangen and Øvre Årdal is partly dispersion.

It is also believed that the shoaling effects caused higher period waves to increase in height more than lower period waves. Possible resonance effects may also have been present, although this was not particularly investigated.

The maximum waves decreased with distance from the slide area. In Fig. 15 is shown maximum wave heights at different distances from the slide. The envelope of the waveheight data is expressed by

$$H = k \cdot H_o \cdot x^{-\delta}$$

where

- k = coefficient
- H_o = wave height in the vicinity of the slide
- x = distance from the slide
- δ = exponent

The envelope of Fig. 15 defines an exponent $\delta = 0.458$.

We have in Fig. 16 plotted the runup along Tafjord due to the slide on 7 April 1934 (1). In this diagram is also drawn an approximate envelope corresponding to $\delta = 0.458$.

A similar diagram Fig. 17 was made regarding runup along lake Loen due to the slide on 13 September 1936 (1). The envelope curve in this case defines an exponent $\delta=0.955$. The differences in the "decay-results" is, however, not possible to explain from the available data.

Results from the preliminary tests regarding waves generated by the underwater slide are shown in Fig. 17. The maximum wave height close to the underwater slide area is shown as a function of maximum slide velocity and sliding distance L. (See Fig. 13).

In interpreting the data from the underwater slide tests the same difficulties are met as mentioned above on the Viddalsvatn slide tests. A better estimate of the slide generated waves would require more data and knowledge on the properties of the underwater masses.

The results from the model tests are used to evaluate different safety measures against the slide generated waves. No final decisions have been made so far.

5. GENERAL COMMENTS.

As stated above, hydraulic model tests are of value in estimating the height of slide generated waves. The problem is a geological/ geotechnical and hydraulic one. It is the geotechnical/geological data that are the input in the model whether this is a mathematical or hydraulic one. In the case study at Årdalsvatn the input in the model is reliable when the size of the piece of rock has been estimated by the fault system. In the case of the slides in the masses in the Viddalsvatn reservoir and the underwater slide in Årdal lake the input is not adequately known. To be able to give a better prediction of waves generated by possible slides of sediments, it is necessary to have more knowledge on the behaviour of the sediments during sliding.

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2. MILLER, D. J. (1960): Giant waves in Litua Bay, Alaska. Shorter Contributions to general geology 1960, p. 51-86. US Department of the Interior, Geological Survey, Professional paper 354.

3. WILSON, B. W. and TØRUM A.: The tsunami of the Alaskan Earthquake 1964. Engineering evaluation. Technical Memorandum No 25, May 1968. US Army Corps of Engineers, Coastal Engineering Research Center.

