E3 - SCHELDETUNNEL

SILTATION INVESTIGATIONS

Report No. 6

15 Mai 1965

DANISH INSTITUTE OF APPLIED HYDRAULICS
DANISH ACADEMY OF TECHNICAL SCIENCES

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C O N T E N T S

LIST OF PLANS

A: General Plans

LIST OF PLANS

B: Suspended Load

No.	Vertical	Tide	Date
201	Locations of Verticals		
202	S1	Spring	10- 7-1964
203	C1	"	21-10-1964
204	C1	Neap	14-10-1964
205	S2	Spring	9- 7-1964
206	C2	"	10- 7-1964
207	C2	"	22-10-1964
208	C2	"	5-11-1964
209	C2	"	19- 1-1965
210	C2	"	6- 2-1965
211	C2	Neap	15-10-1964
212	C2	"	28-10-1964
213	C3	Spring	10- 7-1964
214	C3	"	23-10-1964
215	C3	"	4-11-1964
216	C3	Neap	16-10-1964
217	C3	"	29-10-1964
218	S3	Spring	8- 7-1964
220	C4	Neap	30-10-1964

LIST OF PLANS

C: Current Velocities

No.	Vertical	Tide	Date
301	Locations of Verticals		
302	S1	Spring	10- 7-1964
303	C1	"	21-10-1964
304	C1	Neap	14-10-1964
305	S2	Spring	9- 7-1964
306	C2	"	10- 7-1964
307	C2	"	22-10-1964
308	C2	Spring	5-11-1964
309	C2	"	19- 1-1965
310	C2	"	6- 2-1965
311	C2	Neap	15-10-1964
312	C2	"	28-10-1964
313	C3	Spring	10- 7-1964
314	C3	"	23-10-1964
315	C3	"	4-11-1964
316	C3	Neap	16-10-1964
317	C3	"	29-10-1964
318	S3	Spring	8- 7-1964
319	C4	"	10- 7-1964
320	C4	Neap	30-10-1964

1. INTRODUCTION

1.0 General

The present Report No. 6 on Siltation Investigations in connection with the building of the E3-Scheldetunnel contains a summary and an analysis of all results of the investigations performed by the Danish Institute of Applied Hydraulics for the purpose of evaluating the sedimentation to be expected in the tunnel trench during the construction period.

Naturally, the emphasis has been on the field investigations, the main purpose of which has been to measure current velocities and concentrations of suspended silt, as these quantities vary with the seasons, with the tidal range, over the tidal period, with the depth, and across the river. A part of the field investigations has been devoted to the study of sedimentation in two test pits.

By the laboratory investigations, which partly took place on the boat, a number of grain size distributions of suspended load have been determined, both under in-situ and under various flocculation conditions. In addition, the hydraulics of flow in the trench has been investigated by scale model tests.

The theoretical investigations have comprised an analysis of the sedimentation problem, the development of an approximate theory for the mechanism of sedimentation in the trench, and a calculation on an electronic computer of the sedimentations to be expected on the basis of the approximate theory and the field data.

Finally, this report contains the conclusions of the investigations with regard to the expected rates of sedimentation, as well as to the expected geotechnical properties of the deposits. On certain points the data underlying these conclusions are still very scarce, such that a few supplementary field investigations as recommended in a previous report are still desirable. Otherwise this report is assumed to conclude the investigations requested from the institute.

1.1 Previous Reports

In the course of these investigations a number of preliminary reports have been submitted. A list of these reports is given below together with short descriptions of their contents.

Report No. 1, submitted before the tendering for the tunnel, gives the results of introductory field investigations and an approach to calculating the sedimentation in the trench, as well as the preliminary results of such a calculation.

Report No. 2 describes the results of field investigations made in July 1964.

Report No. 3 describes in summary form the results of field investigations made in October-November 1964.

Report No. 4, prepared after the conclusion of the final field investigations in January-February 1965, contains the preliminary conclusions of the investigations and calculations. These conclusions remain largely unchanged in the present report.

Report No. 5, (not yet submitted), will deal with the variation in density of the water in the trench with a view to its effect on the sinking operation for the tunnel elements.

1.2 Acknowledgments

The Danish Institute of Applied Hydraulics would like to express its sincere appreciation to the E3-Scheldetunnel Consortium for having been entrusted with the present task, which has been highly stimulating scientifically and also has contributed greatly to the institute's experience.

Throughout the investigations we have received highly valuable advice and help from the Antwerpse Zee-diensten, who have also generously given us access to invaluable observation data compiled by them in the past.

The field investigations in Antwerp performed by the institute were conducted under the leadership of Mr. O. Beuck. Valuable contributions to the investigations have also been made by Mr. A. V. Joshi, Dr. C. Greated and Mr. J. Sharp of the institute's staff.

2. CONCLUSIONS

From the investigations performed the following conclusions may be drawn:

a. Origin of Deposits

Practically all the material that will be deposited in the tunnel trench will originate from the suspended load.

b. Geotechnical Properties of the Deposited Material

The material deposited in the trench in the sand bed section will be fine sand with a small content of silt, i.e. essentially a frictional material. In the Boom clay section the silt content will be higher with the result that this material will be essentially a cohesional material though the main part of it is fine sand.

In both cases the material will not flow longitudinally along the trench. Thus the trench may be redredged in sections without danger of material from adjacent parts of the trench flowing into the dredged section.

c. Calculated Rates of Sedimentation for Winter Conditions

The sedimentation calculations indicate that the average rates of sedimentation under January-February conditions will be in the order of 8.5 t/m per day in the sand bed section and 3.0 t/m per day in the Boom clay section.

d. Variation with the Tidal Range

According to the sedimentation calculations the variation of the rate of sedimentation from spring tide to neap tide is from 1.6 to 0.4 times the average rate of sedimentation.

e. Estimated Volume of Sedimentation

The unit weight of the deposited material is estimated to be about 1.6 - 1.7 t/m^3 in the sand bed section and, at least, 1.4 t/m^3 in the Boom clay section. These figures yield average rates of sedimentation of 8.5 m^3/m per day in the sand section and 4.5 m^3/m per day in the Boom clay section.

f. Estimation of Summer and Autumn Rates of Sedimentation

Since the technique for finding the grain size distribution of undisturbed material in suspension was not developed until a late stage of the investigations, the grain size distributions of the suspended load for summer and autumn conditions remain unknown. Hence, the sedimentation for these seasons can only be estimated by assuming the same grain size distributions (or rather distributions of settling velocities) as found for the winter conditions.

On this assumption the sedimentation becomes directly proportional to the concentrations of suspended load, leading to the following upper limits of average rates of sedimentation during summer and autumn:

Sand bed section 21 t/m per day, corresp. to 21 m^3/m/day
Boom clay " 7 " " " " " 10 "

It is possible that the average rates of sedimentation will be only 60% of these figures.

It should be pointed out that although a large difference in the settling velocities of the suspended grains from winter to summer is not probable, there could easily be an important difference in the relative contents of flocculated grains, which would lead to other conclusions with regard to the volumes and the consistencies of the deposits.

g. Change in Rates of Sedimentation

The rates of sedimentation given above are initial rates, i.e. for the fully dredged trench. As the trench becomes shallower the sedimentation rate decreases. When the bottom of the trench is about 10 m below the surrounding level a very considerable reduction of the rate of sedimentation may be expected.

h. Sedimentation on Side Benches

The above figures for the sedimentation in the tunnel trench represent only that part of the sedimentation that will occur in the portion of the trench that lies below the surface of the Boom clay.

In the sand section side benches are provided to both sides of this part of the trench. Some sedimentation will, of course, take place on these side benches, and the calculations show that initially the rate of sedimentation in this region will be about 50% of the values for the trench proper.

However, as soon as the excavation starts, there will be a tendency to erosion of the upper part of the sand slopes, because the flow after having passed the trench will pick up new material from this region. Thus, the alternating tidal flow will cause the major part of the material deposited on the side benches with one flow direction to be removed with the opposite flow direction.

i. Recommendations

Because of the lack of measurements of grain size distributions of the suspended load under summer conditions, there is a considerable uncertainty inherent in the estimation of the rates of sedimentation during this season. Therefore, it is recommended that a limited number of such measurements be performed in June or July of the present year.

In connection with such measurements it would be of considerable interest to carry out soundings at test pit P3 and to take samples of the material that has been deposited in this pit.

Finally, we should like to emphasize the desirability of following up the present investigations with adequate observations and measurements when the actual trench is dredged. In the present case, thanks to the foresight of the contracting consortium, an unusual effort has been made to analyse this important problem. However, this effort will attain its full value only if followed up by such measurements and observations in the actual trench.

15th May, 1965

H. Lundgren Torben Sørensen

3. HYDRAULIC CONDITIONS

3.0 General.

The site of the proposed tunnel is 80 km above the mouth of the Schelde at Vlissingen. The hydraulic conditions at the site are determined largely by tides. These tides are semi-diurnal tides.

By the time the tide reaches Antwerp, the sea water that has entered the Schelde has become well mixed up with the fresh water discharge of the river. This can be seen from the salinity measurements (see Report No. 5), which show very little variation of salinity with depth.

The tidal volume is considerably larger than the average fresh water discharge of the river (about 36 times as large during spring tides and 30 times during neaps). The river velocities are therefore completely dominated by the tidal current.

3.1 Tidal Range.

From the information kindly supplied to us by the Antwerpse Zeediensten, who maintain records of tides at Antwerp, the following figures, which are based on data for the years 1951 to 1960, can be given:

Mean tidal duration:	Flood 5 h 16 min. Ebb 7h 09min.
Mean high water level:	+5.04 m above N.K.D. datum
Mean low water level:	+0.23 m above N.K.D. datum
Mean high water springs:	+5.42 m above N.K.D. datum
Mean low water springs:	+0.08 m above N.K.D. datum
Mean high water neaps:	+4.58 m above N.K.D. datum
Mean low water neaps:	+0.48 m above N.K.D. datum

3.2 Variation of Velocity with Season, Depth and Tides.

In order to understand the behaviour of the suspended load and to find the reasons for its variation with the tidal cycle and along the tunnel axis, velocity measurements were made at 4 different depths at each of several verticals, S_1 to S_3 and C_1 to C_4, the locations of which have been shown on Plan No. 101.

These measurements were normally made at spring and neap tides. A list of these measurements is given in the index, while Plans Nos. 302 to 320 show the variation of velocities with the tides and at different depths.

Because the tidal volume is considerably larger than the river discharge, there is hardly any seasonal variation in velocities which can be attributed to the varying river discharge. The river is well mixed and the velocities at various depths follow the mean velocity of the river. The velocities vary considerably with the tides, being larger at spring tides than at neaps. The variation during a tidal cycle can be seen from Plans Nos. 302 to 320. (An interesting feature that can be observed from the velocity curves is the well defined secondary maximum during flood tides).

3.3 Variation of Velocities along the Tunnel Line.

A comparison of the measurements of velocities at different points on the cross section of the river indicate that maximum velocities occur at a point between C_2 and C_3. The velocities decrease as the banks are approached. A typical case is shown on Plan No. 103.

4. CONCENTRATIONS AND GRAIN SIZES OF SUSPENDED LOAD.

4.0 General

The investigations performed include a large number of observations of concentrations of suspended load in order to obtain data describing the way in which the concentration of suspended load varies over the cross section of the river, with the time relative to the tidal motion within the tidal period, with the amplitude of the tide as it changes from spring tide to neap tide, and with the seasons.

These observations have, in general, been made in four verticals, C_1 to C_4 (Plan No. 201). Observations were made in July 1964 (one spring tide), in October-November 1964 (two spring and two neap tides) and in January-February 1965 (two spring tides).

The results of all of these observations have been plotted on the enclosed Plans Nos. 202 to 220 together with the mean velocity of the current at the vertical in question as calculated from the velocity measurements made simultaneously with the suspended load observations.

4.1 Variations of Concentrations Over the Tidal Period.

From Plans 202 to 220 it may be seen that the concentration of suspended load in a given point varies strongly with the current velocity. The maximum concentration is obtained some time after the current velocity has passed its maximum. This time lag is caused by the fact that the turbulent mixing close to the bed is not strong enough to ensure an immediate adjustment of the concentration profile to the changing velocity conditions. Thus, it must be concluded that the shape of the concentration profile is not normally identical to that corresponding to steady flow conditions. However, the discrepancy is likely to be greatest in a thin layer very close to the bed.

In some cases there are very high concentrations shortly after the reversal of the current at slack water. These peaks do not result from high current velocities, but may - as suggested by Mr. H. Jongedijk of Christiani & Nielsen - be caused by the fact that a bed with ripples formed by one current direction is very unstable in flow with the opposite direction.

4.2 Seasonal Variation.

The possible occurrence of seasonal variations in concentrations of suspended load has been examined by calculating values of the average concentration over a full tidal period and comparing these values for the different times of the year. The resulting values of average concentrations have been listed in Table No. 1 below.

TABLE NO. 1 AVERAGE CONCENTRATIONS OF SUSPENDED LOAD(g/l)

	Vertical C_1 (S_1)			Vertical C_2			Vertical C_3			Vertical C_4		
HEIGHT ABOVE BED (m)	0.3	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0	0.3	1.0	3.0
July 10-7-64	10-7	10-7	10-7	10-7	10-7	10-7	10-7	10-7	10-7			
SPRING TIDE	0.67	0.59	0.54	1.86	1.54	0.99	1.49	1.30	0.84			
OCT. 14-16	14-10	14-10	14-10	15-10	15-10	15-10	16-10	16-10	16-10			
NEAP TIDE	0.47	0.39	0.31	0.70	0.56	0.26	0.63	0.50	0.30			
OCT. 21-23	21-10	21-10	21-10	22-10	22-10	22-10	23-10	23-10	23-10			
SPRING TIDE	0.58	0.65	0.58	1.53	1.36	0.92	1.94	1.65	1.04			
OCT. 28-30				28-10	28-10	28-10	29-10	29-10	29-10	30-10	30-10	30-10
NEAP TIDE				0.64	0.56	0.42	0.45	0.42	0.29	0.36	0.29	0.20
NOV. 4-5-64				5-11	5-11	5-11	4-11	4-11	4-11			
SPRING TIDE				1.21	1.13	0.73	0.83	0.64	0.48			
JAN. 19,65				19-1	19-1	19-1						
SPRING TIDE				0.59	0.55	0.47						
FEB. 6, 65				6-2	6-2	6-2						
SPRING TIDE				0.45	0.39	0.33						

Plan No. 102 shows for spring tide conditions and a point 1 m above the bottom a plot of the average concentrations over the tidal period at vertical C_2, and the average concentrations during an interval of about 1 hour before high water to 4 hours after high water at verticals C_1 and C_3 as well as the salinities (occuring at high water slack). It is quite evident that there is a variation in concentration of suspended load which is probably of a seasonal nature, the values from July and October-November representing similar and rather high concentrations, whereas the values from January-February are smaller by a factor of about 0.4.

It appears that the seasonal variation in concentrations of suspended load is somehow related to the same mechanism by which the salinity is reduced drastically in the winter season. There are various possible explanations of such a relationship, but the present investigations are insufficient for the clarification of this point.

4.3 Variations from Spring Tides to Neap Tides.

The calculated average concentrations also illustrate the variations in concentrations of suspended load with the velocities of the tidal currents as they change from spring to neap conditions, the neap tide concentrations being at all seasons considerably smaller than the spring tide concentrations.

4.4 Variations across the River.

The concentrations of suspended load vary across the river along the tunnel axis, partly because the current velocity varies, being smaller at smaller depths, but mainly because the bed near the right bank consists of Boom clay, while the remaining part of the bed consists chiefly of fine sand (Plan No. 103).

In the Boom clay section only a small amount of fine sand and silt grains is available on the bed for the current to bring into suspension. The reason for this must be that secondary currents (helical flow) continuosly sweep such material as is brought into this part of the cross section - e.g. by diffusion - over towards the sand bank at the left side of the river. The result is that the suspended load concentrations - especially the peak values - are much lower over the Boom clay than over the sand bank, where an unlimited supply is available.

The variation along the tunnel axis of suspended load concentrations 1 m above bottom is illustrated by the observations plotted on Plan No. 103.

4.5 Grain Sizes of the Suspended Load.

At an early stage in the investigations it became evident that almost all the material that will be deposited in the trench will originate from the suspended load. Thus, for the purpose of calculating the amount of sedimentation in the trench it was equally evident that knowledge of the grain size distribution of the suspended load was necessary, because the rate of sedimentation of suspended particles depends decisively on the grain sizes.

Unfortunately, determination of grain size distributions on samples of suspended load is a rather complicated problem. The concentrations of suspended load in the river are so small that the existing standard methods of grain size analysis for such particles, e.g. hydrometer analysis, are impracticable. Further, it was felt that to obtain a reliable analysis it would be necessary to avoid settling of the suspended material in the sample before performing the analysis, since this might lead to the formation of greater flocs and thereby to misleading results.

A further complication is the fact that the grain size distribution of the suspended load varies considerably with the current velocity as well as with the bed material (Boom clay or sand), such that a description of the grain size distributions could be made only on the basis of a large number of samples taken at different points of the cross section, at different tidal conditions, and at short time intervals within the tidal period.

A technique for performing grain size analysis under such conditions has, apparently, not been known, and a suitable method was not developed by the institute until the end of 1964. Thus, an adequate description of grain size distributions was not possible until the investigations in January-February 1965.

The method developed for this purpose is a method for the determination of settling velocities of fine grains, and the apparatus is an adaptation of the so-called "Andreasen's Pipette Apparatus". By this new apparatus the volume of the samples was large enough to allow determination of the very small quantities of each grain size fraction, and the analysis could be started on board the boat immediately after the sample had been taken, such that the suspended material was not allowed to settle before the grain size analysis.