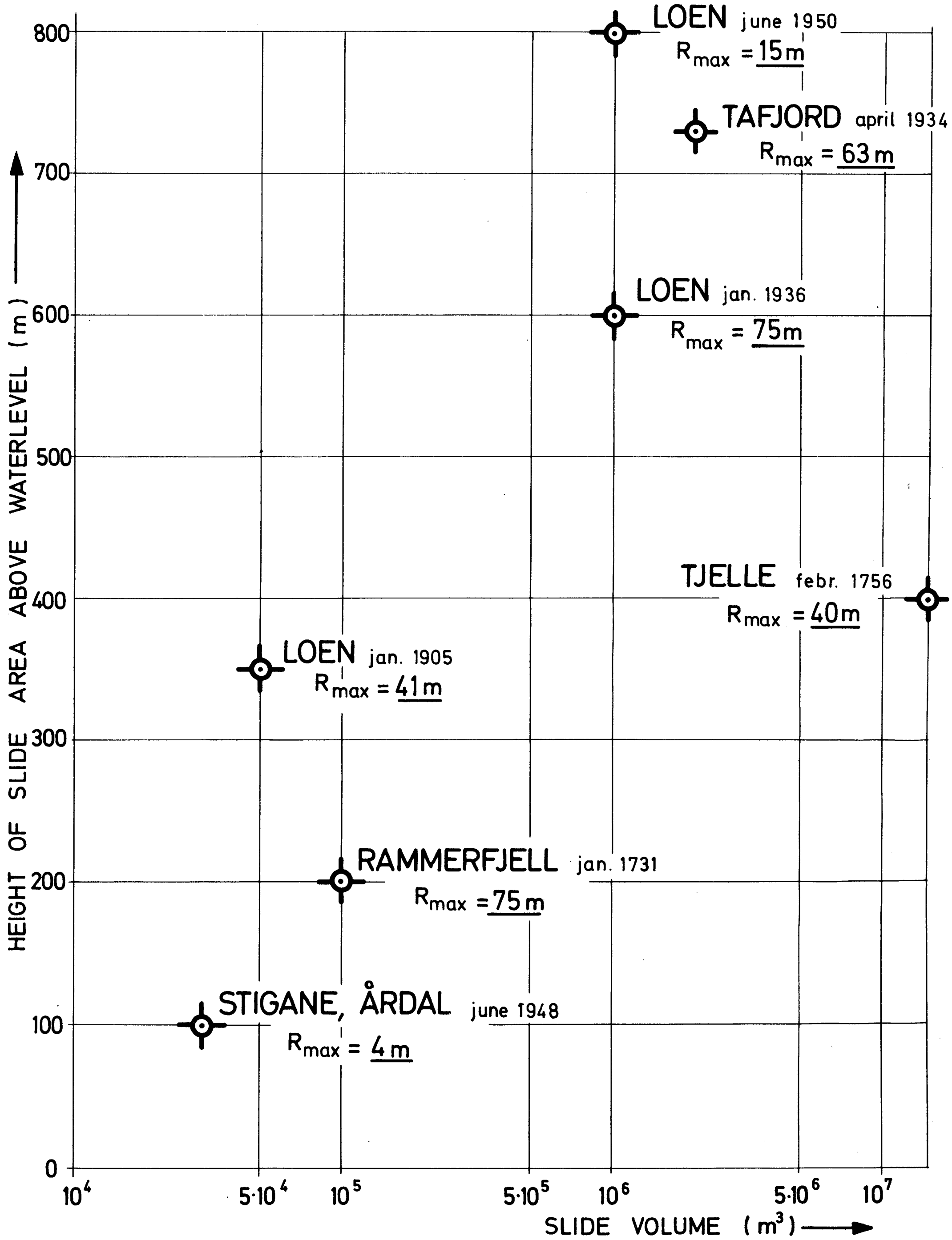


FIG. 1 MAX RUN-UP AT DIFFERENT NORWEGIAN SLIDES

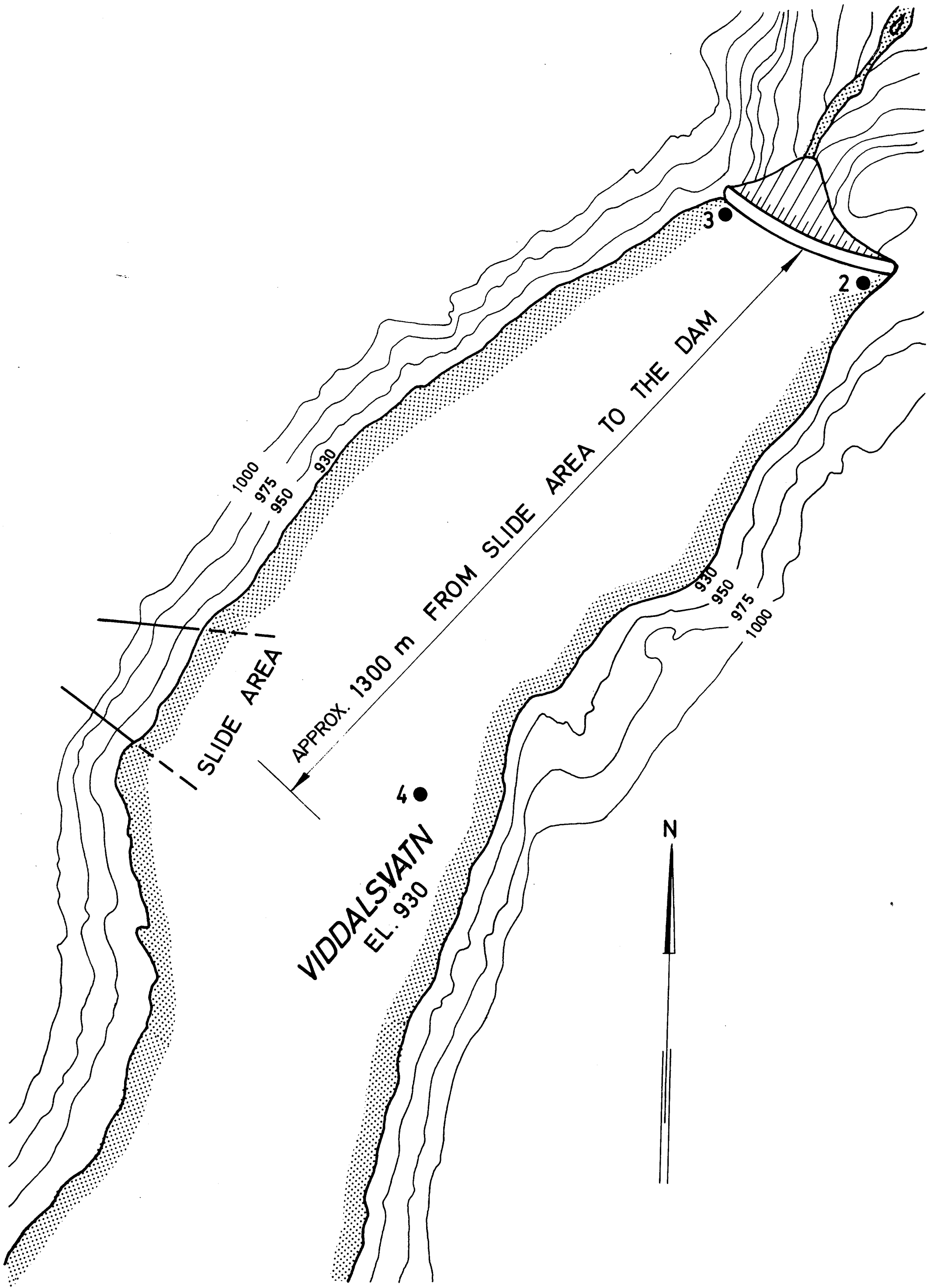


FIG. 2 MAP OF PART OF THE VIDDALSVATN RESERVOIR

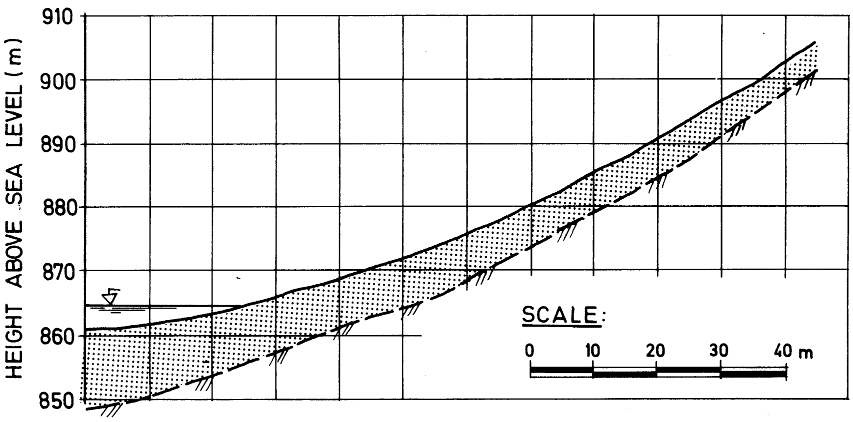


FIG. 3. VIDDALSVATN
PROFILE TROUGH THE SLIDE AREA.

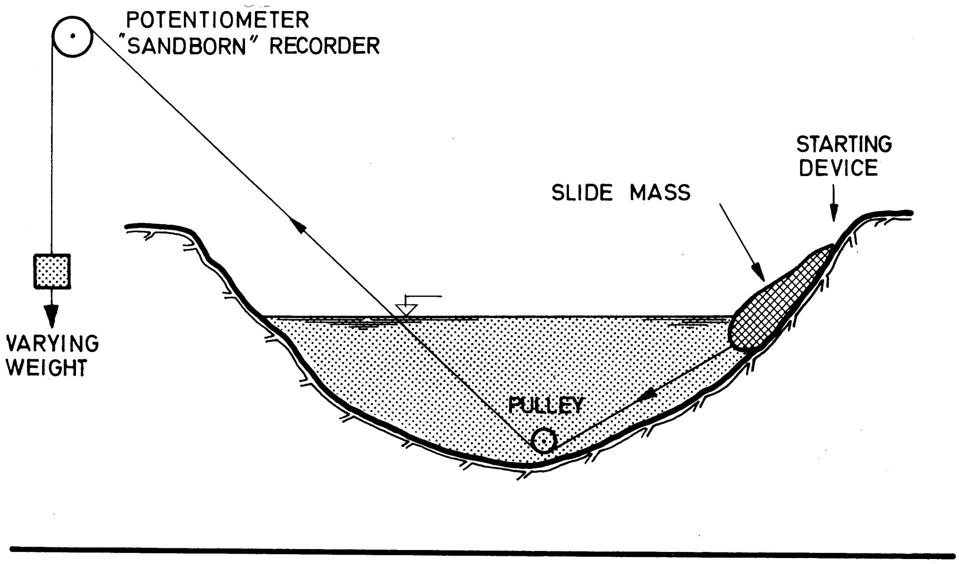


FIG. 4 VIDDALSVATN
TEST ARRANGEMENT

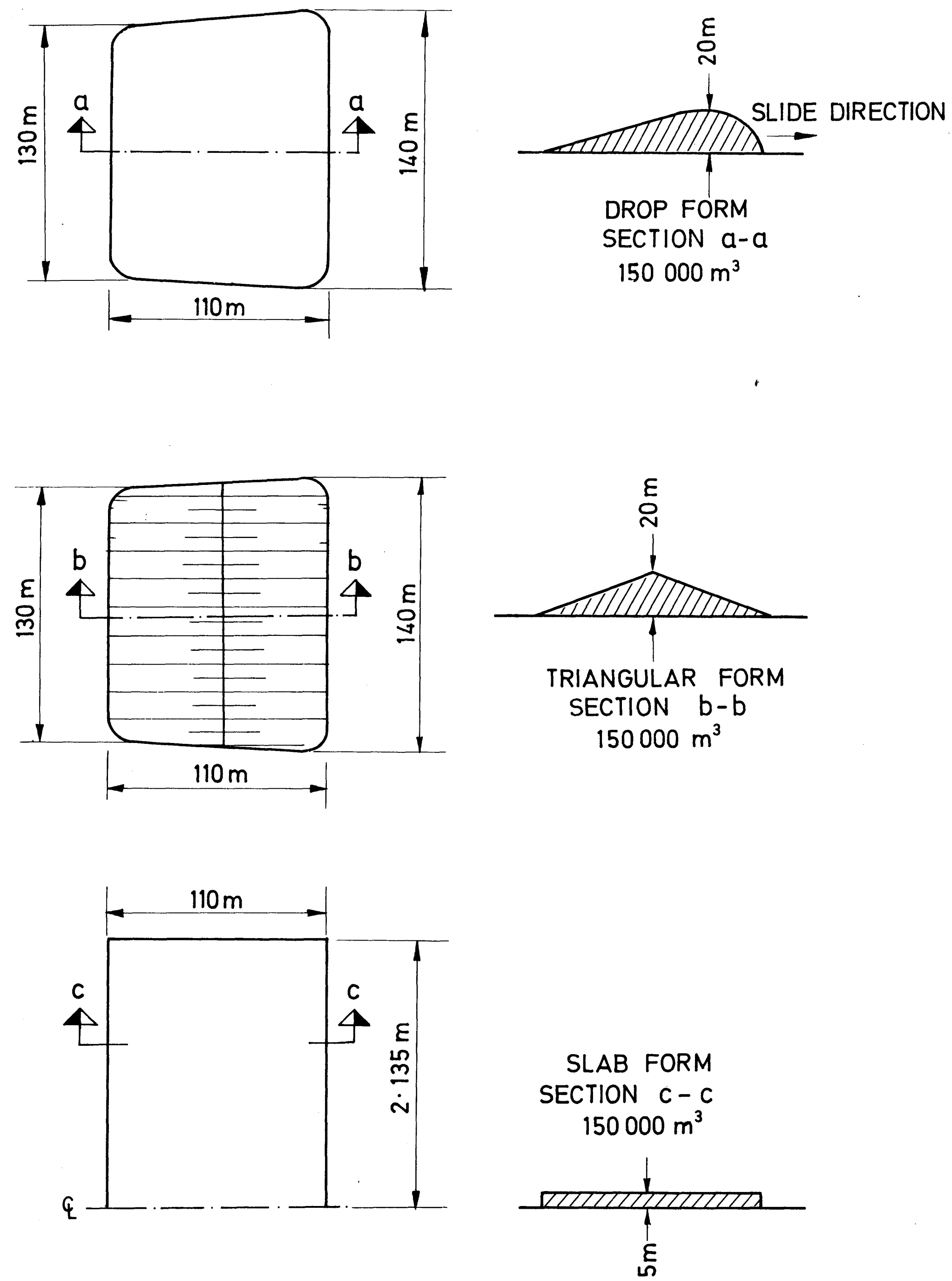
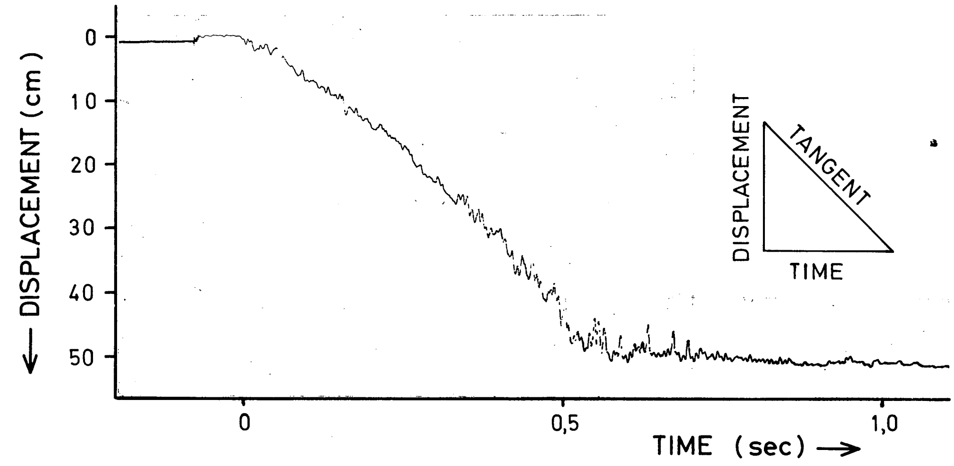
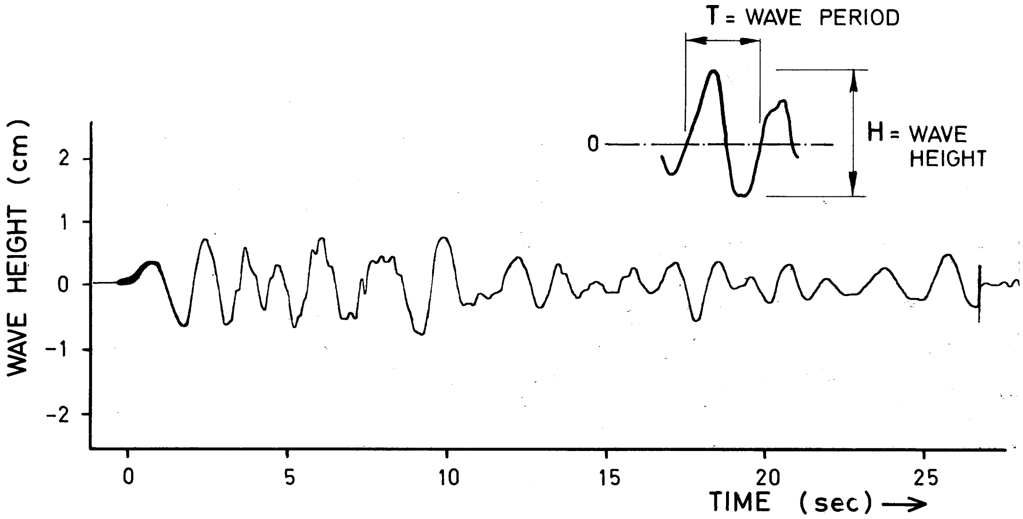


FIG. 5 VIDDALSVATN

DIFFERENT SLIDE CONFIGURATIONS



DISPLACEMENT— TIME CURVE



WAVE RECORDING

FIG. 6 VIDDALSVATN

SAMPLES OF DISPLACEMENT - TIME - CURVE AND WAVE RECORDINGS (MODEL - DATA)