By means of this apparatus a number of grain size distributions of suspended load were found for neap tide and spring tide conditions in February 1965 at C_1 and C_3, 1 m above the bed. The samples were taken at short time intervals during a period from 1 hour before high water to 4 hours after high water, because this period will usually include the maximum velocities both at flood and at ebb, as well as the high water slack. Thus it should give a good description of the range of variations of the grain size distribution.

The results of these observations have been plotted on Plans Nos. 112 to 118. On these plans both the ordinary grain size distributions in terms of percent by weight of each fraction and the variation in concentration of each grain size fraction with time are given.

It may be seen from these plans, especially Plan No. 116 showing conditions at C_3, spring tide, that the large increases in concentrations occurring around the maximum velocity, consist almost exclusively of the coarsest grains (larger than 0.08 mm), which remain in suspension only for a relatively short period around the maximum velocity. Some variations in concentrations occur also for grains between 0.08 and 0.01 mm, whereas the concentration of grains finer than 0.01 mm remains almost constant throughout the periods (?). of measurement.

Similar trends, but less pronounced, are discernible at C_3, neap tide, and at C_1, spring and neap tide. When examining these results it should be remembered that in several cases where the grains are very fine the quantities of each fraction are extremely small and the determination therefore somewhat inaccurate. Fortunately, in such cases the contributions of these fractions to the sedimentation in the trench are also extremely small, and these inaccuracies are therefore unimportant.

4.6 Flocculation Tests.

The salinity of the Schelde at Antwerp is much higher during the summer than during the winter. Since it is known that flocculation of very fine particles is accelerated by salinities above a certain limit and the salinity at the time of the grain size determinations might be below this limit, it was clearly desirable that the possible effect of a higher salinity on the grain size distribution should be known.

In order to investigate this, three samples of suspended load were taken simultaneously from the same point (C_2, 1 m above the bed). The grain size distribution of one of these samples was determined at once. The salinity of the other two samples was increased to about 10 g/l, whereupon they were agitated for one and two hours, respectively, before determination of their grain size distributions.

The three resulting grain size distributions are shown on Plan No. 119. It can be seen, that the increased salinity had little effect on the grain size distribution. Indeed, the distributions are so close to each other that this test provides a demonstration of the accuracy obtained by the applied method for determination of grain size distributions.

The result of these flocculation tests should not, however, be considered quite conclusive with regard to the grain size distributions likely to be encountered under summer conditions. During summer conditions the content of flocculable clay may be considerably higher than at the time of this experiment. In the winter observations the grains with large settling velocities were found to consist almost exclusively of fine sand grains. During summer conditions there may be appreciable quantities of flocculated grains with large settling velocities.

5. TEST PITS.

5.0 General.

During the present series of investigations two test pits (P2 and P3) were excavated. The rate of sedimentation was observed by taking echo soundings at regular intervals.

5.1 Test Pit P2.

This test pit was placed on the tunnel axis and near the centre of the river in the portion where the river bed is sand. (see Plan No. 151). The pit was about 2.3 m deep and had a volume of about 3500 m^3. Soundings were taken for a period extending over a month, and typical plots of these soundings can be seen on Plans Nos. 156 and 157. Sections parallel to the current direction through the pit have also been drawn and these are shown on Plans Nos. 152 to 155.

From these sections it can be seen that material has been deposited in the portion of the pit which lies near the left bank, whereas very little material has been deposited at the right bank side, although the pit was deepest on that side. (see profiles A and E). The rate at which material came into the pit was much larger in the beginning than towards the end of the period of measurements, as may be seen by comparing the change in the profiles at different dates. The average rate, from 20-12-1964 to 21-1-1965 at which this test pit was filled up was about 2.6 cm/day. This rate is the average rate considering the entire bottom portion of the pit.

The material that came into this test pit was fine sand. This was confirmed by the grain size analysis of samples taken from the bottom of the test pit (see Plan No. 120). Direct confirmation of this was also obtained when, for another purpose, the skin diver inspected the pit.

It is quite evident from the shape of the bottom profiles of the pit at the various stages of filling-up that the bulk of the material deposited in the pit was carried into the pit as suspended load. If it had been mainly bed load, the pit would have filled up from the two sides instead of almost evenly.

It can be seen from the sounding profiles parallel to the direction of the current that some erosion has occurred on the bed adjacent to the pit. This takes place in the following way: After the flow has passed the pit, where it has been deprived of some of its content of transported material, it picks up new material from the area immediately downstream of the pit. This, of course, happens whether the material is transported as bed load or as suspended load.

Since it was quite clear that test pit P2 was too shallow to demonstrate the rate of sedimentation that would occur in the tunnel trench, an attempt was made to determine the rate of siltation that would occur in a much deeper excavation under the conditions prevailing at this place and time.

In this experiment a small bucket, 12 cm in diameter and 40 cm deep, was placed on the bottom of the pit on January 11, 1965 (neap tide) during 5 hours of ebb current. During this period 8 cm of fine sand (mean diameter approximately 0.10 - 0.15 mm were deposited in the test bucket.

This experiment demonstrates that with a deeper trench, where the hydraulic conditions would approach those occurring in the test buckets, much greater rates of sedimentation than those found in the test pit may occur. On the other hand, the test bucket experiment could not be taken to represent directly the average rate of sedimentation in the large trench, since the rate of sedimentation in the test bucket would depend on its location in the test pit.

5.2 Test Pit P3.

This test pit was excavated near the right bank in the portion where the river bed consists of Boom clay (Plan No. 151). The pit was about 5 m deep and had a volume of 1900 m^3. Echo soundings of the pit were made at frequent intervals between January 12, and January 28, 1965. A section of the pit as found from two soundings at the beginning and the end of the observation period, respectively, can be seen on Plan No. 158. The two sections practically coincide, the differences being no larger than could be expected from the inevitable inaccuracies of echo soundings on rather steep slopes. The rate of sedimentation in this pit was negligible, which again in this case was confirmed by a skin diver, who on inspection of the test pit at the end of the observation period stated that the bottom of the pit consisted of hard clay except for small regions near the corners between the steep sides and the bottom, where a muddy material was found.

Velocities and concentrations of suspended load were measured in the deepest part of the pit. These are shown on Plan No. 159, where it should be noted that the current meter gave only a numerical value of the velocity, and it is quite likely that the velocity is reversed at the bottom.

The concentration curve shows a constant concentration in the pit. Grain size distributions of the suspended load were determined for three water samples taken 30 cm above the bottom of the pit. These are shown on Plan No. 121. From these it can be seen that about 50% of the suspended load consists of sand, (D 50% = 0.07 mm), the remaining is silt.

As in test pit P2, test buckets were lowered in the pit. The first time on January 22, 1965 during mean tide (i.e. between spring and neap) 6 cm were collected in 5 hours during ebb. The second time on February 17, during spring tide. This time 7 cm were collected in 5 hours during flood. The grain size of this material can be seen on Plan No. 122. The material collected in the test bucket was fine sand with a certain anount of silt content. The silt had come in mainly at slack water and could be seen by the layered nature of the deposit. The unit weight of the deposited material was found to be about 1.4 t/m^3.

It is indeed surprising that none or very little of the coarser fractions of the material, found in the samples of suspended load from this test pit, as well as in the material deposited in the test buckets, was deposited in the pit. The lack of sedimentation in test pit P3 may to some extent be explained by the fact that its width (parallel to the tunnel axis) was very small, which would influence the hydraulic conditions in the pit.

Both test pit P3 and test pit P2 indicate that the rate of sedimentation in the tunnel trench will decrease considerably as the trench gets shallower by sedimentation.

6. MODEL TESTS.

6.0 General.

In the course of the investigations the flow pattern in the trench was studied in a small two-dimensional scale model of the trench. These tests were made partly as a preparatory work in connection with possible three-dimensional model tests to be performed at the Waterbouwkundig Laboratorium in Borgerhout. In the end the tests in Borgerhout had to be given up, and the two-dimensional tests therefore form the only experimental data available for the description of the flow pattern that will be encountered in the trench.

There will, undoubtedly, be some three-dimensional effects in the trench, which - as it is - remain unknown. Such three-dimenaional effects are likely to be generated by the varying depth of water along the tunnel line as well as by the curvatures of the river on both sides of the tunnel line. However, it is felt that such three-dimensional effects are unlikely to be so strong as to be of significant importance with regard to the sedimentation problem.

The influence of the access trench on the flow conditions and the sedimentation in the tunnel trench has not been studied and may be of some importance.

6.1 Model Scales.

The test series included tests on trench sections and on a section of test pit P3. The models of the tunnel trench were all to a scale of 1:150 while the model of the test pit was to a scale of 1:100.

The model tests were performed by Mr. H. Jongedijk of Christiani & Nielsen in our 10 cm flume.

Results of three of the model tests are shown on Plan Nos. 171-173.

6.2 General Flow Pattern in the Trench.

The flow of the river remains unchanged until it arrives at the upstream edge,"the leading edge", of the trench. Downstream of the leading edge the flow can be divided into three different zones. (see Plan No. 170).

In the uppermost part of the flow the current velocity is practically constant over the vertical. Below this there is a wedge-shaped region with a horizontal plane of symmetry and with its apex at the leading edge of the trench. The lower boundary of this region is defined as the line above which the discharge remains constant. Within the wedge the velocity decreases gradually, almost linear, towards the lower boundary. This is a zone of so-called free turbulence, in which the turbulence is not generated along a fixed boundary but through the velocity differences between the passing flow and the water below the wedge which, on the average, is stagnant.

Below the wedge the mean motion of the water in the trench is one of a large vortex rotating slowly about an axis parallel to the centre line of the tunnel. Near the bottom of the trench the flow in the vortex is in the opposite direction to that of the river flow. At the upstream side of the trench the flow in the vortex is upwards, and at the downstream side downwards. The turbulence constantly exchanges water between the top of the vortex and the zone of free turbulence.

Where the flow within the wedge of free turbulence hits the downstream slope of the trench it is deflected upwards giving rise to considerable upward velocities.

6.3 Test Results.

Plan No. 171 shows the results of a model test on the Boom clay section of the trench. Velocities were measured at a number of points along different verticals. These measurements are plotted on the verticals. The velocities shown are the prototype velocities and are the maximum velocities during a spring tide.

From the plan it is seen that the velocities measured conform quite closely to the general flow pattern described above, although the line separating the zone of free turbulence from the vortex beneath can only be found through calculation from the velocity profiles.

The velocities in the lower part of the vortex are of the magnitude of 0.4 m/sec, or about 20% of the maximum velocity in the river. At vertical 2 and at vertical 7 the velocities in the vortex are respectively upwards and downwards. Since the current meter was placed to record horizontal velocities it did not in these verticals measure the maximum velocities in the vortex.

Vertical 8 shows an interesting picture. Near the bottom of the vertical the velocity is 0.4 m/sec. in the direction of the river flow. The absolute magnitude of the velocity at this point is somewhat larger than 0.4 m/sec.as the velocity is inclined upwards. The velocity gradient at this vertical is much steeper than that in the vortex itself. One would therefore expect little sedimentation when the trench is filled to the level indicated by the lower end of this vertical (about 6 m above the bottom of the trench). The point of stagnation, which separates the upslope flow from the downslope one, is located somewhere between the bases of verticals 7 and 8.

Plan No. 172 gives the results of a test with a trench profile in the sand bed section. While the trench in the above-mentioned model had a bed of smooth sheet metal, the sheet metal for this particular test was coated with sand.

The general picture of flow remains the same as in the previous test. The velocities at the bottom of the trench are somewhat lower, only about 12% of the maximum velocities in the river. An interesting point is the formation of a small vortex on the upstream side bench. The velocities at the bottom of this vortex are opposite to the direction of the river flow. Because of this, small plastic spheres dropped in the flow tended to collect at a point somewhere near the upstream edge of this bench.

The point of stagnation on the downstream slope is located somewhere between verticals Nos 12 and 18. This point is considerably higher than that in the Boom clay section.

The velocity measurements made in the model of test pit P3 are shown on Plan No. 173. The velocities on the downstream slope of the test pit are considerably larger than in the tunnel trench. There is hardly any stationary vortex, and the small vortex that exists is confined to the upstream slope. The point of stagnation is near the bottom of the test pit.

In addition to the results of the tests enclosed with this report, some additional tests, with different velocities, water levels etc., were made, all of which indicated the same general picture.

7. ANALYSIS OF THE SEDIMENTATION PROBLEM.

7.0 General.

From the preceding description of the investigations performed it is abundantly clear that the problem of the sedimentation that will occur in the tunnel trench is an extremely complex one. The decisive magnitudes, i.e. the current velocities and the concentrations and grain sizes of the transported material, vary with the height above the bed and from point to point along the tunnel axis, especially from the Boom clay section to the sand bed section of the river. They also vary strongly within the tidal period, from spring tide to neap tide and, apparently, with the season of the year.

In addition to these very complex variations of the basic parameters, there are the difficulties in establishing a reasonably adequate theory for the manner in which part of the material transported by the river flow will settle out in the trench. To our knowledge such a theory has not hitherto been established, let alone checked with observations from nature.

It would indeed have been desirable to investigate this problem by means of hydraulic model tests if this had been possible. However, the problem of producing a representative model of such phenomena as the present one has not yet been solved and therefore this line of approach was abandoned at an early stage of the investigations.

It was hoped, at a certain time, that some check on the validity of the sedimentation calculations described below could be obtained from the results of the test pits. However, the sedimentation rates observed in the test pits were so low compared with the calculated rates that the discrepancy could only be referred to the fact that the small sizes of the test pits cause the hydraulic picture of the flow in the trench, upon which the calculations are based, to become irrelevant with regard to the test pits. Thus, the test pits do not offer a basis for adjustment of the theoretical calculations of the sedimentation, unless a more complete description of the hydraulic problem than has so far been possible is provided.

The situation therefore is that the rate of sedimentation in the tunnel trench will have to be inferred from the various and partly insufficient data obtained through field investigations and on the basis of a theoretical picture of the mechanism of sedimentation, the validity of which it has not been possible to examine by comparison with past experience, since no such relevant experience has been available.

7.1 Sediment Transport in the River.

Sediment is transported in the river in large quantities by the tidal flow by the two distinctly different mechanisms of bed load and suspended load transport.

The bed load transport is the transport of sand grains rolling along the bed in intermittent contact either with the bed or with other moving grains. This mechanism is active only for some millimetres - at extreme velocities up to a few centimetres - above the bed.

The suspended load transport is the transport of grains which are maintained in suspension by the turbulent mixing of water from lower strata having greater concentrations with water from higher strata of smaller concentrations. The individual particles move relative to the water with their settling velocity, but the downward motion caused by the settling velocity is balanced by this mixing.

The transport of suspended load takes place over the entire depth of the river, the concentrations decreasing towards the surface.

The transition between bed load and suspended load is gradual, but it takes place within a very short distance (millimetres or centimetres) at the top of the bed load layer. Indeed, it is the magnitude of the bed load which, through this transition, determines the concentrations of the suspended load.

It follows from the above that it is, in principle, and also in practice, quite impossible to measure the bed load directly, when there is also suspended load of the same grain sizes.

The ratio of suspended load transport to bed load transport varies with the grain size and with the current velocity. Thus, it may be mentioned that the bed load transport at high velocities is independent of the grain size, whereas the suspended load transport varies strongly with the grain size. Therefore it is not possible to give general figures to this ratio, but from the existing data its order of magnitude at high velocities would seem to be about 20-30.

When the current velocity varies as in the tidal flow the bed load transport is immediately adjusted to the changing flow conditions, whereas the suspended load follows only with a certain time lag because the net upward trasnsport of material involved in the adjustment of the concentrations of suspended load takes a certain time.

In the Boom clay section of the river the bed load transport is much smaller than in the sand section, because only a very limited quantity of sand is available. Therefore also the suspended load transport, especially of the larger grains, is much smaller than in the sand bed section.

7.2 Mechanism of Sedimentation in the Trench.

The general pattern of the flow of the water in and above the trench has been described above in the section on the model tests. On the basis of this flow pattern a number of important conclusions may be drawn with respect to the mechanisms of sedimentation in the trench for bed load and suspended load, respectively.

When the bed load transport on the sand bed reaches the trench it encounters, on a more or less gentle slope at the side bench, a region either with reversed flow (if the slope is rather steep) or with a bed shear stress of only a few percent of the normal shear stress upstream of the trench (if the slope is gentle). The result is that the entire bed load transport is immediately deposited on this slope.

When the tidal flow is reversed, the slope upon which the bed load transport was deposited in the first case is now being subjected to a converging flow with a high bed shear stress, but since this flow arrives without any bed load,material from the slope is then picked up in a quantity corresponding to the bed load transport capacity of the flow.

It appears from this short analysis, that for a very large trench, such as that under consideration, the slopes on both sides of the trench will quickly adjust themselves to an equilibrium shape on the uppermost parts,in such a way that the resulting supply of bed load transport to the trench proper approximates to the difference between the bed load transport in the two directions of the flow. If such a difference exists, the result is that one of the slopes becomes flatter and flatter until the trench has been filled to such an extent that bed load transport again begins to take place across the trench, i.e. until the trench has been almost completely filled up.

Calculations of the magnitude of the bed load transport in the two directions indicate that, except in rare cases with very high flood velocities, the difference between the bed load transport in the two directions is negligible, such that the problems arising from this type of transport are unimportant.

At high spring tides the quantity of bed load transport within half a tidal period may be in the order of 2 m^3/m. It is easily visualised that a quantity of this magnitude without difficulty may be deposited on an equilibrium slope of a length of about 20-40 m in such a way that it is removed again during the other half of the tidal period, provided the transport capacities of the two flows tally.