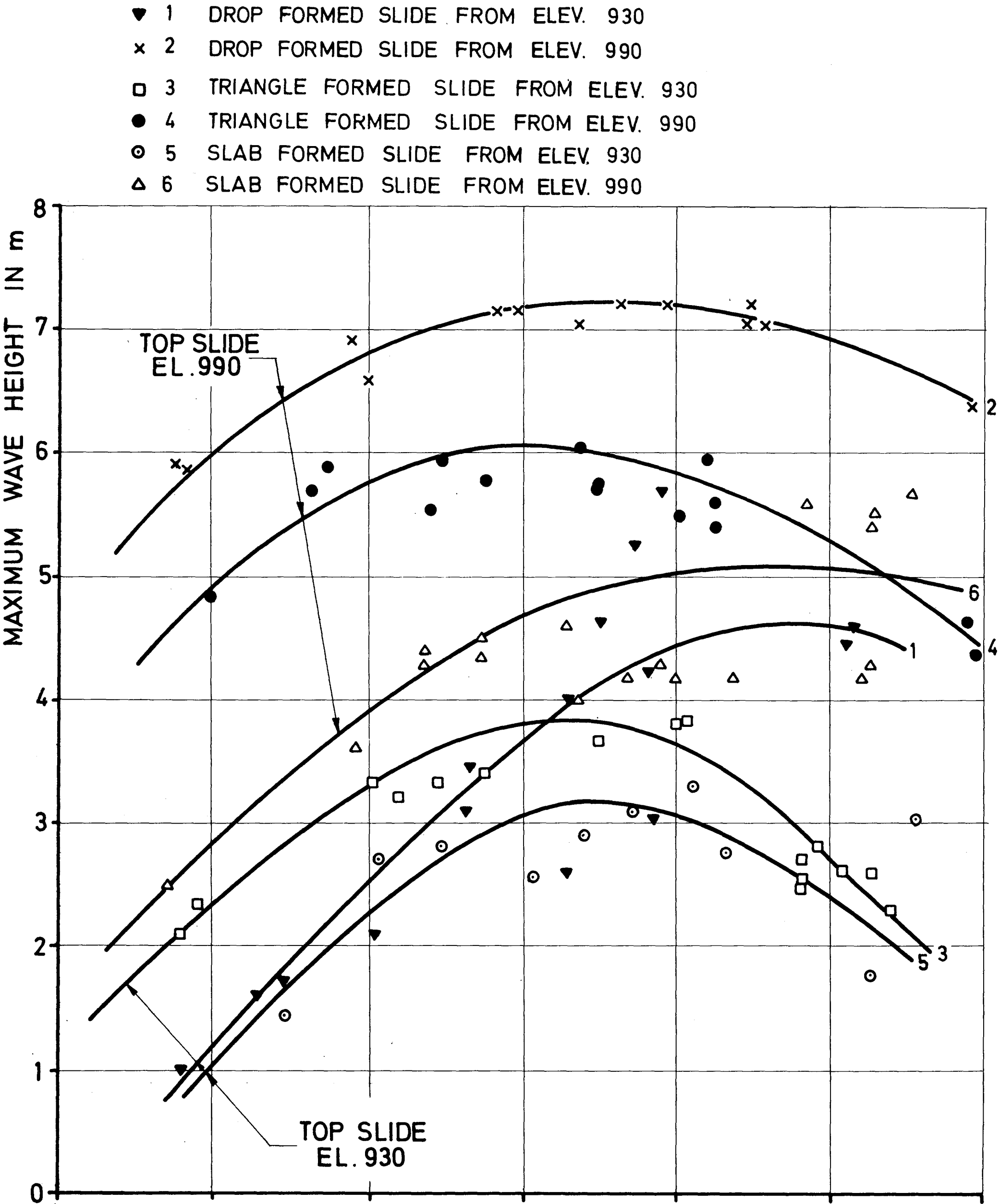


FIG.7 VIDDALSVATN

MAXIMUM WAVE HEIGHT IN POINT 2.
WATERLEVEL IN RESERVOIR + 930,0

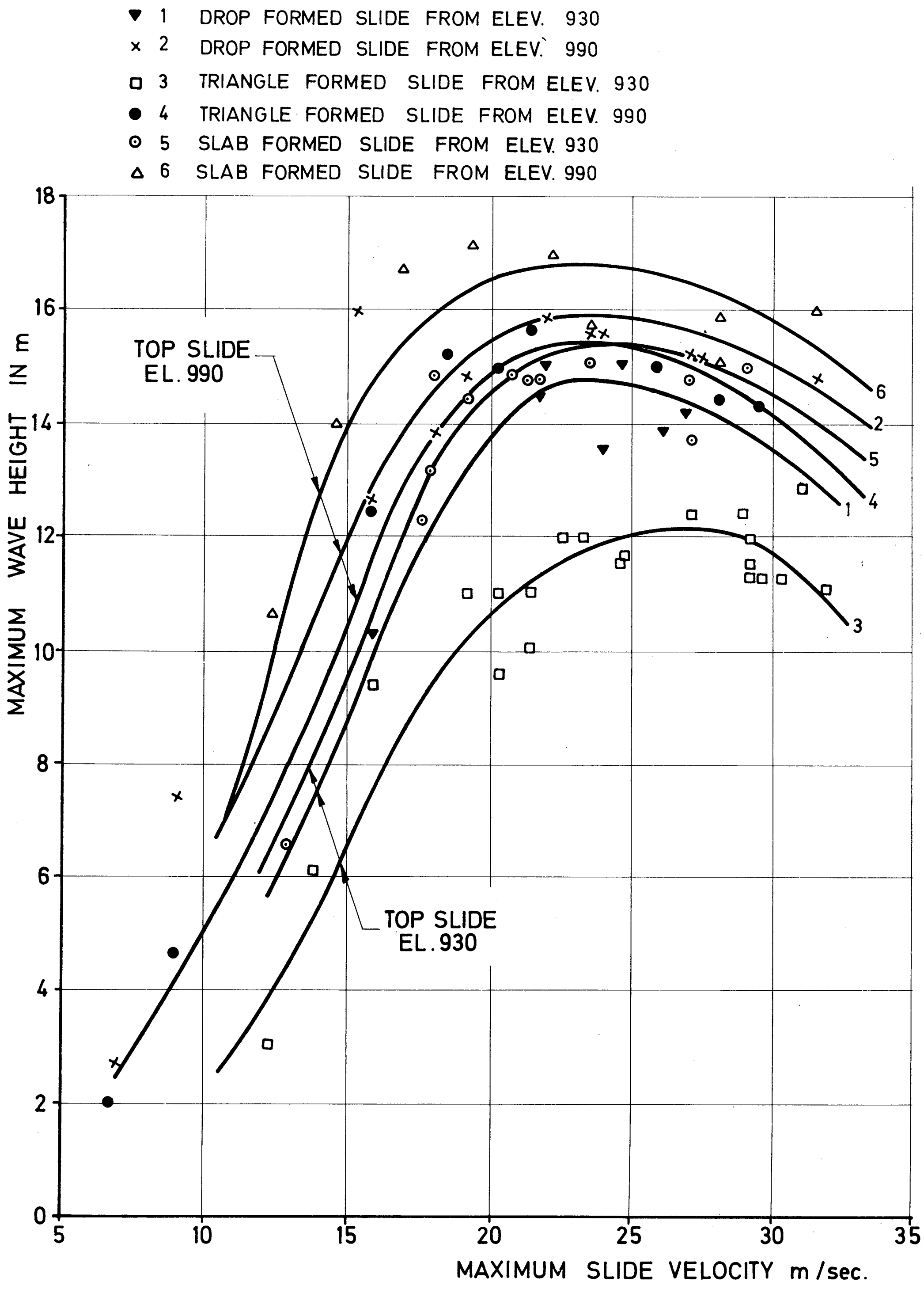


FIG. 8 VIDDALSVATN.