It is also evident from this analysis, that the provision of side benches is a rational approach to the problem of minimizing the quantity of bed load material reaching the trench proper at any time during its period of existance.

With regard to the suspended load transport the mechanism of sedimentation in the trench is completely different from that described above for the bed load transport, except for suspended material transported in the region of transition between bed load and suspended load, i.e. for the lowest few centimetres of the flow.

What happens to the suspended load transport is that the balance between the settling of the grains due to gravity and the upward transport of grains by turbulent mixing and concentration gradients prevailing in the normal flow upstream of the trench is disturbed when the flow passes the trench, because the very high concentrations at the bed provided by the bed load transport in the normal flow disappear as soon as the flow reaches the slope of the trench or the side bench. These very high concentrations close to the bed are necessary for the maintenance of this balance, and when they disappear the suspended material begins to settle into the vortex region of the flow in the trench.

Since the settling velocities of the largest suspended grains are of the order of magnitude of 1 cm/s and the grains travel with the current velocity of the order of 1 m/s, it is quite clear that this settling out of suspended grains will take place over the entire width of the trench.

It is also evident that there is no hope of designing any means by which this settling out of suspended grains might be prevented.

When suspended grains have entered the vortex region in the trench they will, on the whole, statistically remain in this region, participating in its mean rotatory motion and settling through the water with nearly the same settling velocity as in still water.

If such grains are sand grains (and not flocculated clay particles) they will, after having finally reached the bed, remain on the bed, but possibly with a slight motion (as bed load) in the opposite direction of the flow in the river, so long as the trench is deep. There is no possibility of such grains being brought into suspension again by the flow occurring in the deep trench.

If the entire flow picture, including the intensity of turbulence as described by the eddy diffusion coefficient at all points in and above the trench were known, it would, in principle, be possible to devise a complete and accurate calculation of this sedimentation process for given concentrations and grain size distributions of suspended load in the undisturbed river flow. The solution of this problem is, however, only now beginning to become within reach, and it has, for the present purposes, only been possible to deal with this problem with the help of certain simplifying assumptions.

In conclusion, it may be stated that the bulk of the sedimentation that will occur in the trench will take place through sedimentation of suspended load in the manner described qualitatively above. The approximative calculation of the sedimentation according to this process has been described in the following section.

8. BASIS OF SEDIMENTATION CALCULATIONS.

8.0 General.

The grain size distribution curves and concentrations of suspended load measured one metre above the bed at C_1 and C_3 were used as a basis for computing rates of sedimentation at these positions in the tunnel trench.

The sedimentation at any given time was calculated by considering each of eleven different grain sizes separately. Integration over the tidal period and a summation of all the grain sizes then gave the total rate of fallout for the period of measurement.

In order to construct a theoretical model for the calculations the following assumptions were made: -

1) A wedge of free turbulence extends across the trench starting from the upstream corner, with its upper and lower bounds sloping at 1 in 20 to the horizontal.

2) Below the wedge the velocities are so small that the suspended sediment settles to the bottom with the same velocity as in still water, i.e. according to Stoke's Law.

3) Above the wedge the flow is undisturbed and the velocities and concentrations are the same as those in the flow upstream of the trench.

In the undisturbed flow a logarithmic velocity profile was taken. The concentrations of any given grain size were given by the formula -

$$C = C_a \left[\frac{D-y}{y} \cdot \frac{a}{D-a} \right]^{\frac{V_s}{0.4\,V_f}} \qquad (1)$$

where

C = concentration of suspended grains of a certain size at a height "y" above the bed.

C_a = concentration at a reference level, height "a" above the bed.

D = water depth.

V_s = settling velocity of the grain size under consideration.

V_f = shear velocity.

Considerations of the roughness of the river bed showed that V_f was approximately equal to $0.05\,\overline{V}$, and this was used throughout. ($\overline{V}$ = mean velocity of tidal flow upstream of trench).

8.1 Preliminary Calculations.

Preliminary calculations were first made using the method described in the report of June 1963. Inside the wedge the eddy diffusion coefficient was taken to be
$\epsilon = 0.0014\,\overline{V}\,x$ [1)]
(x is the distance from the leading edge of the excavation).

Here, it was assumed that the rate of settling would equal the rate at which material is lifted up by the turbulence; thus

$$V_s\,C = -\epsilon\,\frac{dc}{dy}$$

Integrating this expression and putting $y = -\frac{x}{20}$ along the lower plane of the wedge and $y = +\frac{x}{20}$ on the upper plane gives

$$C_1 = C_2\,e^{\left[\frac{V_s}{0.014\,\overline{V}}\right]} \qquad (2)$$

where
e = Base of natural logarithm
C_1 = concentration at the bottom of the wedge.
C_2 = concentration at the top of the wedge.

Together eqs. (1) and (2) give an explicit expression for calculation of C_1 at any horizontal position, for a given concentration in the river upstream.

The width of the trench was divided up into five equal sections. Values of C_1 at the centre of each section were calculated and multiplied by the settling velocity and the width of the section, to give the rate of sedimentation per unit width of trench.

1) H. Schlichting: Boundary Layer Theory. Pergamon Press. 1955.

8.2 Improved Calculations Taking Account of Continuity.

In the above procedure the quantity of sediment falling into the trench was assumed to be small compared to the total transport of the stream. Thus the concentration calculation at any section was not affected by the quantity of fallout in the preceding section.

For some grain sizes it was found that the fallout in the trench was a significant portion of the total transport of the river. Disregarding the horizontal continuity did not therefore give a true picture of the type of material being sedimented, or of the distribution of sediment across the trench. It also gave an overestimate of the total answer to the order of 25%. Because of this the method of calculation was altered to take account of continuity, making the following assumptions: -

1) At any section the concentration over the wedge is constant in the vertical direction.

2) Above the wedge the velocities are the same as in the undisturbed stream with a logarithmic velocity profile, and the concentrations are given by Eq. 1.

3) The depth is constant and equal to 10 m.

The procedure for the computations was as follows: -

a) The width of the trench was divided into ten sections, the lengths of the sections being small near to the leading edge, and gradually larger across the width. Plan nos. 163 and 164 show the sizes of the sections used. Over the first section the concentration was constant in the horizontal direction and over all the other sections the variation was linear.

b) The method of Einstein[2] was used to calculate the total transport of suspended sediment for the incoming stream and the transport above the wedge at the end of each section.

2) H. A. Einstein: The Bed-Load Function for Sediment Transportation in Open Channel Flow. U.S. Dept. of Agriculture, 1950.

c) From continuity, the total transport of the stream must be equal to the total transport above the lower plane of the wedge at any section plus the quantity that has fallen into the trench. The transport within the wedge is equal to the mean wedge velocity times the concentration and hence it was possible to calculate the concentrations in the wedge.

d) The rate of sedimentation was found by multiplying the wedge concentrations by the settling velocity and the width of the section.

Using this method the computation proceeded step by step commencing at the leading edge and working across the trench.

A typical example of the rate of fallout across the width of the trench is shown on Plan nos. 163 and 164.
The times at which the greatest rates of sedimentation occur (relative to high water) can be seen on Plan No. 165 for C_3 Spring Tide.

9. RESULTS OF SEDIMENTATION CALCULATIONS

9.0 Summary of Computed Results

The following results give the quantities of sediment deposited over one tidal period in kg per meter length of trench.

Grain Size mm	C_3 Spring	C_1 Spring	C_3 Neap
0.14	4751	0	757
0.115	4146	965	1323
0.09	1310	717	396
0.07	785	542	213
0.055	247	177	85
0.045	160	105	57
0.035	137	68	39
0.025	61	33	25
0.014	38	11	12
0.008	9	2	1
Total	11644	2620	2908

These quantities are deposited across the trench as follows:

	Width of Section m	C_3 Spring		C_1 Spring	C_3 Neap	
Pos. 0	1	382		62	138	
Pos. 1	2.2	703		129	237	
Pos. 2	2.8	638		136	188	
Pos. 3	4	729		158	204	
Pos. 4	10	1502		329	396	
			3954			1163
Pos. 5	12	1490		333	366	
Pos. 6	8	882		202	208	
Pos. 7	20	1987		469	452	
Pos. 8	20	1753		420	383	
Pos. 9	20	1578		382	336	
Total	100		11644	2620		2908

By comparing the above results with those of the preliminary calculations it was possible to arrive at an approximate figure for the fallout at C_1 (Neap Tide) without modifying the calculations to take account of continuity.

The total sedimentation for C_1 Neap was estimated as 600 kg.

9.1 Adjustments for Different Widths of Trench and for Effect of Side Benches

The above calculations are based on a trench 100 m wide at the top. However, the width of the trench in the Boom clay section is only 90 m, the adjustment for which is made below.

In the sand bed section the width at the top of the trench is considerably larger, owing to the flatter slopes in the sand, as well as to the side benches at the top of the Boom clay.

From the distribution of the calculated sedimentation it appears that a considerable part of the sedimentation will take place on the slopes and on the side benches. However, when the flow is reversed with the tide, erosion will take place on the upper part of the slope and on the river bed adjacent to the slope. The result of this and of the deposition on the side bench is that the slope is quickly flattened out until it reaches a temporary equilibrium whereby the material deposited on the slope during the period with one flow direction is largely removed during the following period with the opposite flow direction. Also, in the beginning, the edges of the trench move quickly away from the trench on both sides.

The equilibrium thus reached for the slopes is temporary because, in the end, the slopes will disappear as the trench is completely filled up.

During the period elapsing before the slopes have reached their temporary equilibrium, part of the material which in the calculations has been found to settle on the slopes or on the side benches may in fact slide down into the trench proper. On the other hand, the fact that the edges of the trench in this period are moving away from the trench will tend to reduce the rate of sedimentation in the trench proper.

On the basis of this reasoning it has been found most reasonable to disregard the sedimentation on the slopes and on the side benches when calculating the rate of sedimentation in the trench proper. Thus, the following rates of sedimentation for the trench proper are arrived at:

C_1: Boom clay section

Trench width: 90 m (width below wedge ~ 85 m)

Spring: $2620 - 382 \cdot \frac{15}{20}$ = 2340 kg/m per tide

Neap: $600 \cdot \frac{2280}{2620}$ = 520 kg/m per tide

Average sedimentation in trench: 2860 kg/m per day

C_3: Sand bed section

Trench width at level of river bed: 140 m
Trench width at level of Boom clay: 90 m (below wedge ~ 90 m)

Spring: $11644 - 3954 - 1490 \cdot \frac{5}{12} + 1578$ = 8650 kg/m per tide

Neap: $2908 - 1163 - 366 \cdot \frac{5}{12} + 336$ = 1930 kg/m per tide

Average sedimentation in trench proper: 10580 kg/m per day

Allowing a reduction of about 20% for the decrease in the concentration along the length of the trench (see explanation in section 9.2 below), the net rate of sedimentation in the sand section becomes 0.8 · 10580 = 8450 kg/m per day.

These figures refer to winter conditions.

9.2 Adjustment for Variations Along the Trench

Concentrations and grains size distributions of the suspended load vary along the length of the trench, partly owing to the difference in bed material (Boom clay or sand); partly owing to the variations in current velocities as the depth changes.

Of these variations it has only been possible to investigate the variations in grain size distributions from the Boom clay section to the sand bed section, whereas the variation in grain size distribution owing to different current velocities within the sand bed section had to be neglected in the field investigations. However, it is known that the grain sizes of the suspended material in verticals with lesser depths will be smaller.

If the variations in grain size distributions within the sand bed section are neglected, the sedimentation will be approximately proportional to the concentrations of the suspended load.

Plan 103 shows a typical variation of concentration along the length of the trench. Integrating this concentration curve over the entire length of the sand bed section, from a point between C_1 and C_2 to the left bank, we arrive at a mean concentration of about 1.1 g/l. The concentration at C_3 is 1.3 g/l. The mean concentration is thus some 20% lower than the concentration at C_3.

9.3 Adjustment for Seasonal Variations

Plan 102 shows the variation of average concentrations measured 1 m above the bed, and Table 2 below contains a number of such averages on the basis of which the ratios between these averages for different times of the year have been calculated.

In the table all values except one of the lines for C_2 Spring refer to only a limited part of the tidal period, viz. from one hour before HW to four hours after HW. This was the period covered by the measurements of concentrations and grain size distributions of the suspended load in the winter measurements 1965, and the grain size distributions found lead to the result that a major part of the sedimentation in the trench occurs withnin this period.

Table 2: Correction Factor for
Seasonal Variation in Concentrations

Vertical	Tide	Mean concentrations g/l			Concentration Ratios	
		July	Oct.	Feb.	Conc. July / Conc. Feb.	Conc. Oct. / Conc. Feb.
C_1	Spring	-	1.18	0.45	-	2.6
C_1	Neap	-	0.45	0.18	-	2.5
C_2	Spring*	1.53	1.34	0.38	4.0	3.5
C_2	Spring	1.42	1.71	0.46	3.1	3.7
C_3	Spring	1.38	1.24	0.90	1.5	1.3
C_3	Neap	-	0.42	0.32	-	1.3

*This line covers the entire tidal period.

It will be seen from the table, as well as from Plan 102, that there is a considerable variation, possibly of a seasonal nature, in average concentrations in verticals C_1 and C_2, whereas the variation in vertical C_3 is rather small. When considering these results it should be mentioned that the soundings made in connection with the test pit P2 have shown, that the sand bank in the winter period had been eroded appreciably, as has been indicated on Plan 101. Because of this, it is not entirely impossible that the small concentrations observed in the winter measurements at C_2 may be caused partly by this vertical being placed at that time on a clean Boom clay surface or, perhaps very near to the limit of the sand bank. On the other hand, in the second spring tide in which measurements were made at C_2 during the winter period, this vertical was moved approximately 25 m towards the left bank in order to ensure that it was located over the sand bed. In spite of this the concentrations observed remained very low.

On the whole, it seams very difficult to explain the rather low values observed in the winter measurements without allowing for a certain seasonal variation. On the other hand, a seasonal variation in the observed direction, i.e. with small concentrations in the winter period, is also difficult to account for, because one would normally expect the lower temperature of the water in the winter to give rise to higher concentrations.

On the basis of the figures given in the above table one may expect the concentrations in the summer season to be between 1.5 and 2.5 times as high as in the winter period. On this basis the rates of sedimentation for the summer are expected to be:

Boom clay section:	Between 4 and 7 t/m per day
Sand section:	Between 13 and 21 t/m per day

The above figures are based on the assumption that the grain size distributions measured for the winter conditions remain representative for the summer conditions. This is perhaps not so unreasonable, but the very fact that there seems to be a seasonal variation could hardly be explained in any other way than by assuming that, under summer conditions, there is a higher content of flocculated grains with settling velocities in the same range as that of the fine sand and the coarse silt grains which constitute the major part of the suspended load in the winter observations. The presence of a high content of flocculated grains might influence considerably the geotechnical properties of the deposits.

10. GEOTECHNICAL PROPERTIES OF THE DEPOSITS IN THE TRENCH.

10.0 General.

The geotechnical properties of the deposits are of primary importance for the problem of selecting suitable methods for the removal of deposits prior to the sinking of the tunnel elements.

The geotechnical properties of such deposits, such as their unit weight and shear strength, will depend primarily on the relative content of fine silt and clay particles. If these grain sizes represent more than about 5 percent of the material (by weight), the deposit will have the character of mud, even if the bulk of the material consists of sand particles. In this respect it makes no difference whether the clay is flocculated or not. The flocculation is important only for the rate of settling of the clay particles.

It follows from the above that in order to evaluate the geotechnical properties from the grain size curve of a given material such a grain size curve should be determined with the use of a deflocculating agent, because this alone will show the true content of particles of fine silt and clay.

10.1 Grain Size Distributions of the Deposits.

The probable grain size distributions of the deposits may - for winter conditions - be found from the results of the sedimentation calculations. These theoretical grain size distributions have been plotted on Plan No. 124 for three different tides for which the grain size distributions of the suspended load have been determined in the field investigations and used in the calculations.

When considering these grain size distributions it should be remembered that the grain sizes used have been determined w i t h o u t the use of a deflocculating agent, because it is the settling velocities of the flocculated grains that are decisive for the sedimentation.

Curve 1 on this plan represents the material that will be deposited in the Boom clay section of the trench. This curve may be compared with either of the curves 2 and 3 on Plan No. 122 representing the material deposited in a test bucket in test pit P3. In this comparison it should be noted that the upper parts of the curves on Plan No. 122 have been determined by means of sieve analysis. The coarse grains found hereby consist to a large extent of organic particles with much lower settling velocities than those of quarts grains with the same grain sizes. Therefore, on Plan No. 124 these grains would not be represented as coarse grains, since the curves on Plan No. 124 are based entirely on settling velocities.

With these remarks in mind, the agreement between curve 1 on Plan No. 124 and especially curve 2 on Plan No. 122 is very good. In fact the difference between the two curves practically disappears if curve 2 on Plan No. 122 is shifted to the right corresponding to an increase in grain size of 0.01 mm.

The material described by the grain size curves on Plan No. 122 was a soft sandy mud, as may be expected from the 5% criterion when considering the grain size curve on Plan No. 122 determined with the use of a deflocculating agent (curve 1). The real consistency of the material cannot be detected from either of the curves 2 or 3 on Plan No. 122, and still less from curve 1 on Plan No. 124.

From this it is clear that considerable caution should be exercised when inferring the texture of the deposits from the grain size curves found in the calculations and shown on Plan No. 124.