MAXIMUM WAVE HEIGHT IN POINT 4.
WATERLEVEL IN RESERVOIR + 930,0

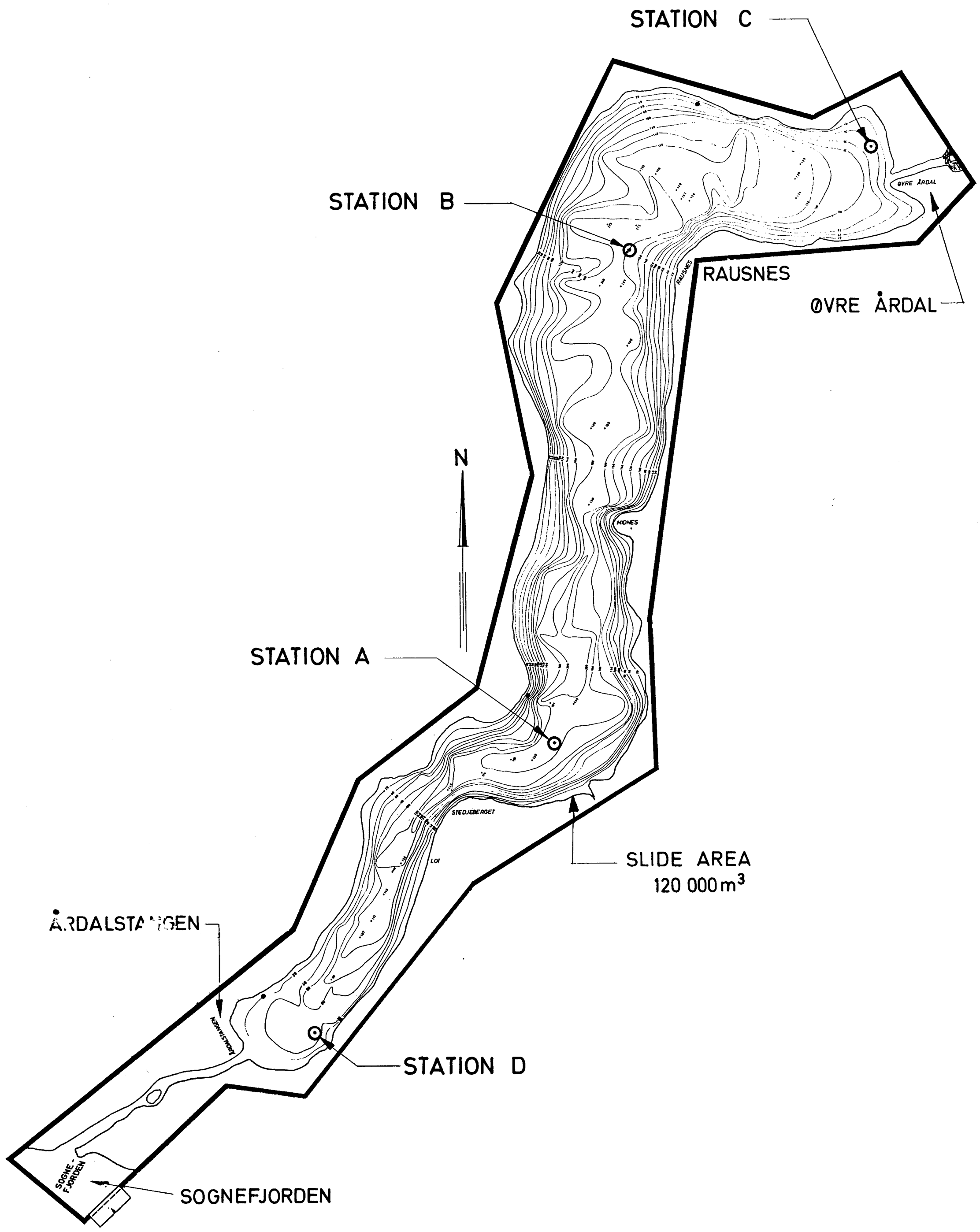


FIG. 9 LAKE ÅRDALSVATN
MODEL BOUNDARIES

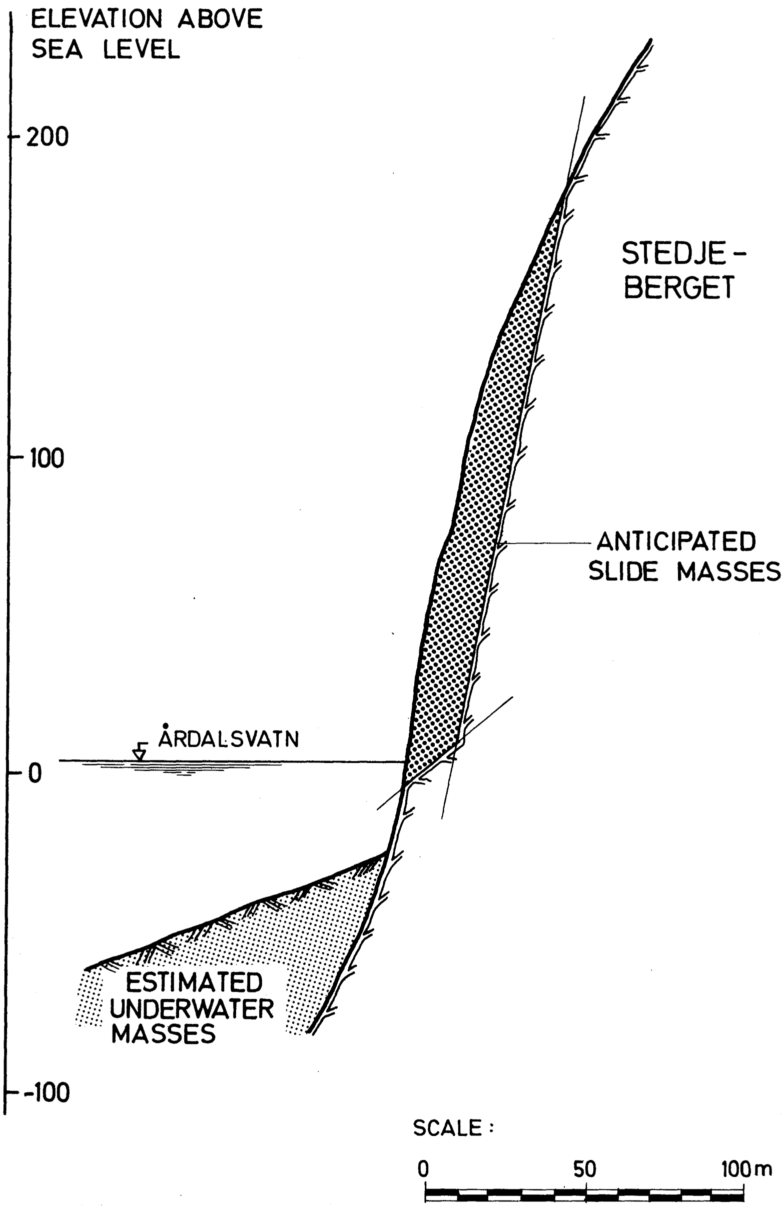


FIG.10 ÅRDALSVATN.
ANTICIPATED SLIDE MASSES AT STEDJEBERGET.