On Plan No. 124 there is a marked difference between the curves 2 and 3 representing the deposits expected in the sand bed section and curve 1 representing the Boom clay section. A similar difference was observed in the character of the material caught in the buckets, which was considerably more "muddy" in P3 than in P2, the latter being described by the observer as being sand, but not quite clean sand. (Unfortunately, the sample taken in this manner from P2 was lost before a grain size curve was determined.)

From the grain size curves on Plan 124 it would appear that the relative content of fine silt and clay particles to be expected under winter conditions in the sand bed section is only some 40 percent of the relative content of such particles in the deposits in the Boom clay section. This and the result of the bucket tests indicate that there will be considerable difference between the properties of the two materials.

10.2 Expected Unit Weight and Shear Properties of the Deposits.

On the basis of the above considerations the deposits in the Boom clay section are expected to have the character of a sandy silt (mud) with a unit weight of about 1.4 t/m^3 (submerged unit weight 0.4 t/m^3). The shear strengths of the material will be small, but, owing to its relatively small submerged unit weight, the material will nevertheless be able to form fairly steep, stable submerged slopes.

Because of the uncertainties inherent in the grain size determinations there is a possibility that the deposit in the Boom clay section may be a silty sand with a somewhat higher unit weight than 1.4 t/m^3.

In the sand bed section the deposits will have the character of a (slightly) silty sand. The unit weight will be somewhat larger than that of the deposits in the Boom clay section, but not so large as the unit weight of a clean sand. The unit weight is expected to be about 1.6 - 1.7 t/m^3.

With regard to shear properties this deposit will probably have the character of a frictional material with slight cohesion. It will probably have a flatter stable slope than the material in the Boom clay section.

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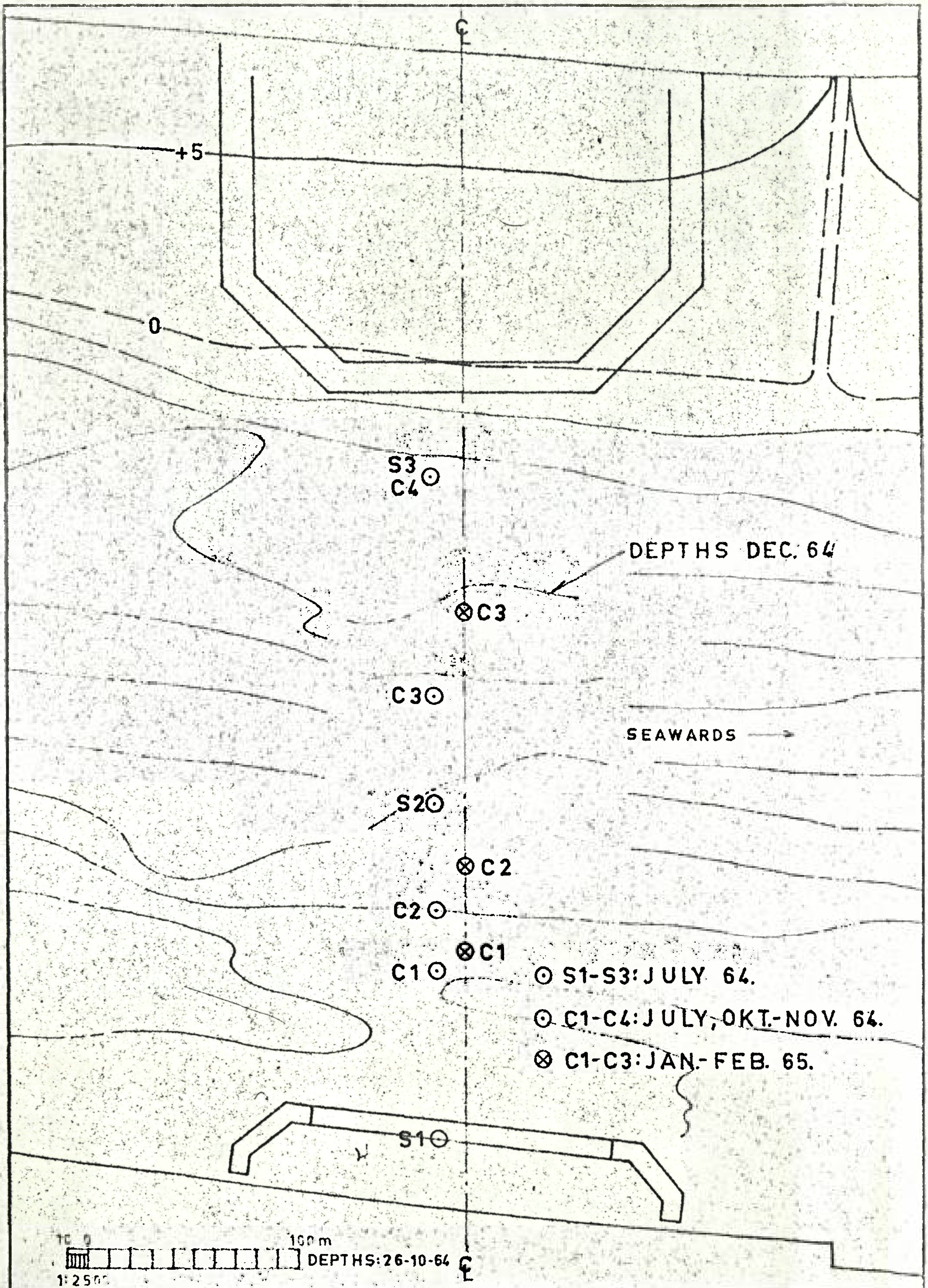
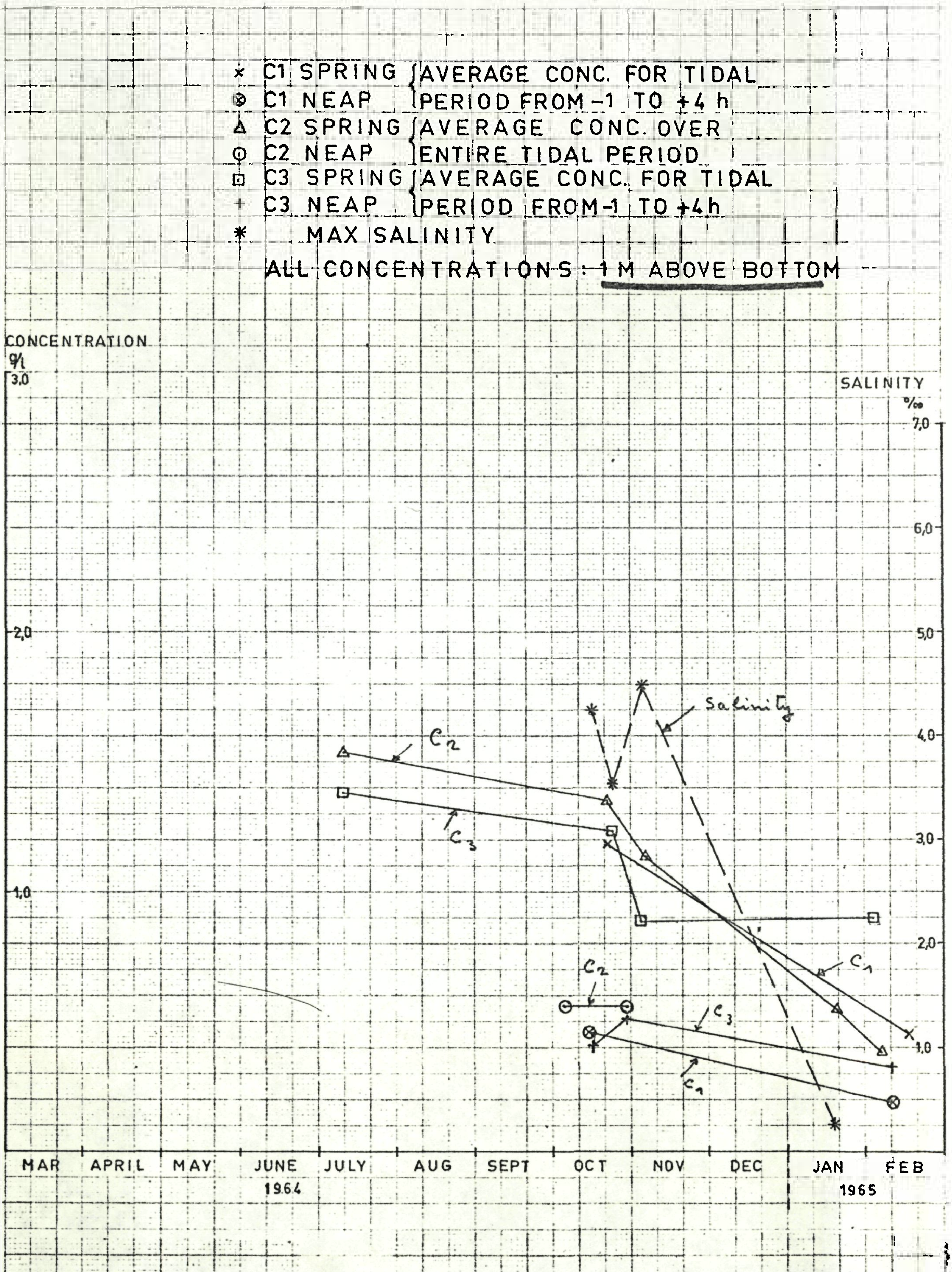
LIST OF PLANS

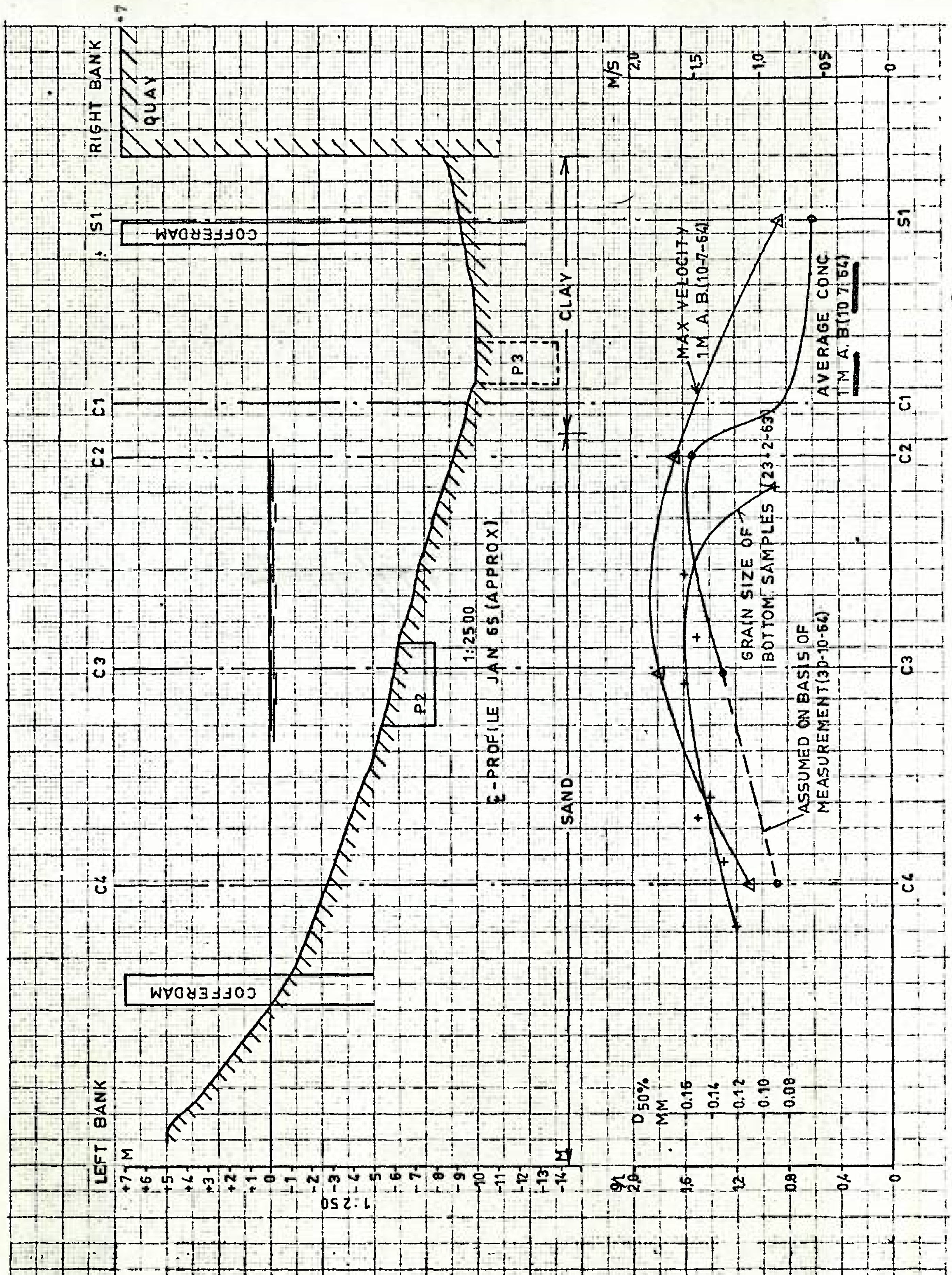
A: General Plans



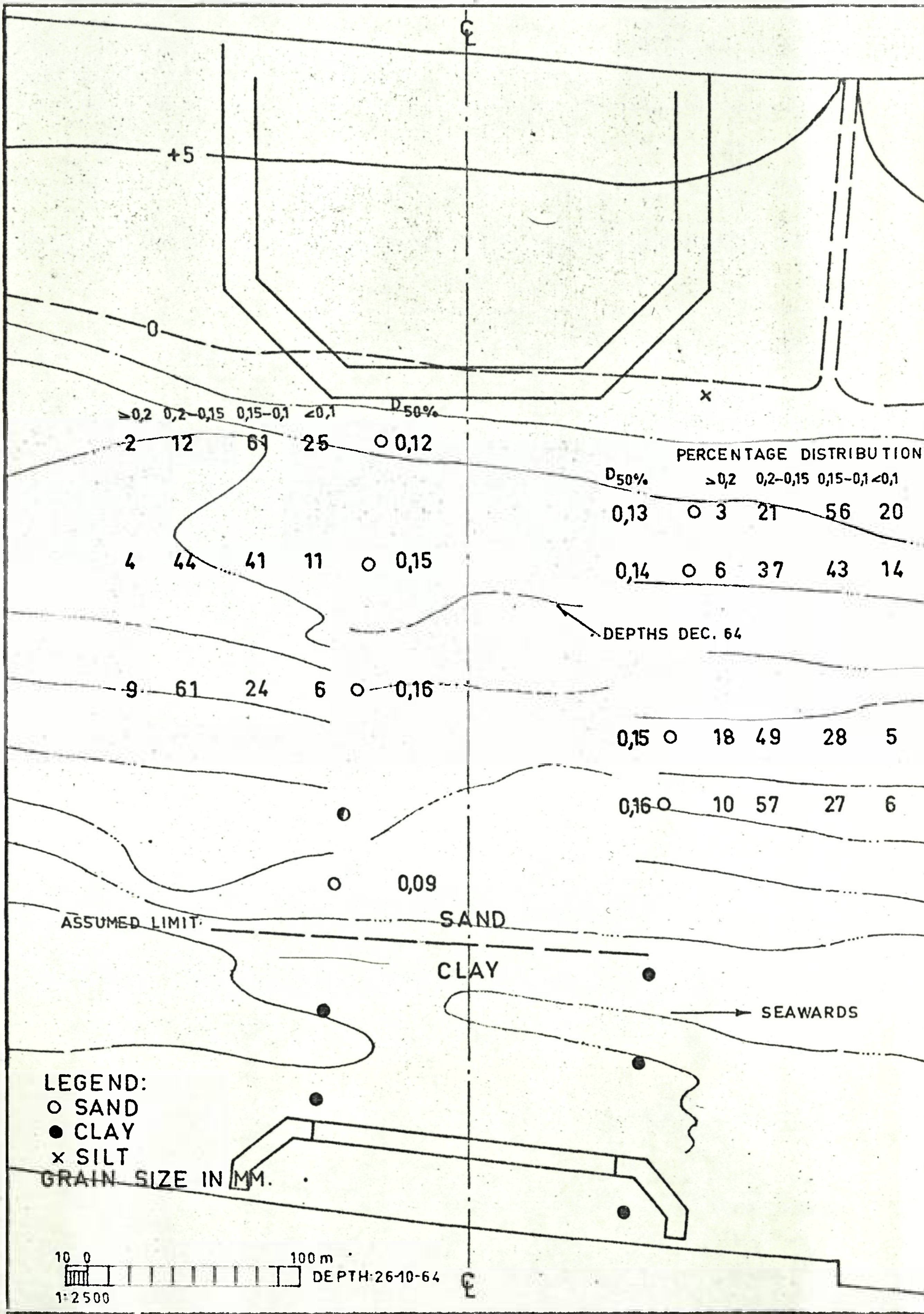
DANISH INSTITUTE OF APPLIED HYDRAULICS	E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE 64-1 · DATE 20-4-65 SCALE 1:2500	LOCATIONS OF VERTICALS	PLAN 101



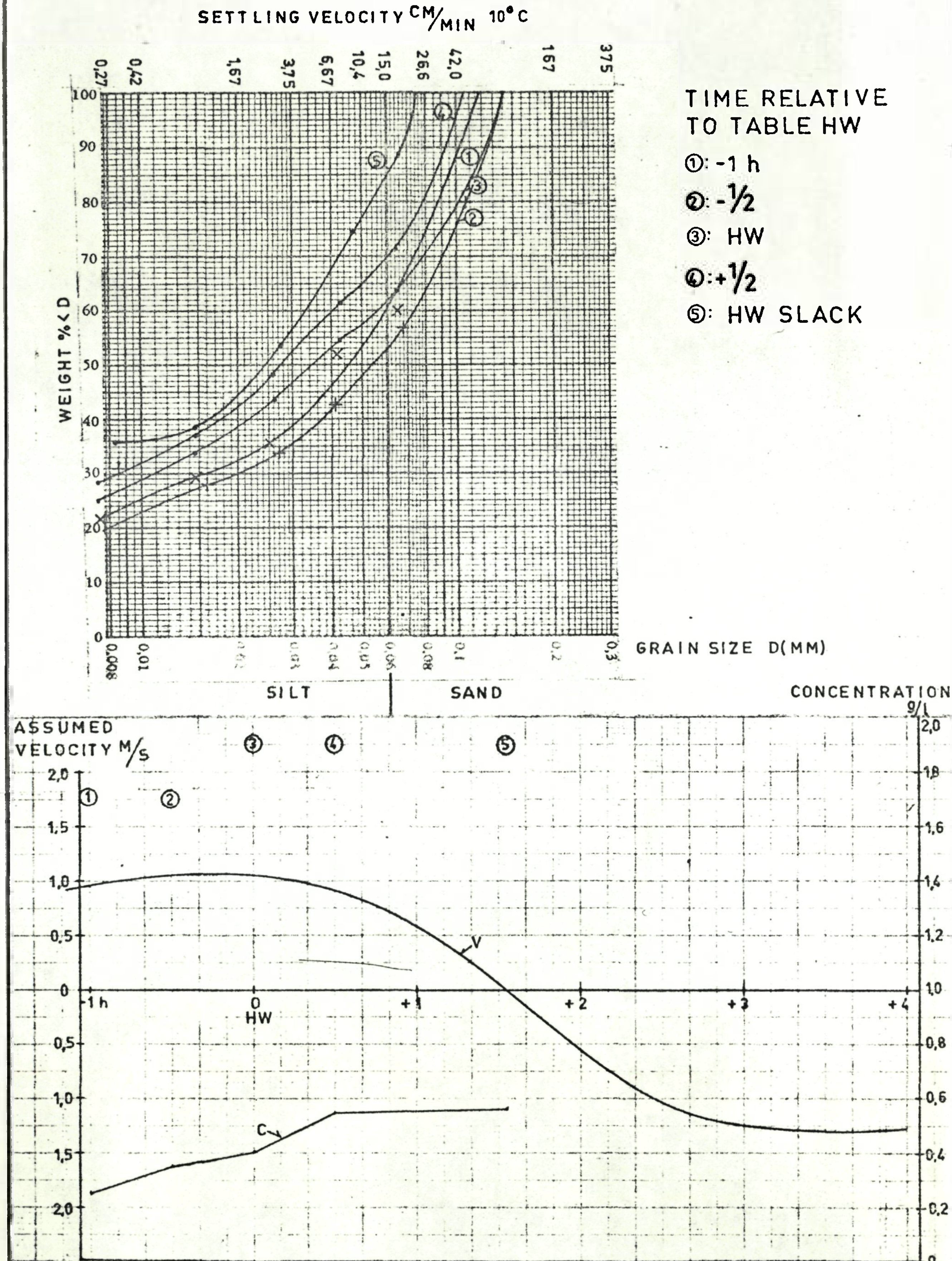
DANISH INSTITUTE OF APPLIED HYDRAULICS	E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1 DATE: 20-4-65 SCALE.	SEASONAL VARIATION IN SUSPENDED LOAD CONCENTR.	PLAN 102



DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	BED PROFILE, BED MATERIAL, VEL. AND CONC. ALONG TUNNEL AXIS	PLAN 103
SCALE:			

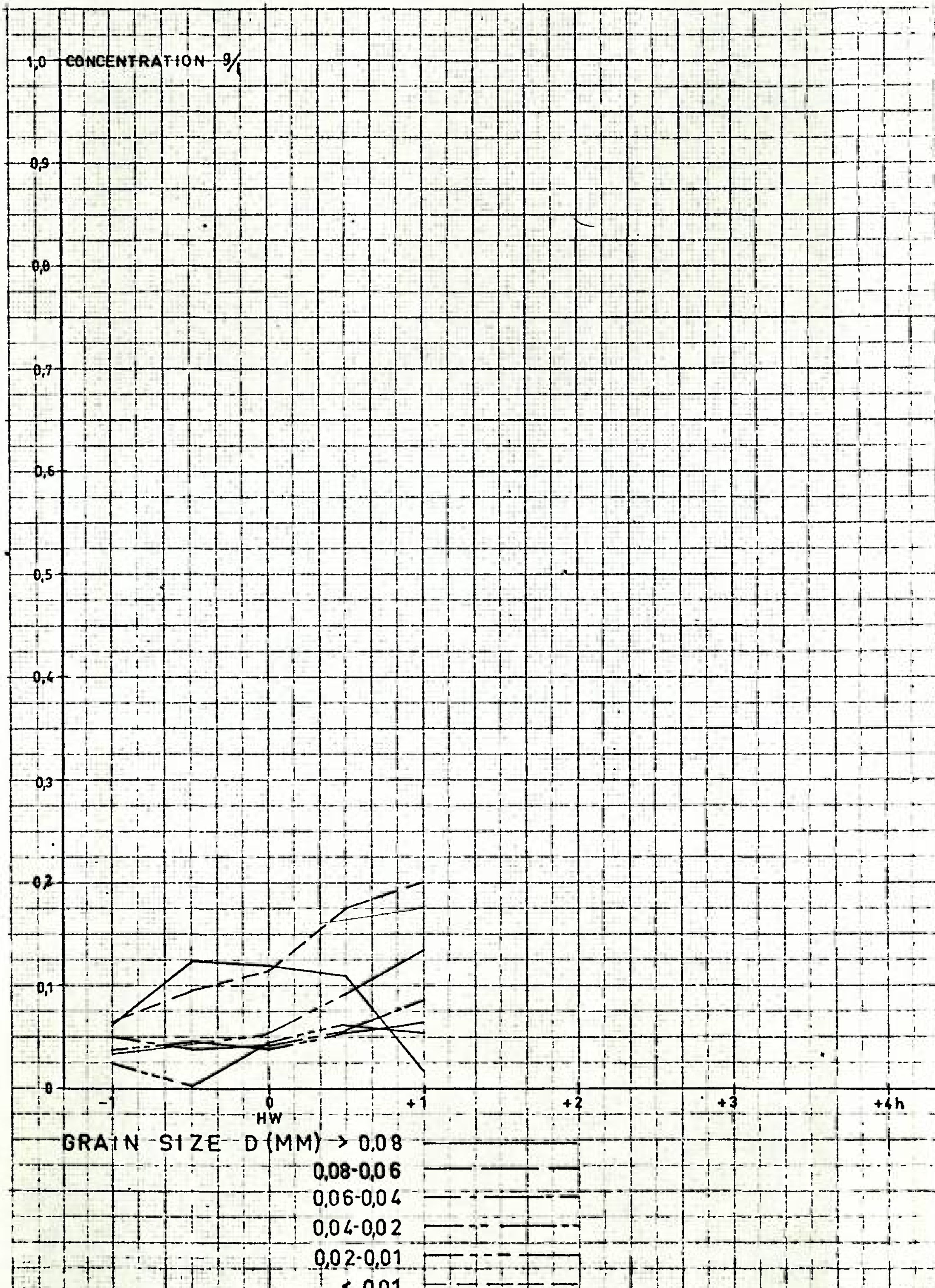


DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE 20-4-65	GRAIN SIZES OF BOTTOM SAMPLES 23-2-63.	PLAN 111
SCALE 1: 2500			

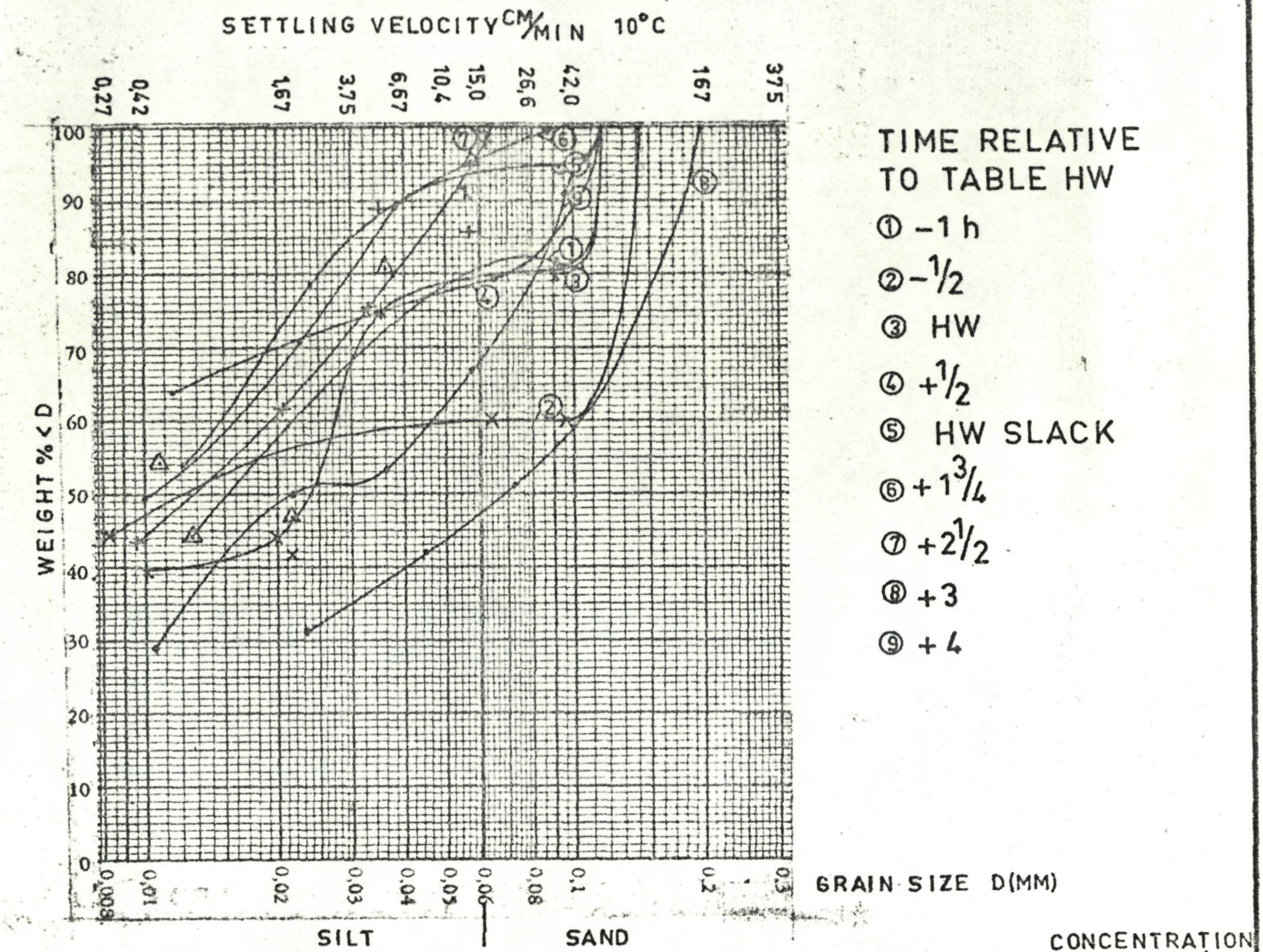


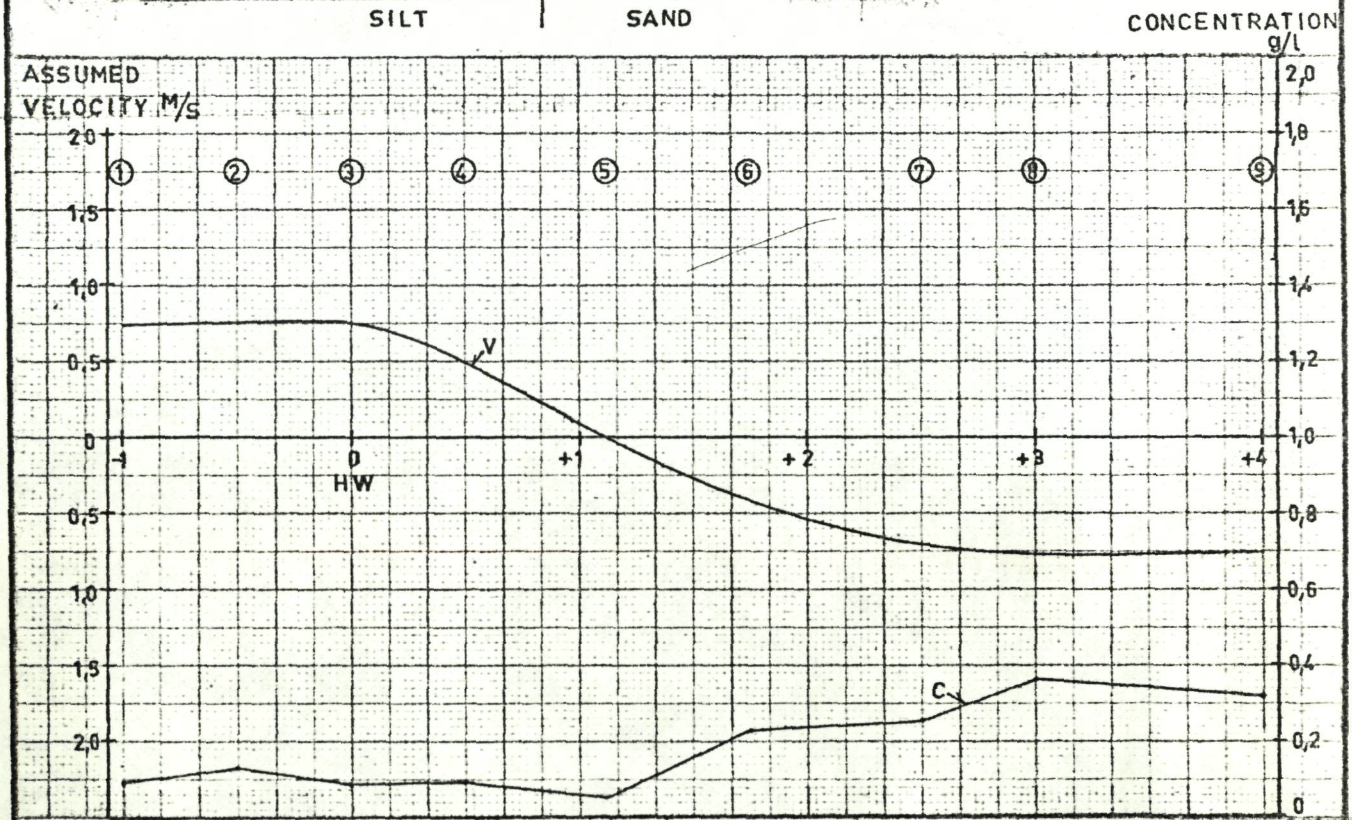
SPRINGTIDE -1 DAY. 1 M ABOVE BOTTOM

DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 23-4-65	GRAIN SIZES OF SUSP. LOAD, C1 17-2-65 (SPRING)	PLAN 112
SCALE:			



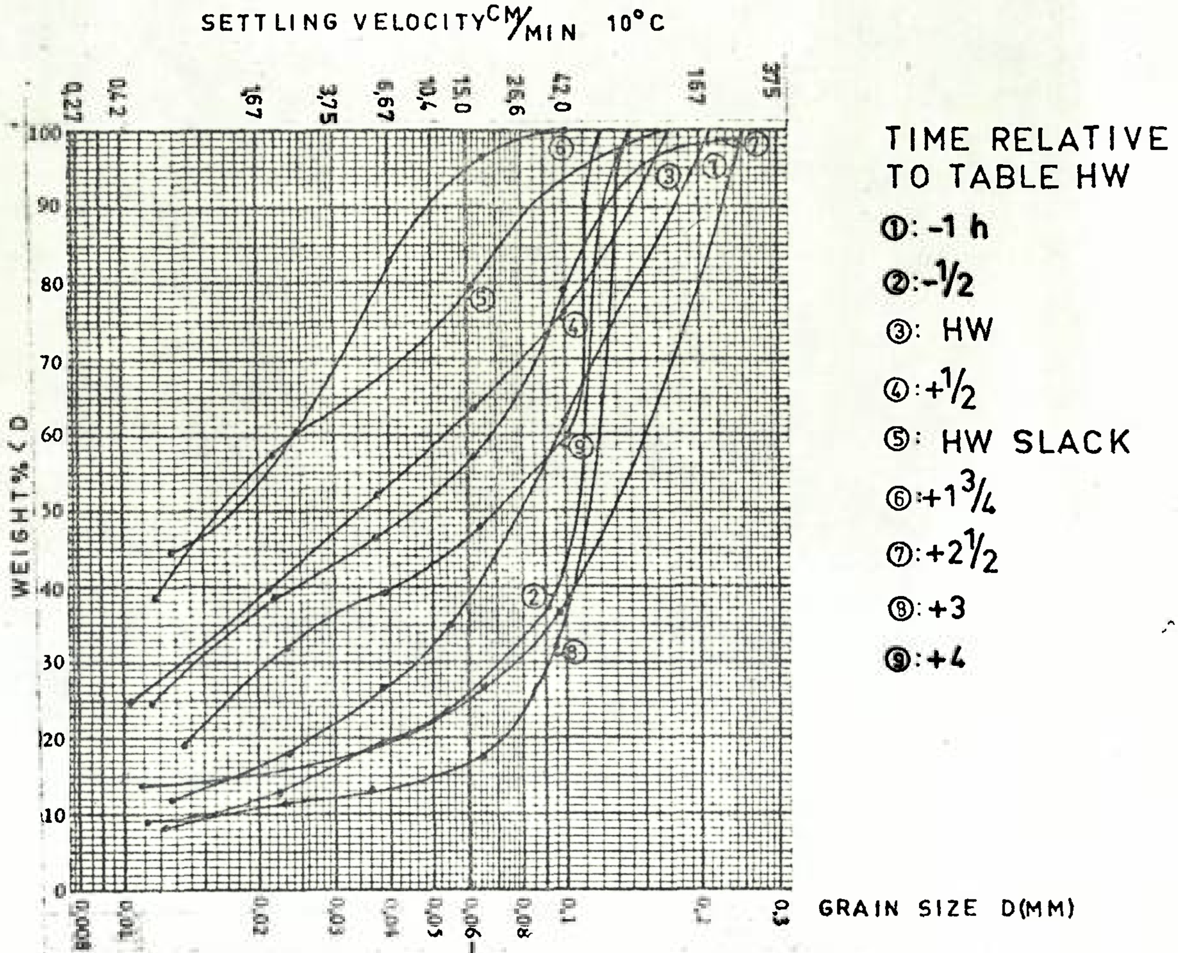
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE 64-1	DATE: 20-4-65	CONCENTRATIONS OF DIFFERENT GRAIN SIZES. C1, 17-2-65 (SPRING)	PLAN 113
SCALE.			