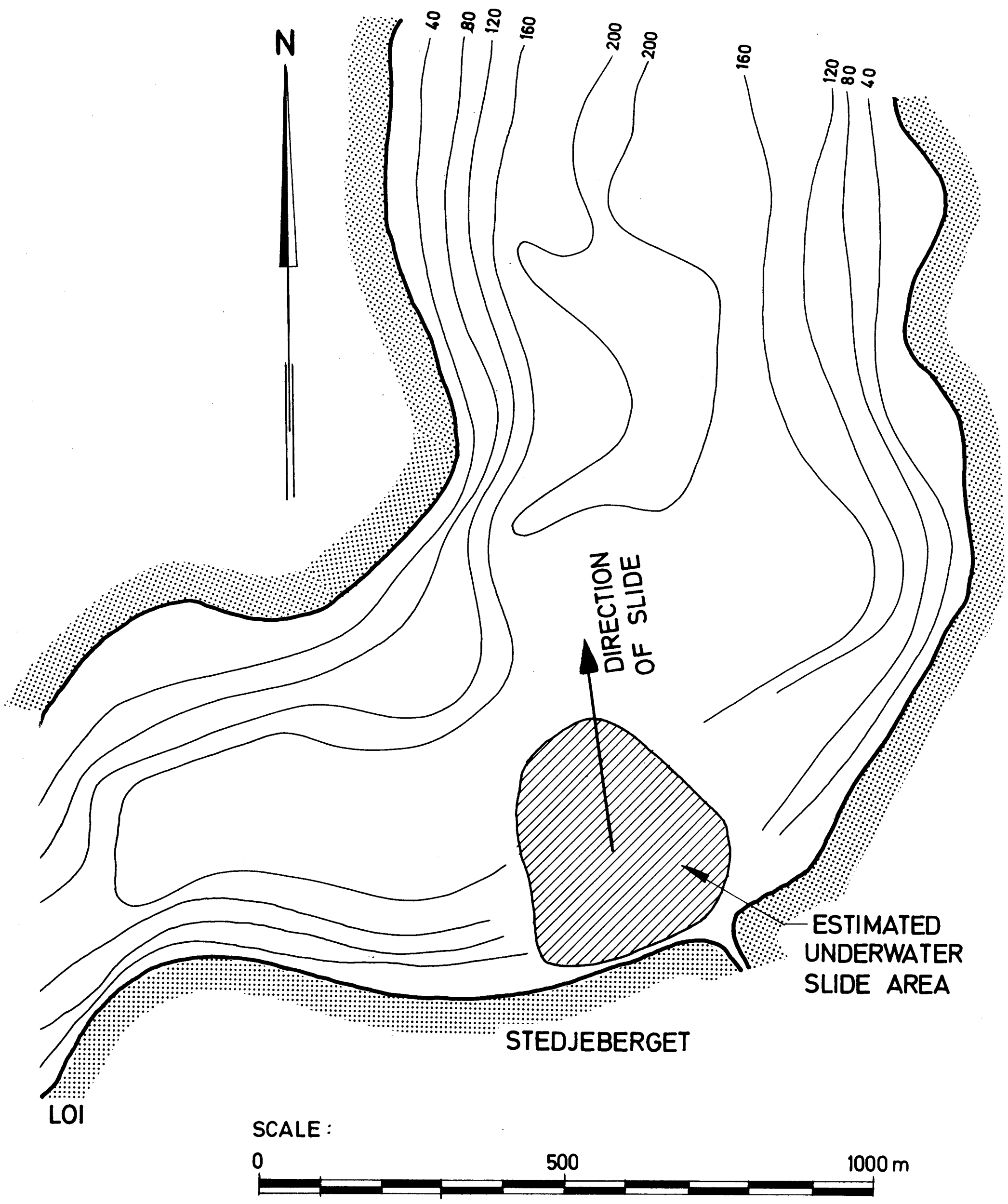


FIG. 11 ÅRDALSVATN
PRELIMINARY ESTIMATED UNDERWATER SLIDE.

FIG. 12 ÅRDALSVATN
SLIDE GENERATED WAVES IN THE MODEL.

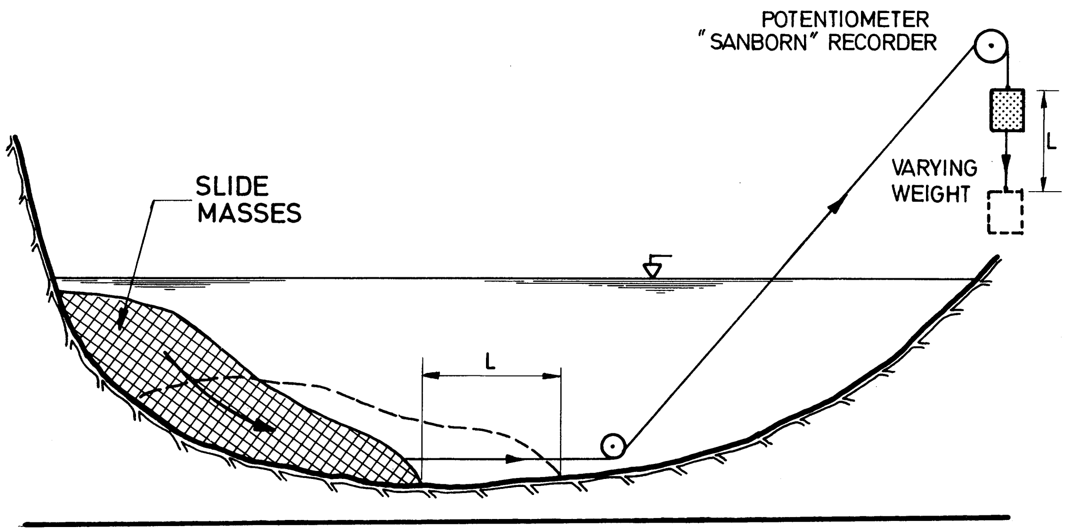


FIG. 13 ÅRDALSVATN
SKETCH OF SLIDE ARRANGEMENT FOR
UNDERWATER SLIDE IN THE MODEL.