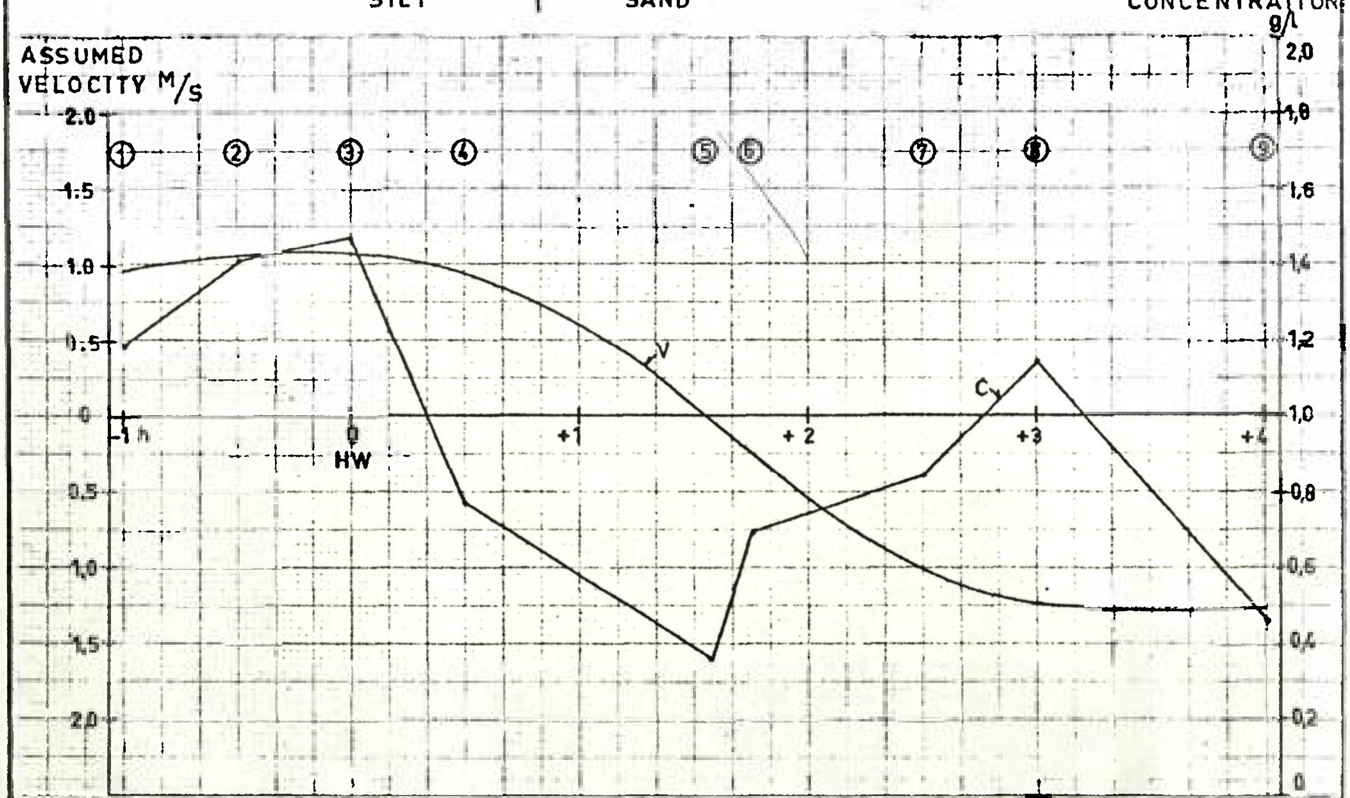




NEAPTIDE. 1 M ABOVE BOTTOM

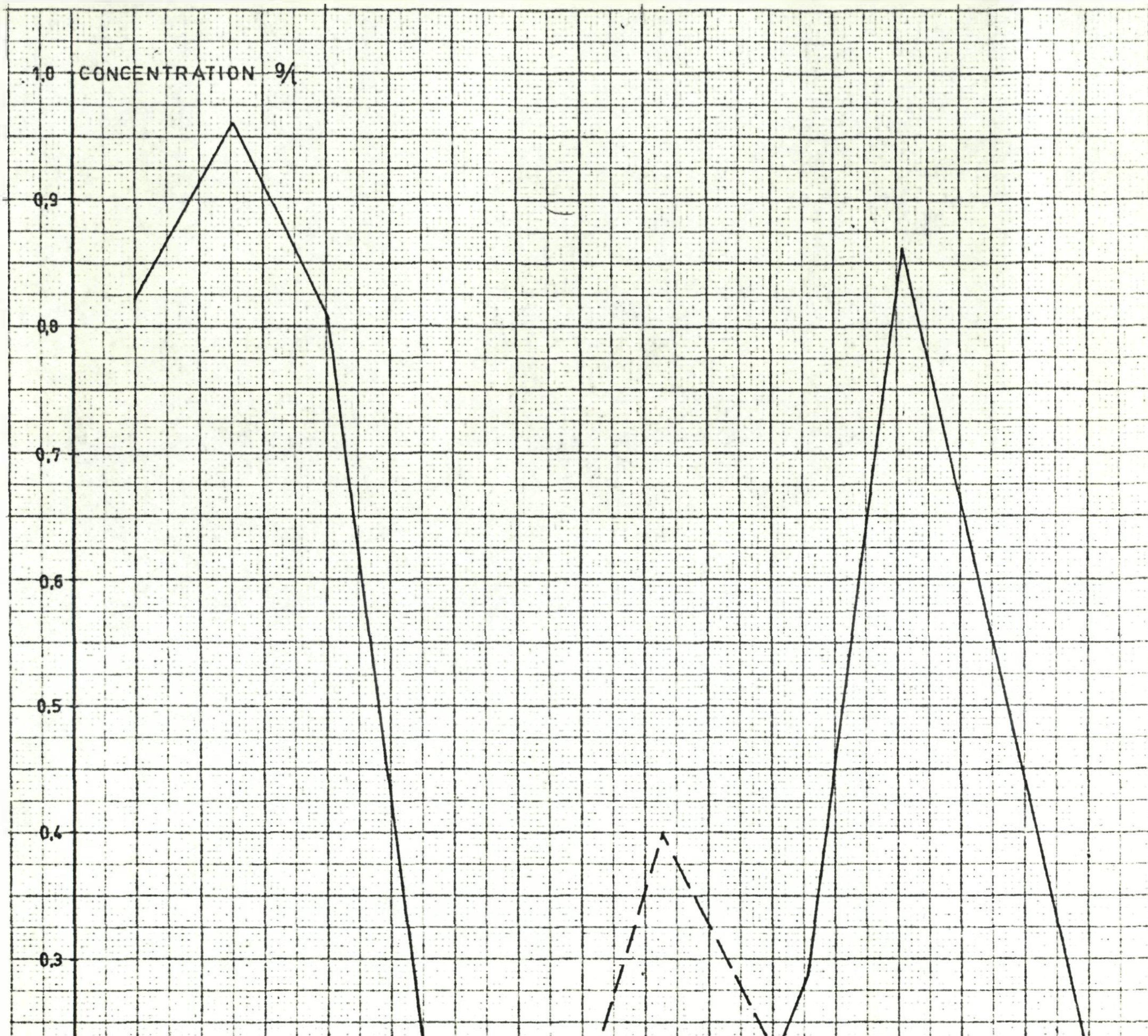
DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 23-4-65	GRAIN SIZES OF SUSP. LOAD, C1 11-2-65 (NEAP)	PLAN 114
SCALE:	-		



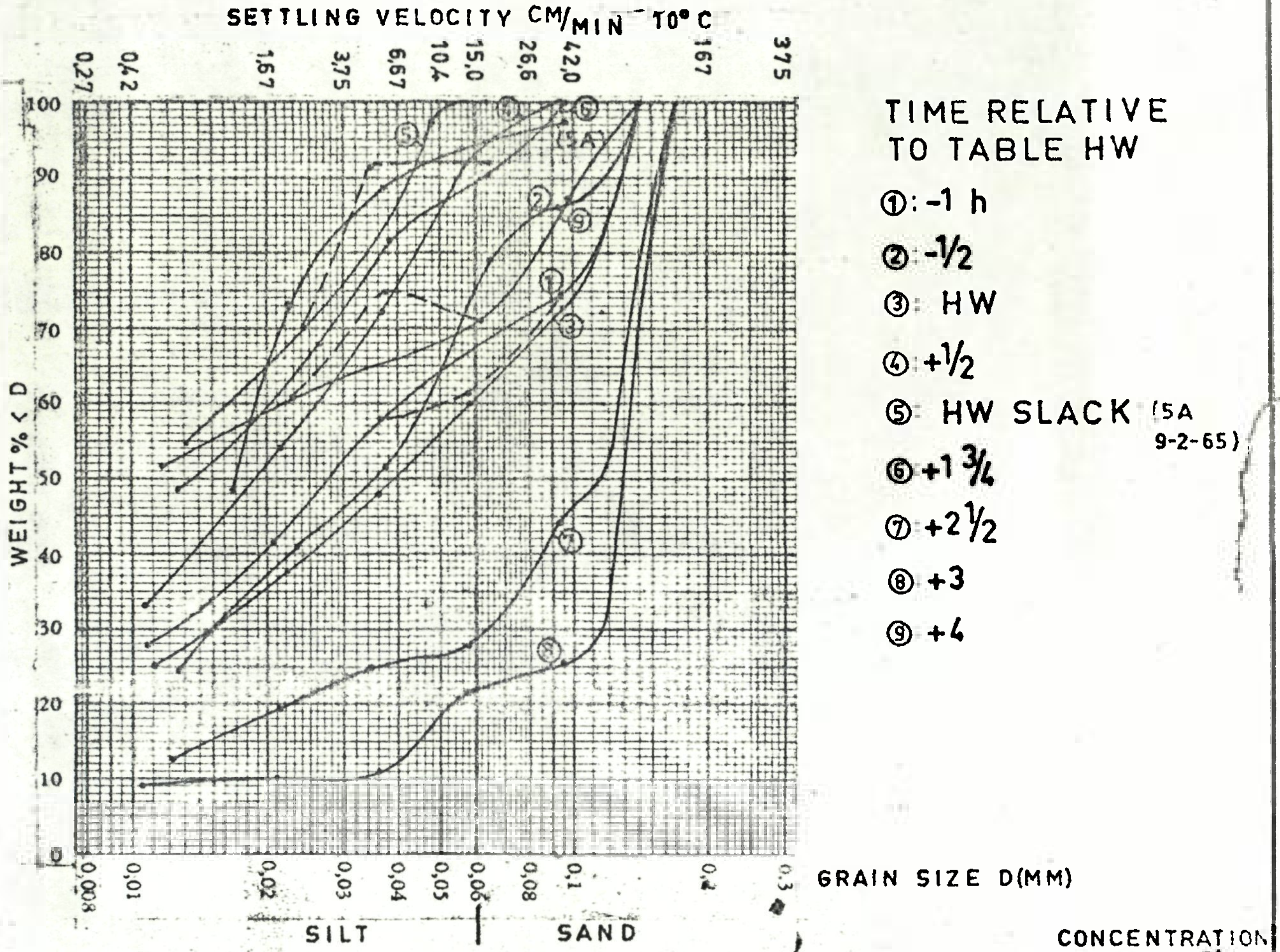


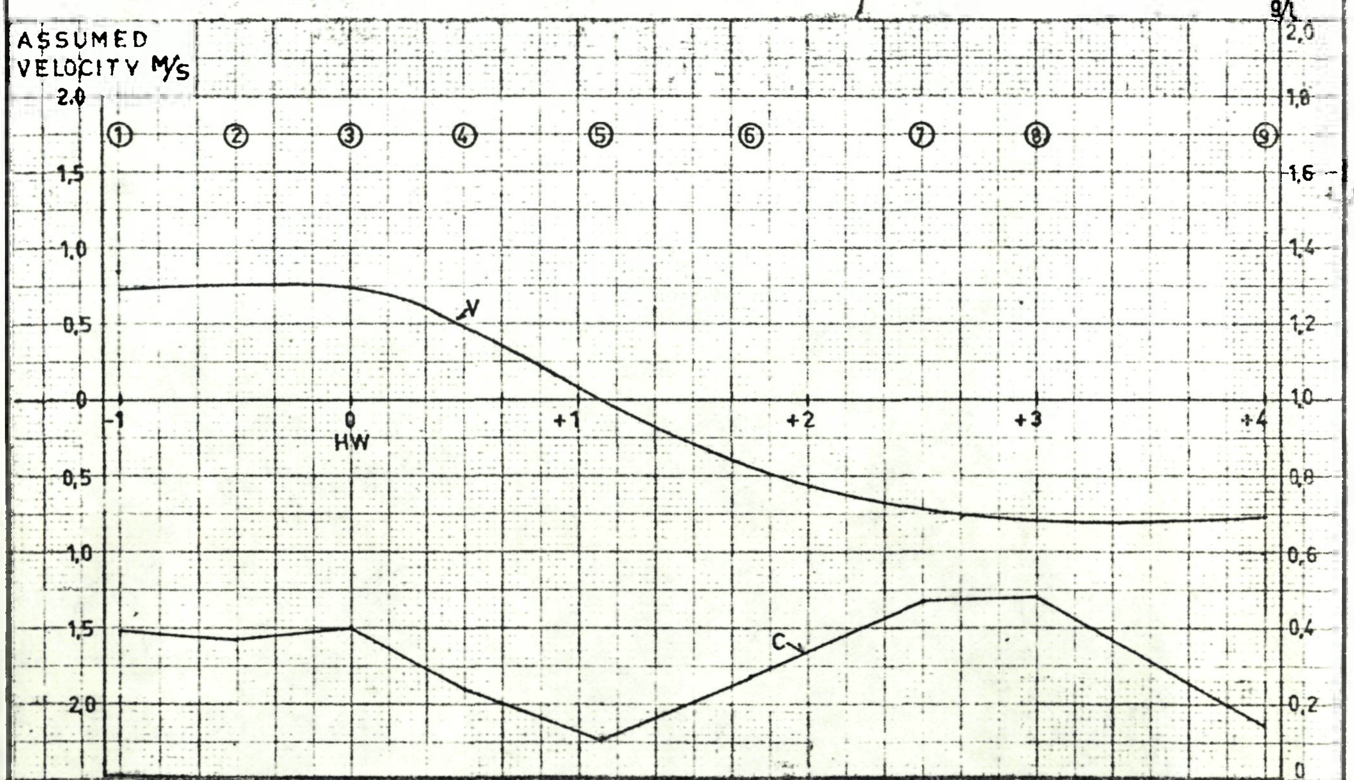
SPRINGTIDE. 1 M ABOVE BOTTOM

DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 23-4-65	GRAIN SIZES OF SUSP. LOAD, C3 3-2-65 (SPRING)	PLAN 115
SCALE:			