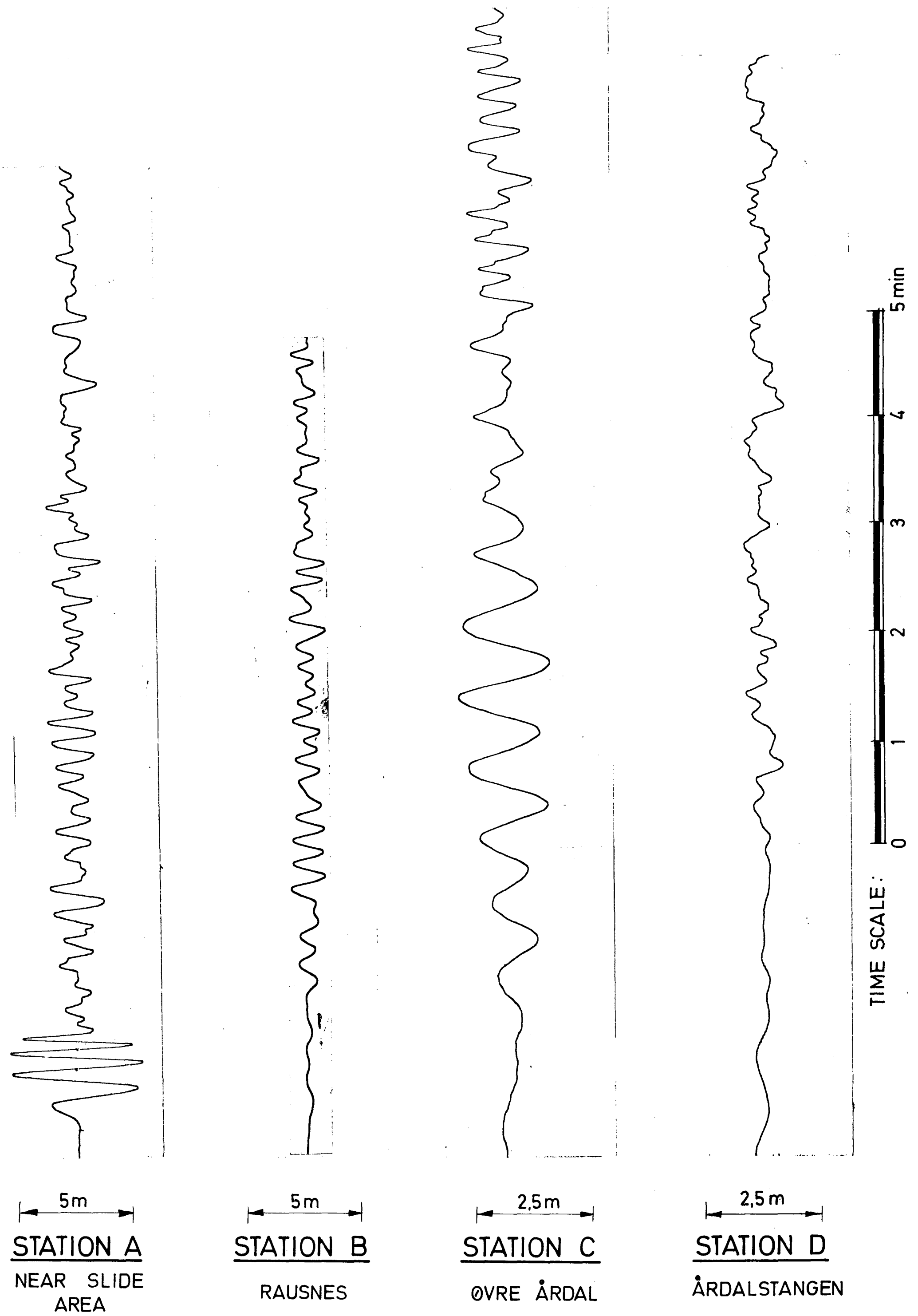


FIG. 14 ÅRDALSVATN
SAMPLES OF WAVE RECORDINGS

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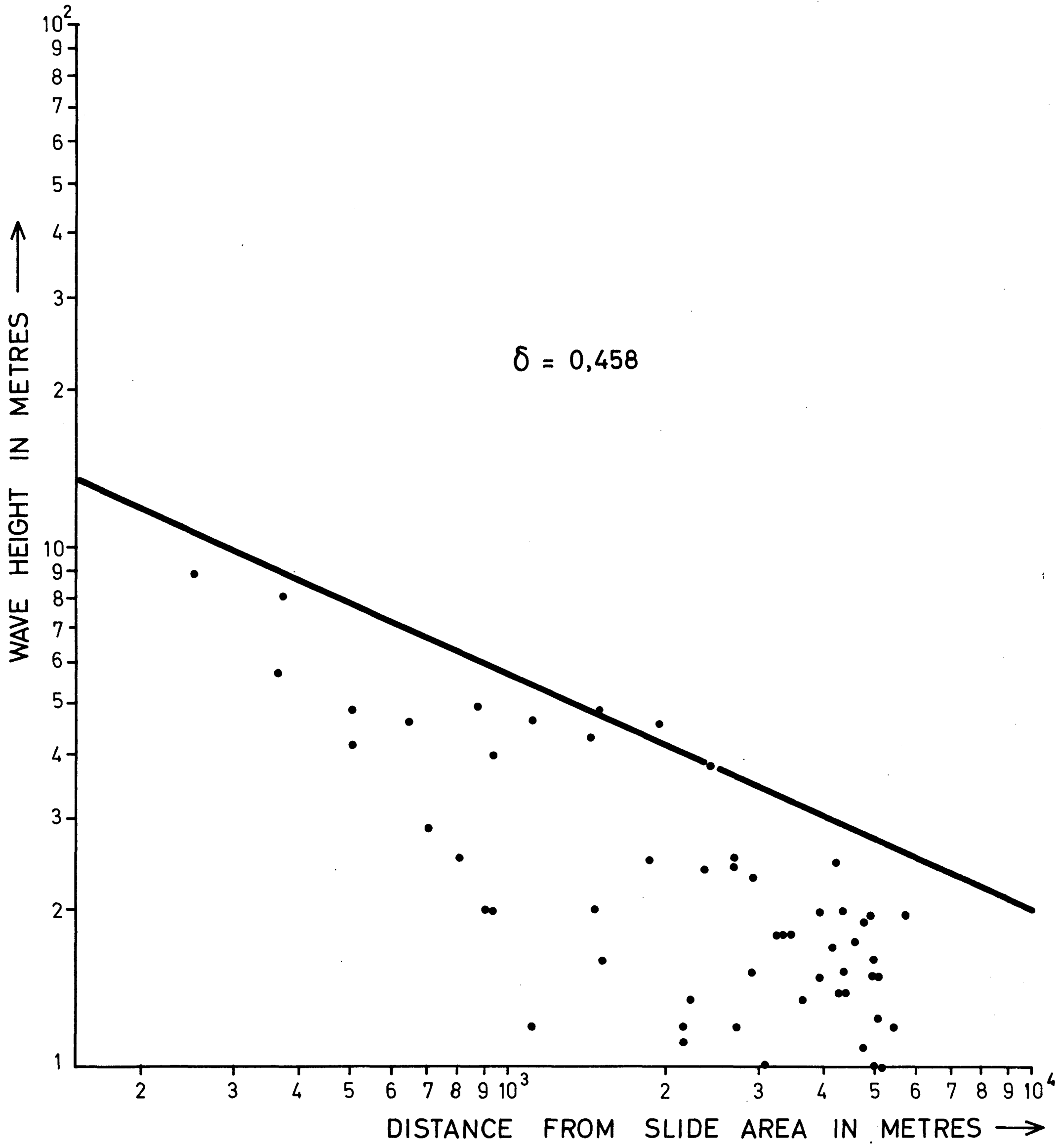

FIG. 15. WAVE HEIGHT AS A FUNCTION OF DISTANCE FROM SLIDE

MODEL TESTS – ÅRDALSVATN

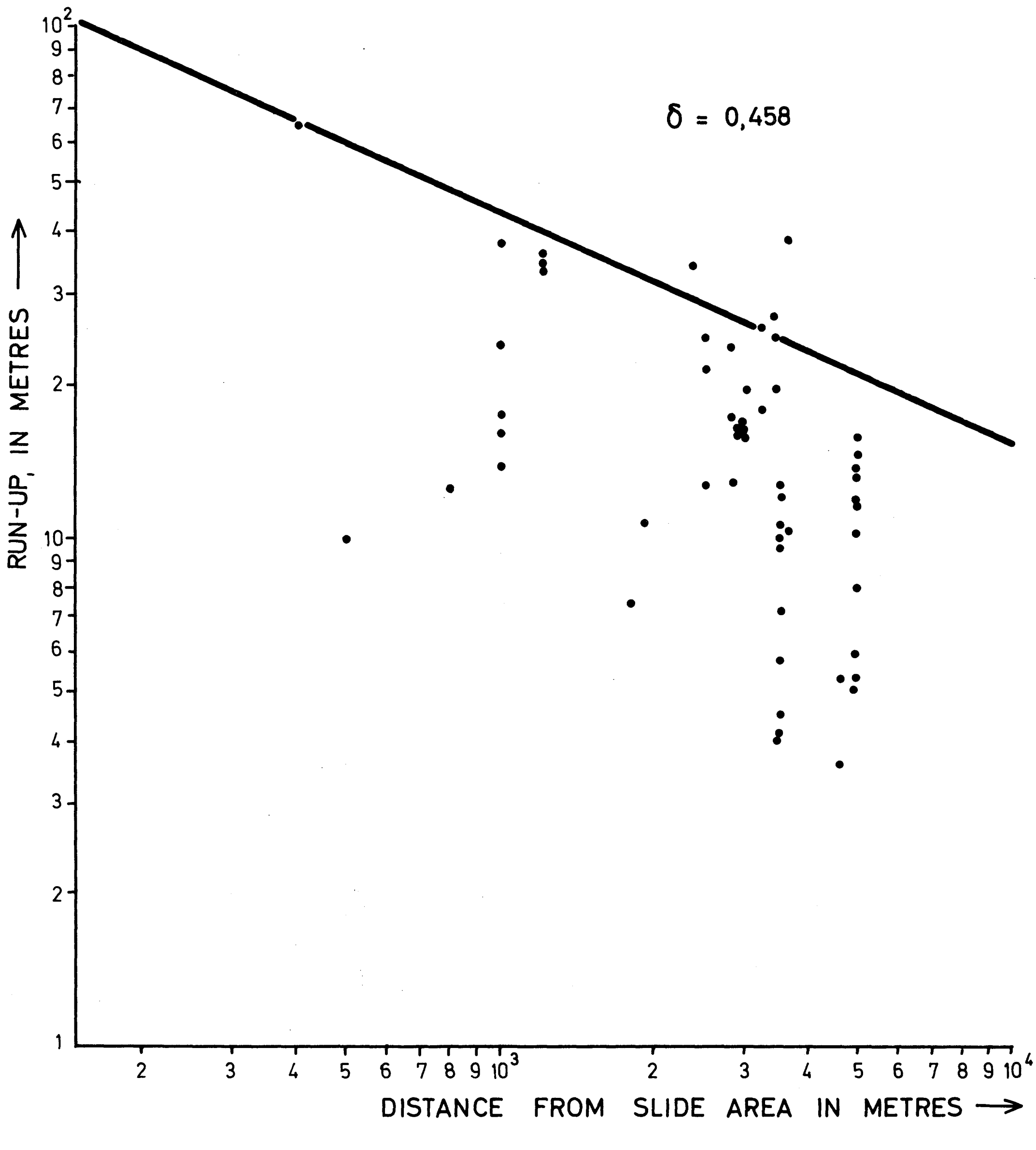

FIG. 16. WAVE RUN-UP AS A FUNCTION OF DISTANCE FROM SLIDE

TAFJORD, 7. APRIL 1934

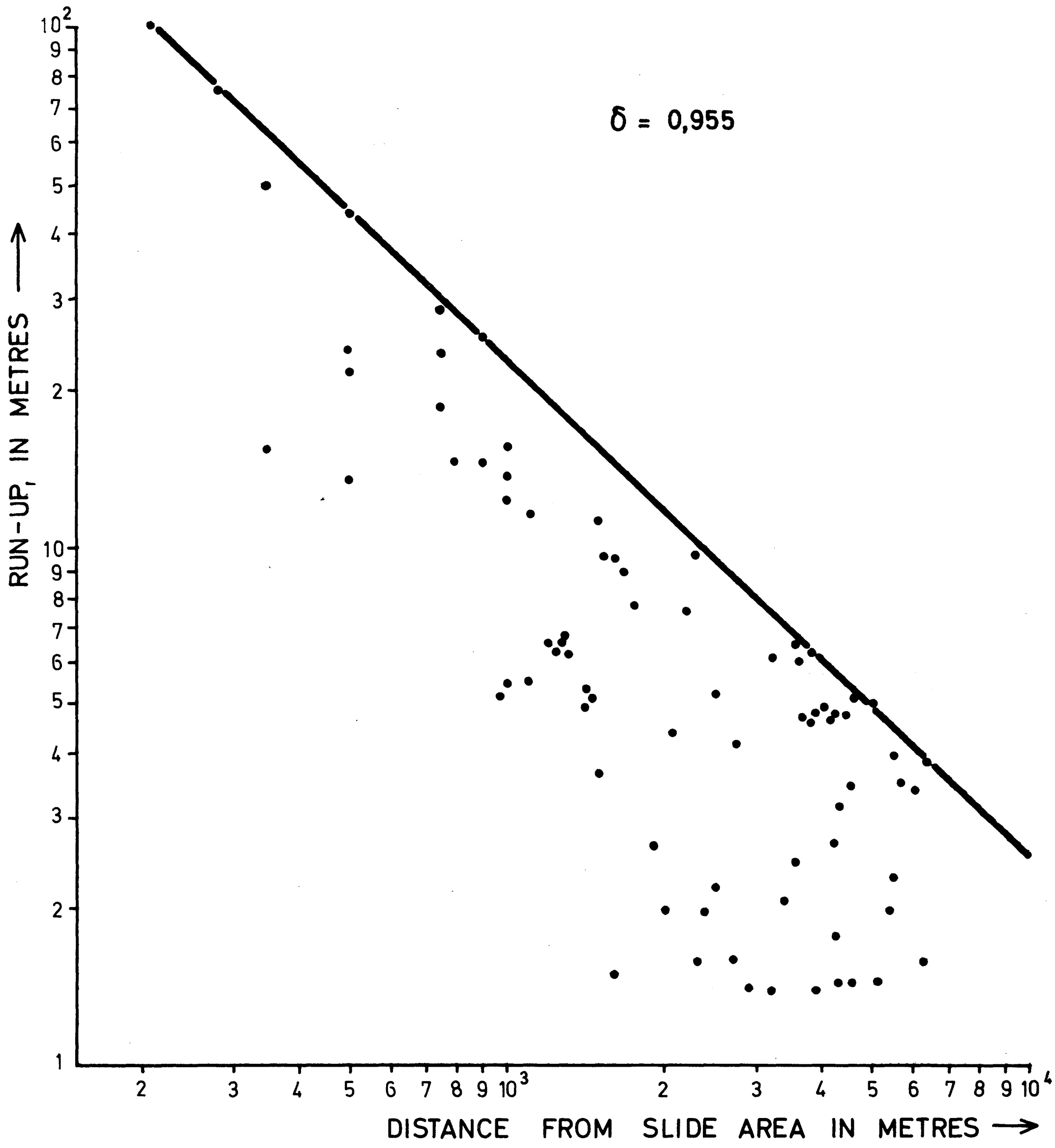

FIG. 17. WAVE RUN-UP AS A FUNCTION OF DISTANCE FROM SLIDE

LAKE LOEN, 13. SEPT. 1936

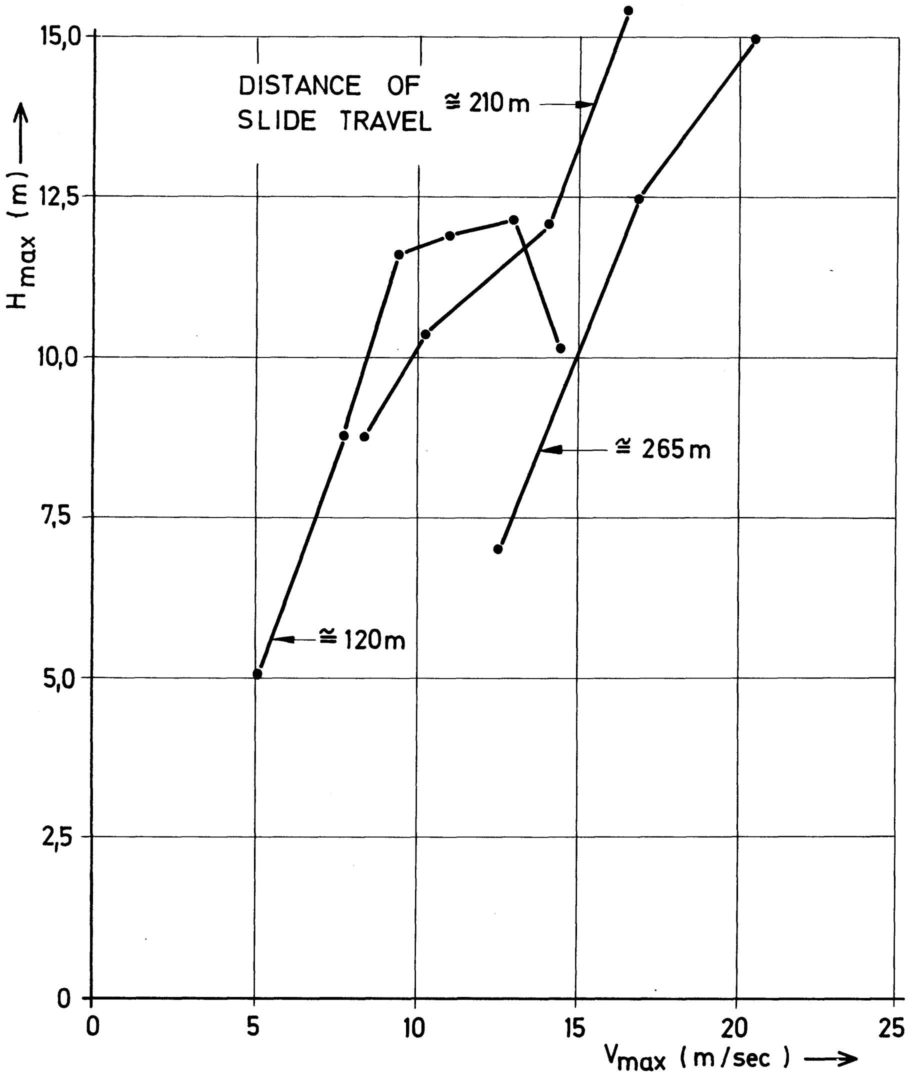

FIG. 18 ÅRDALSVATN
WAVE HEIGHTS CLOSE TO THE UNDERWATER SLIDE AREA.