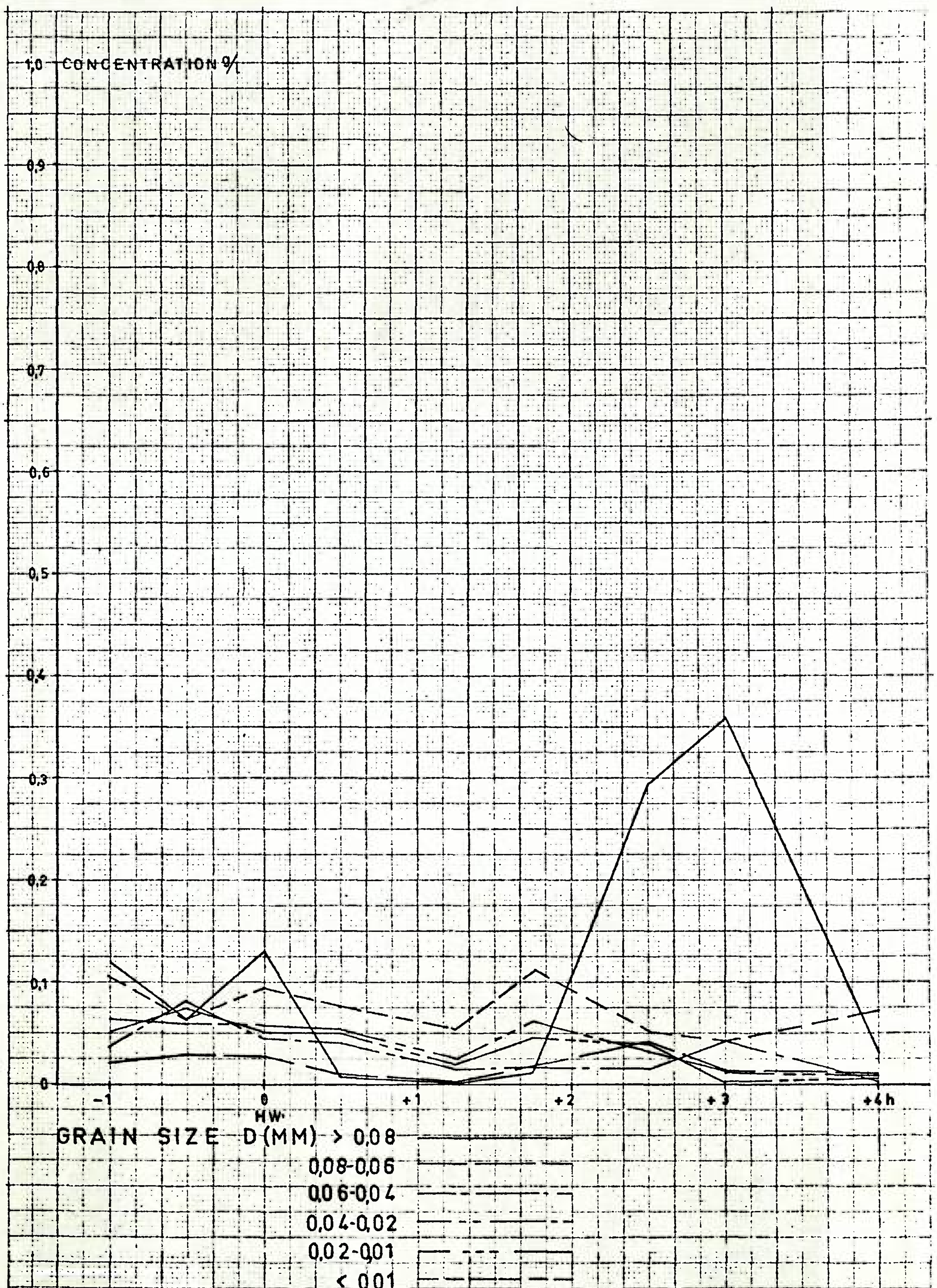
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL	
		SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	CONCENTRATIONS OF DIFFERENT GRAIN SIZES. C3, 3-2-65.(SPRING)	PLAN 116
SCALE:			



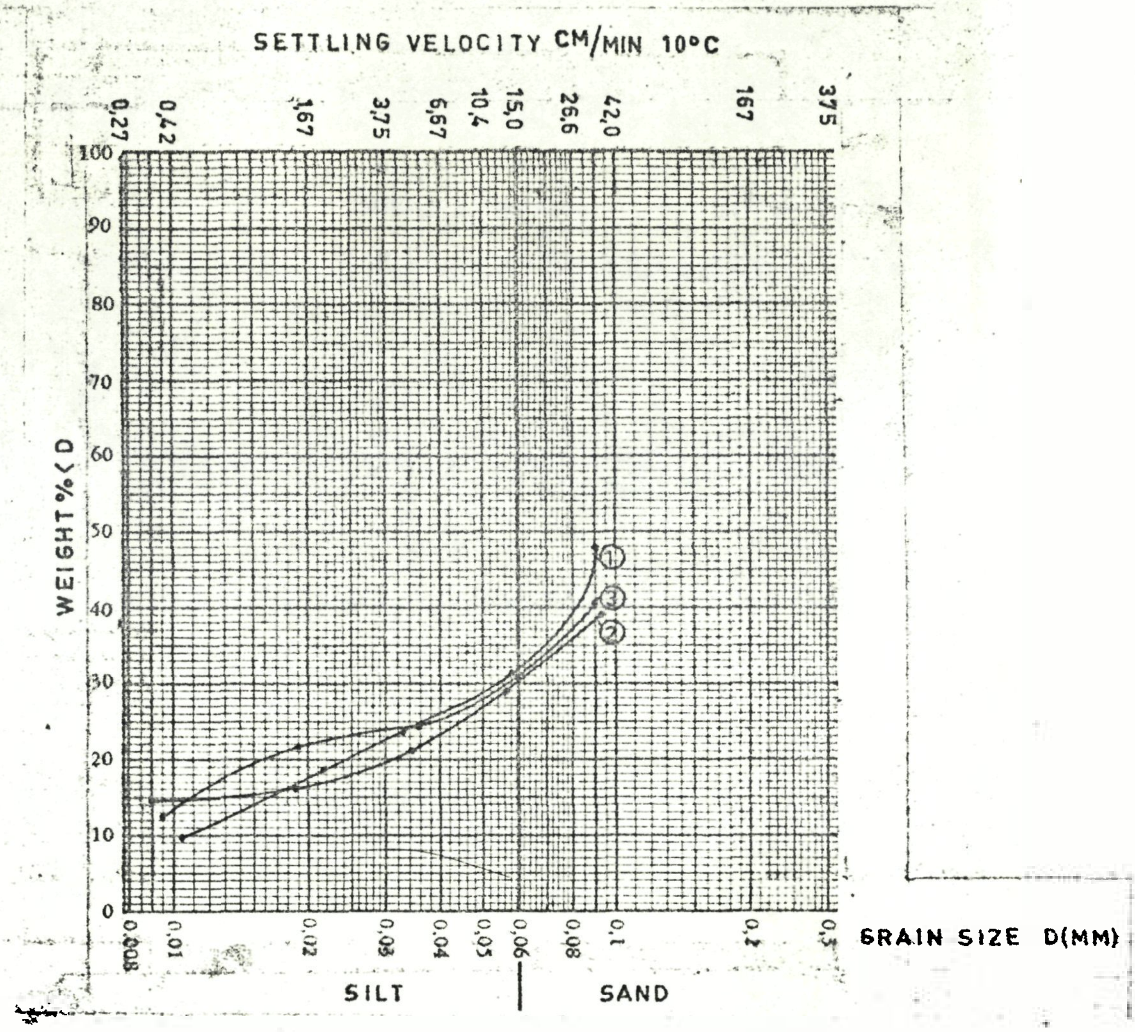


NEAPTIDE -1 DAY. 1 M ABOVE BOTTOM

DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	GRAIN SIZES OF SUSP. LOAD, C 3. 10-2-65 (NEAP)	PLAN 117
SCALE: 1: 5000			

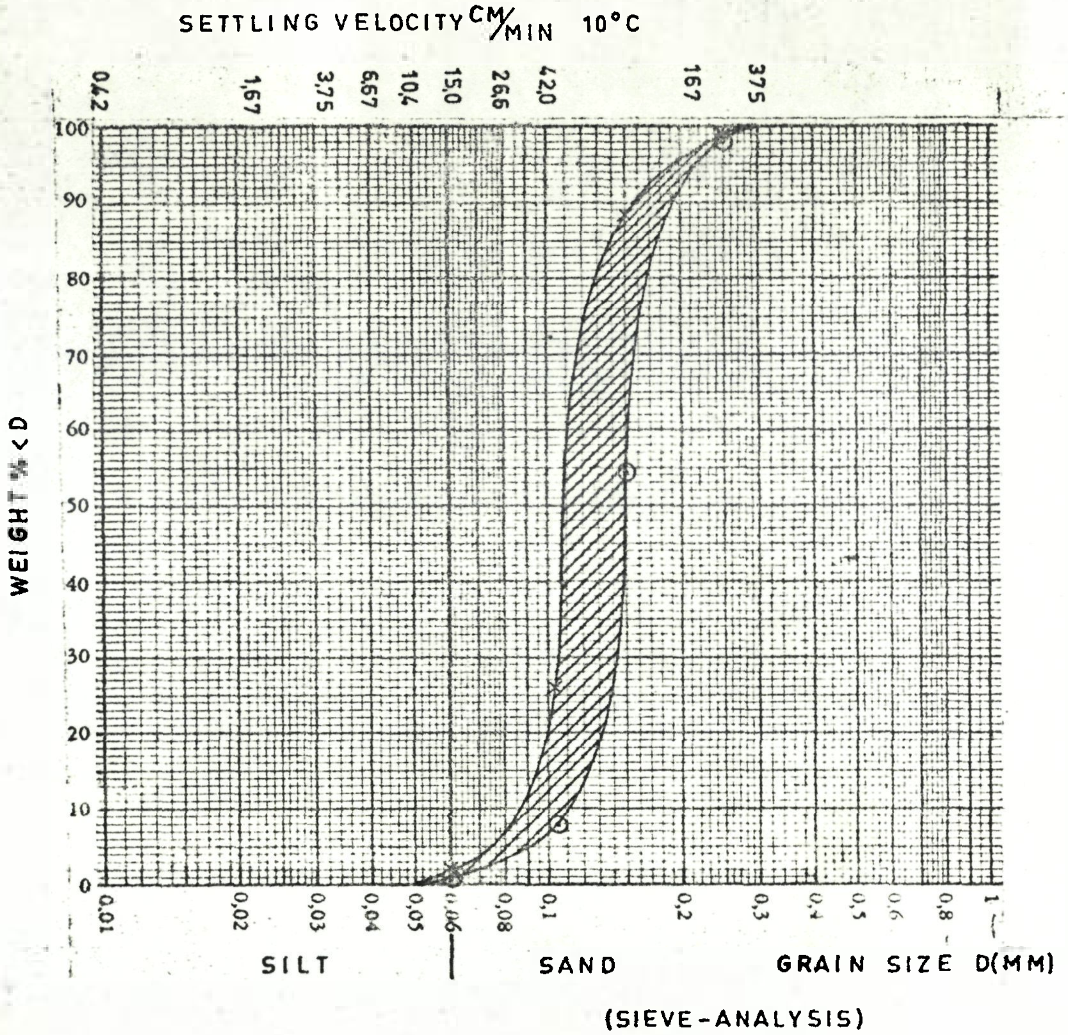


DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	CONCENTRATIONS OF DIFFERENT GRAIN SIZES. C3, 9-2-65. (NEAP)	PLAN 118
SCALE:			

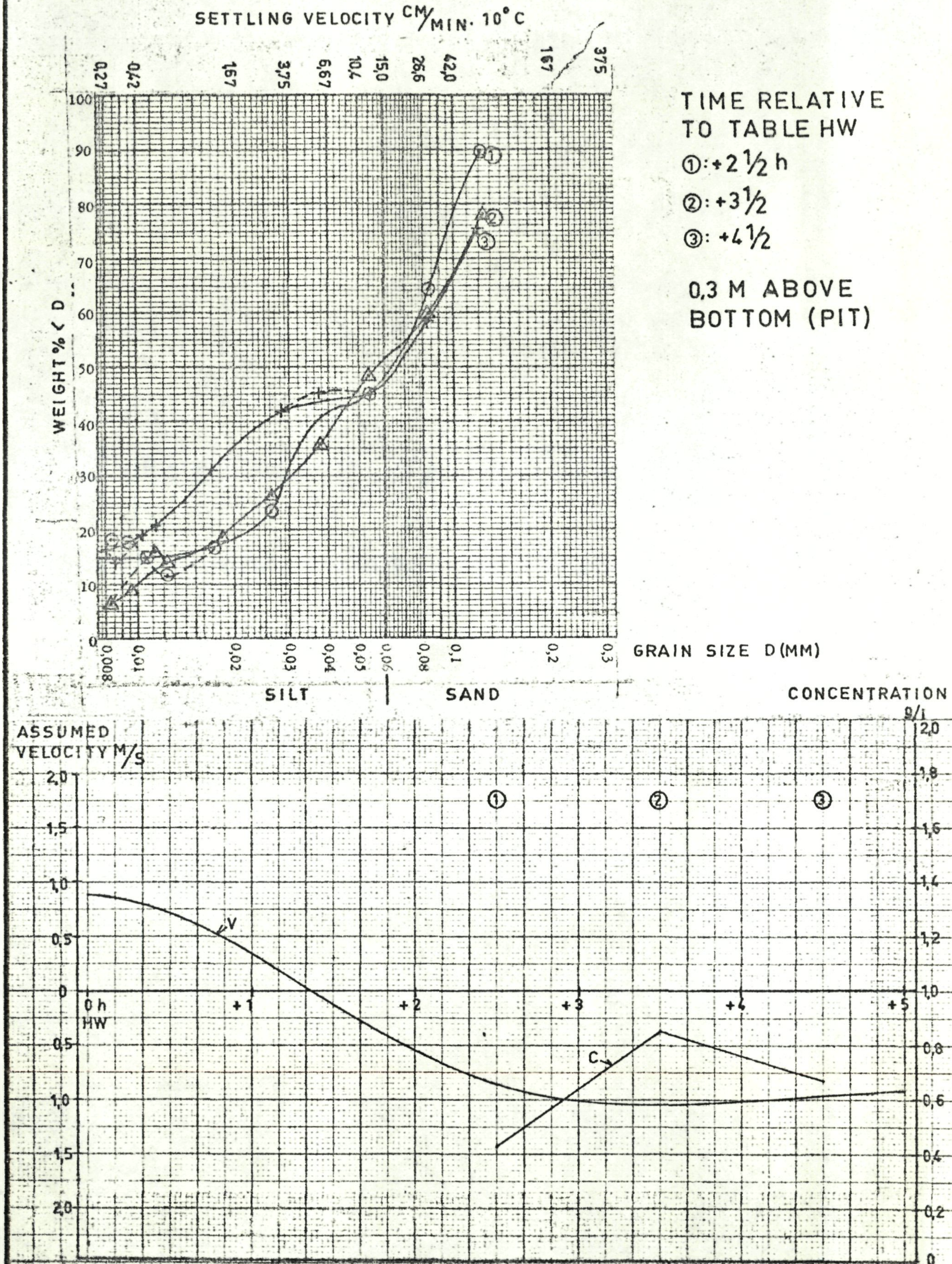


TIME RELATIVE TO TABLE HW + 6,5 h.	SUSPENDED LOAD CONCENTRATION
① Natural salt content.	0,46 g/l
② Additional 10g/l salt mixed 1 hour.	0,47 g/l
③ Additional 10g/l salt mixed 2 hours.	0,49 g/l

DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 23-4-65	FLOCCULATION TESTS, C2 15-2-65 (MEAN)	PLAN 119
SCALE:			

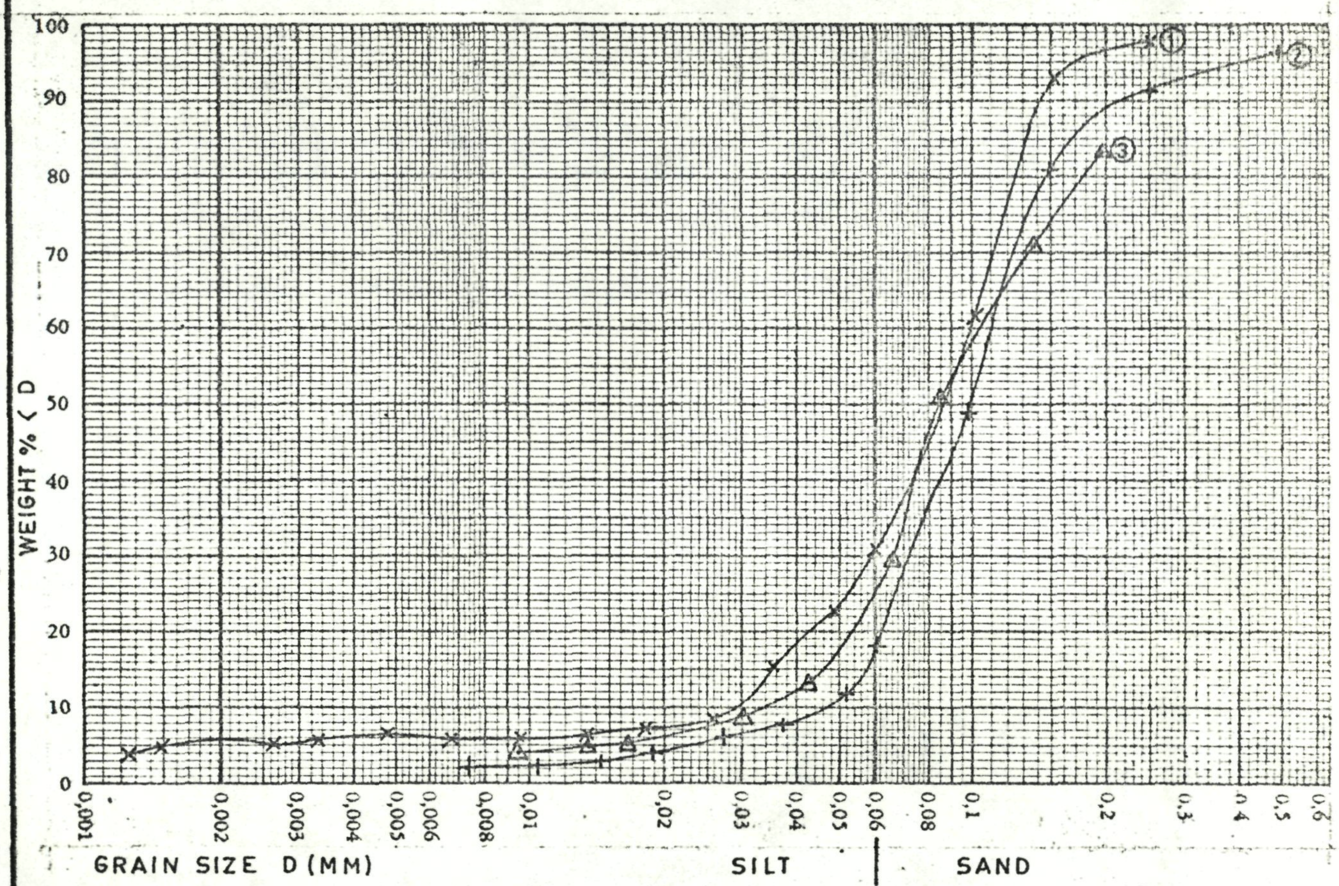


DANISH INSTITUTE OF APPLIED HYDRAULICS	E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	
SCALE:	GRAIN SIZES OF BED SAMPLES FROM P2	PLAN 120



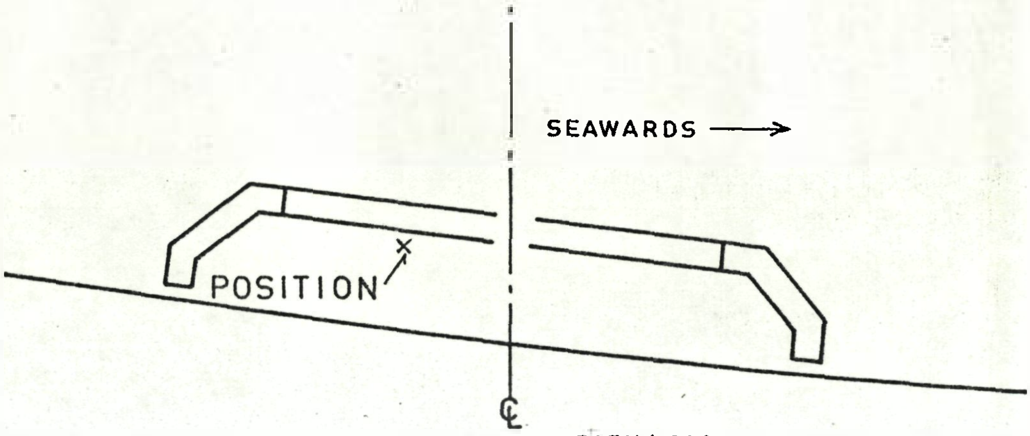
SPRINGTIDE +3 DAYS. VELOCITY 1M ABOVE BOTTOM (RIVER)

DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	GRAIN SIZES IN TEST PIT P3. 22-1-65. (MEAN)	PLAN 121
SCALE:			

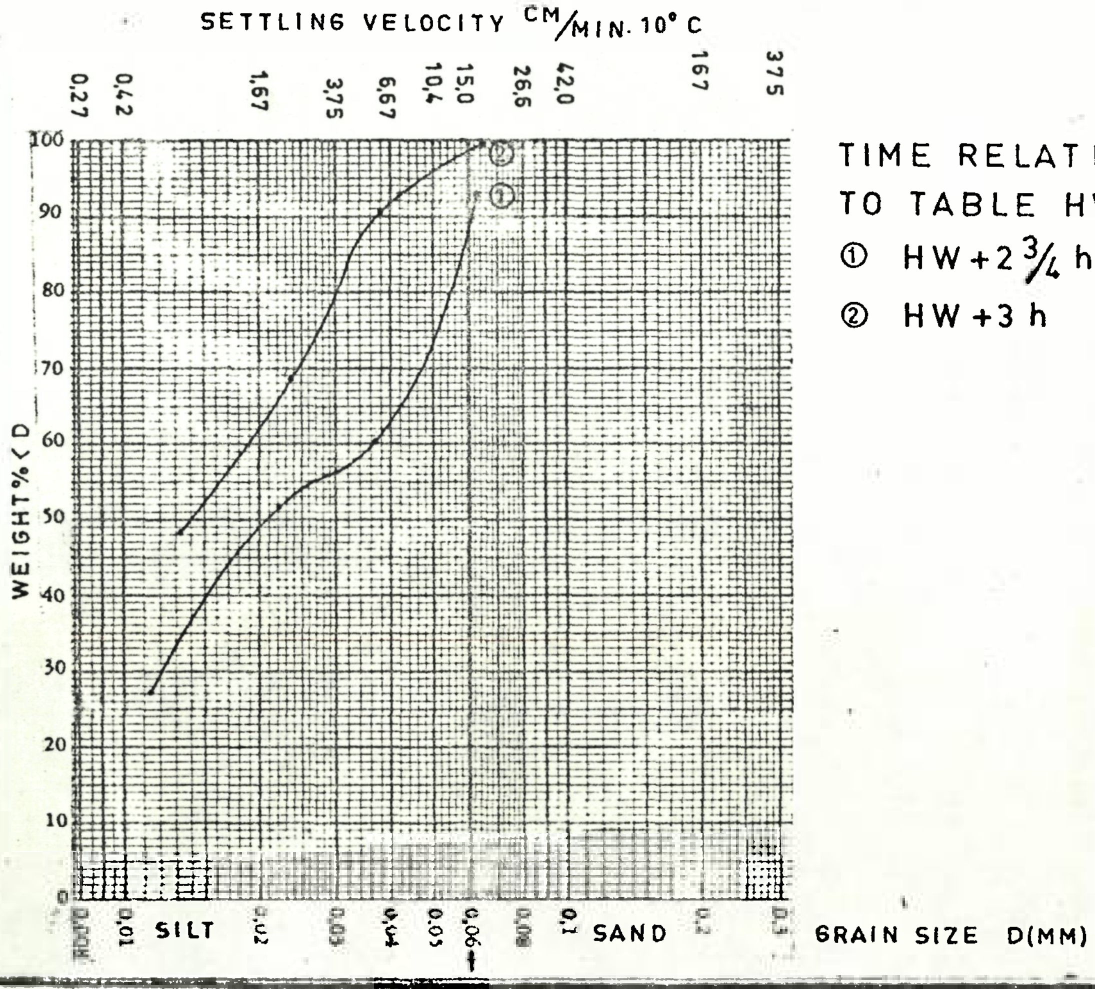


① HYDROMETER METHOD WITH DEFLOCCULATING AGENT (22-1-65)
② – – – 1,5 g/l SEA SALT (17-2-65)
③ ANDREASENS – – 1,5 g/l – – (17-2-65)

DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	GRAIN SIZES BUCKET TEST PIT P3.	PLAN 122
SCALE.			



SITUATION 1: 2500

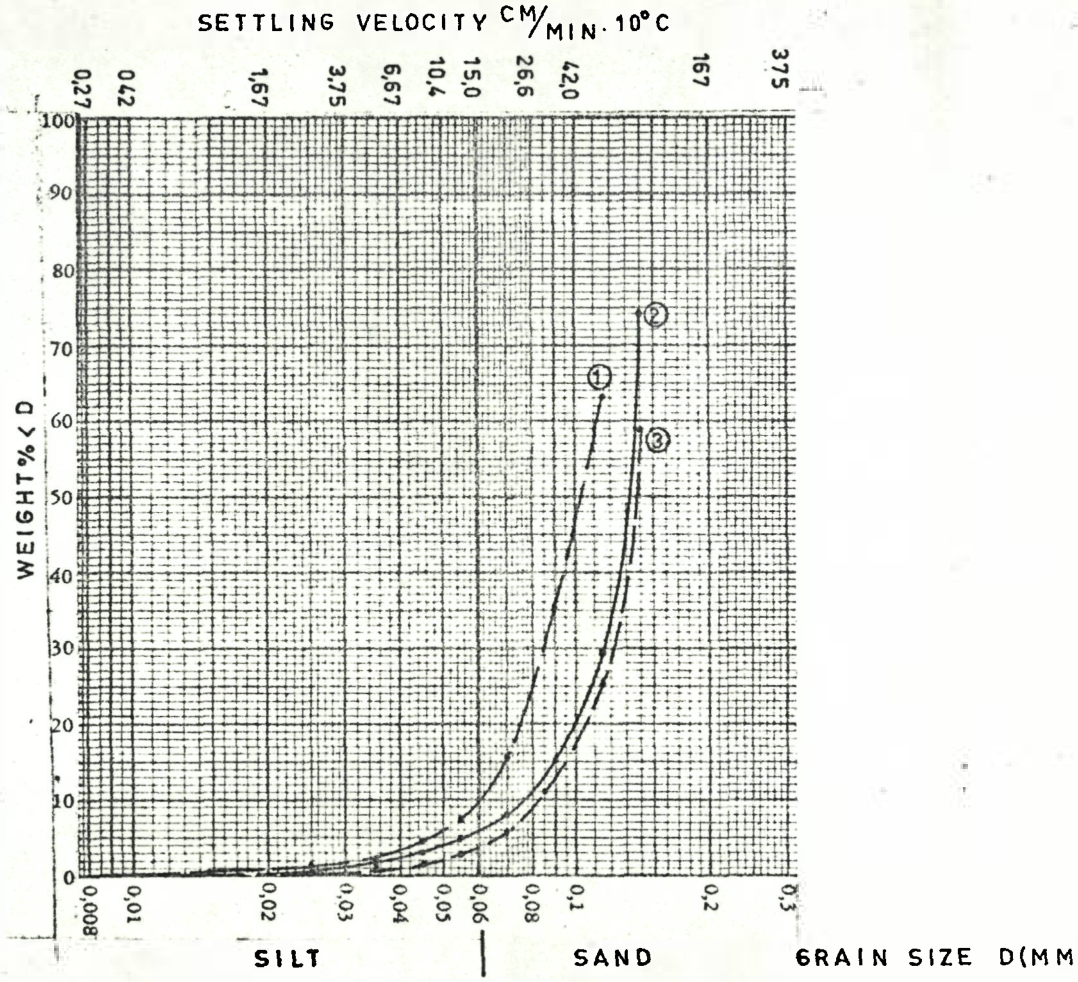


TIME RELATIVE TO TABLE HW

① HW + 2 3/4 h

② HW + 3 h

DANISH INSTITUTE OF APPLIED HYDRAULICS	E. 3. SCHELDETUNNEL
	SILTATION INVESTIGATIONS
FILE: 64-1 / DATE: 20-4-65	GRAIN SIZES OF SUSP. LOAD COFFERDAM 8-2-65. / PLAN 123
SCALE:	

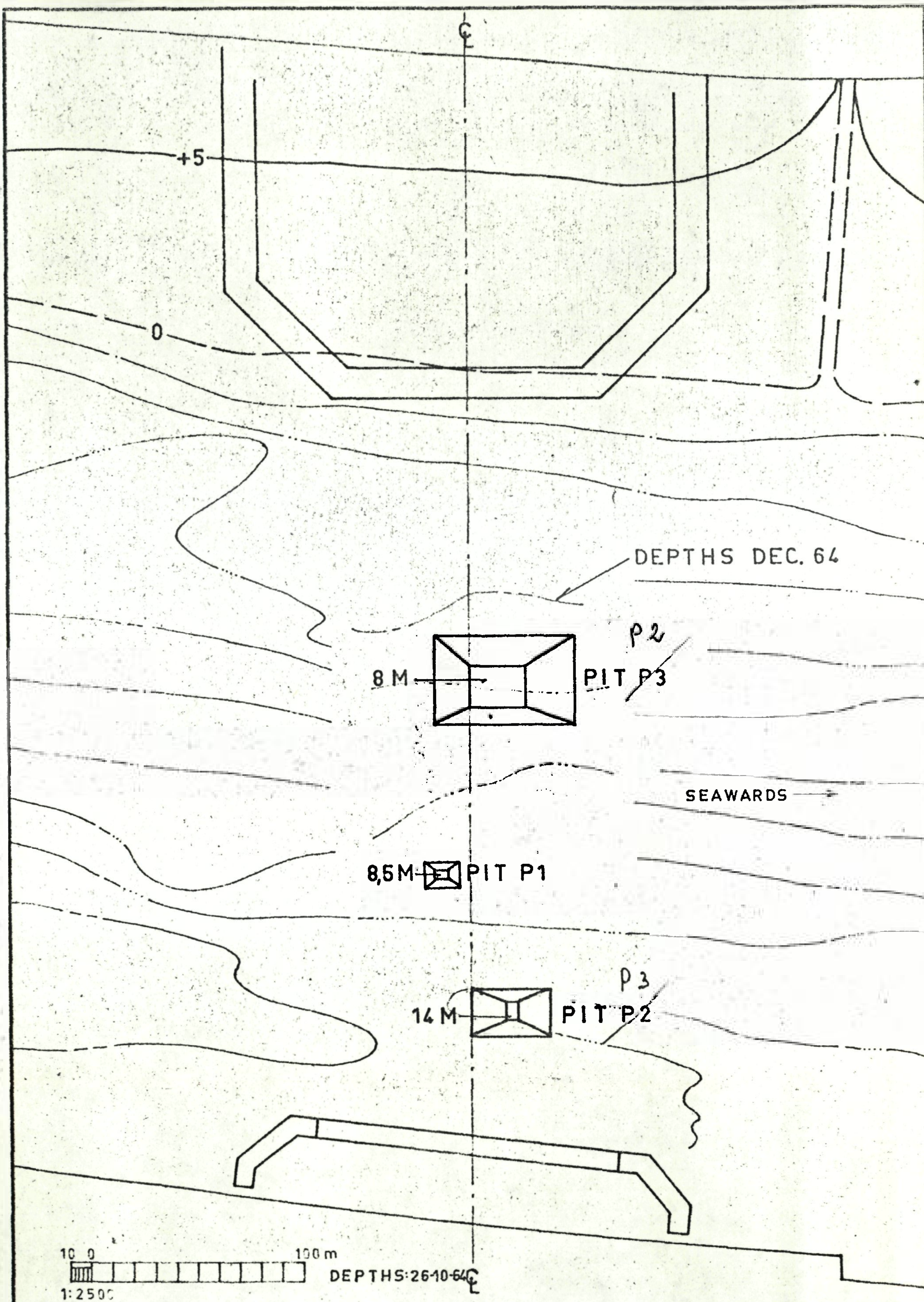


① C1 SPRINGTIDE 17-2-65

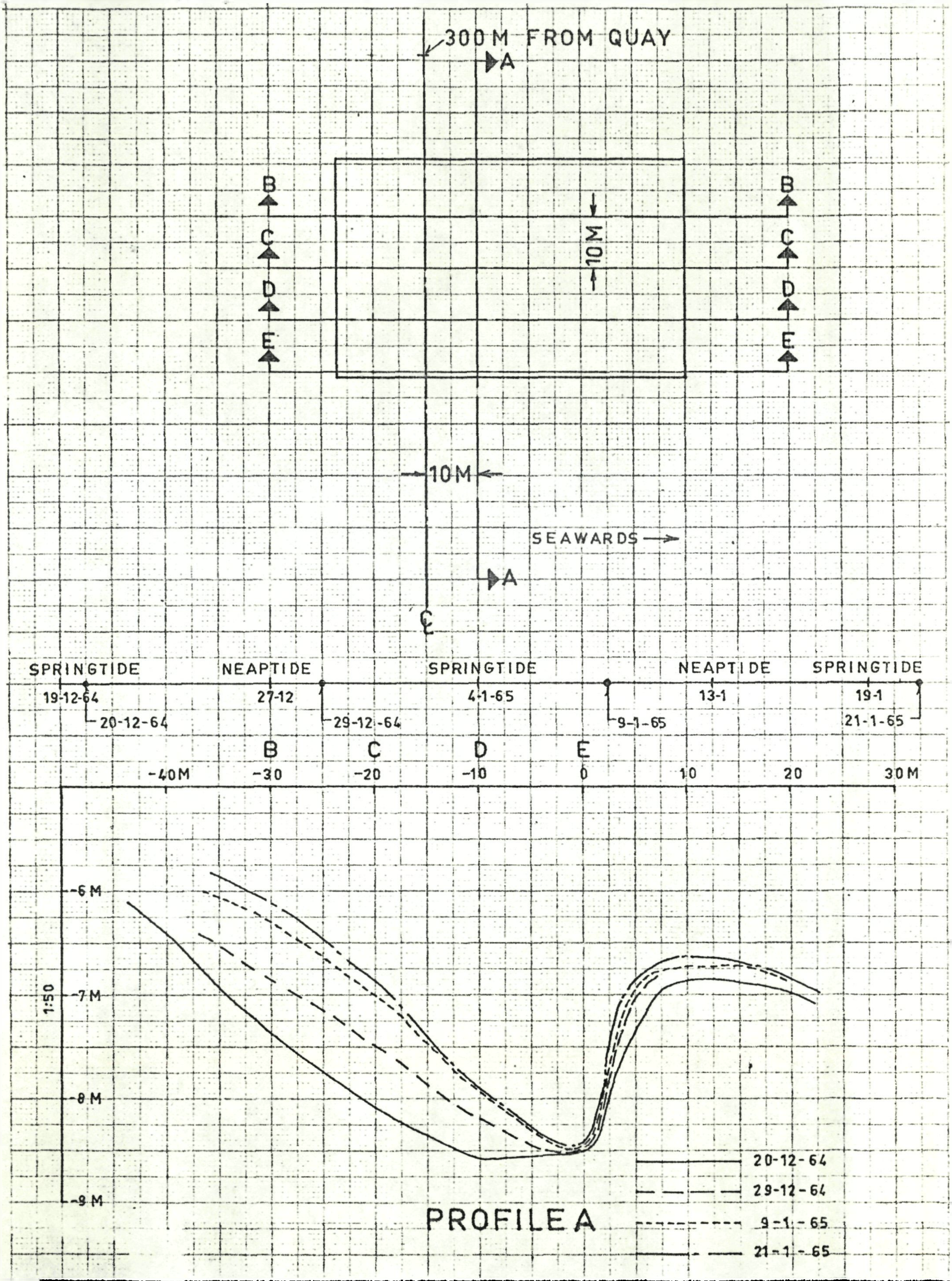
② C3 NEAPTIDE 10-2-65

③ C3 SPRINGTIDE 3-2-65

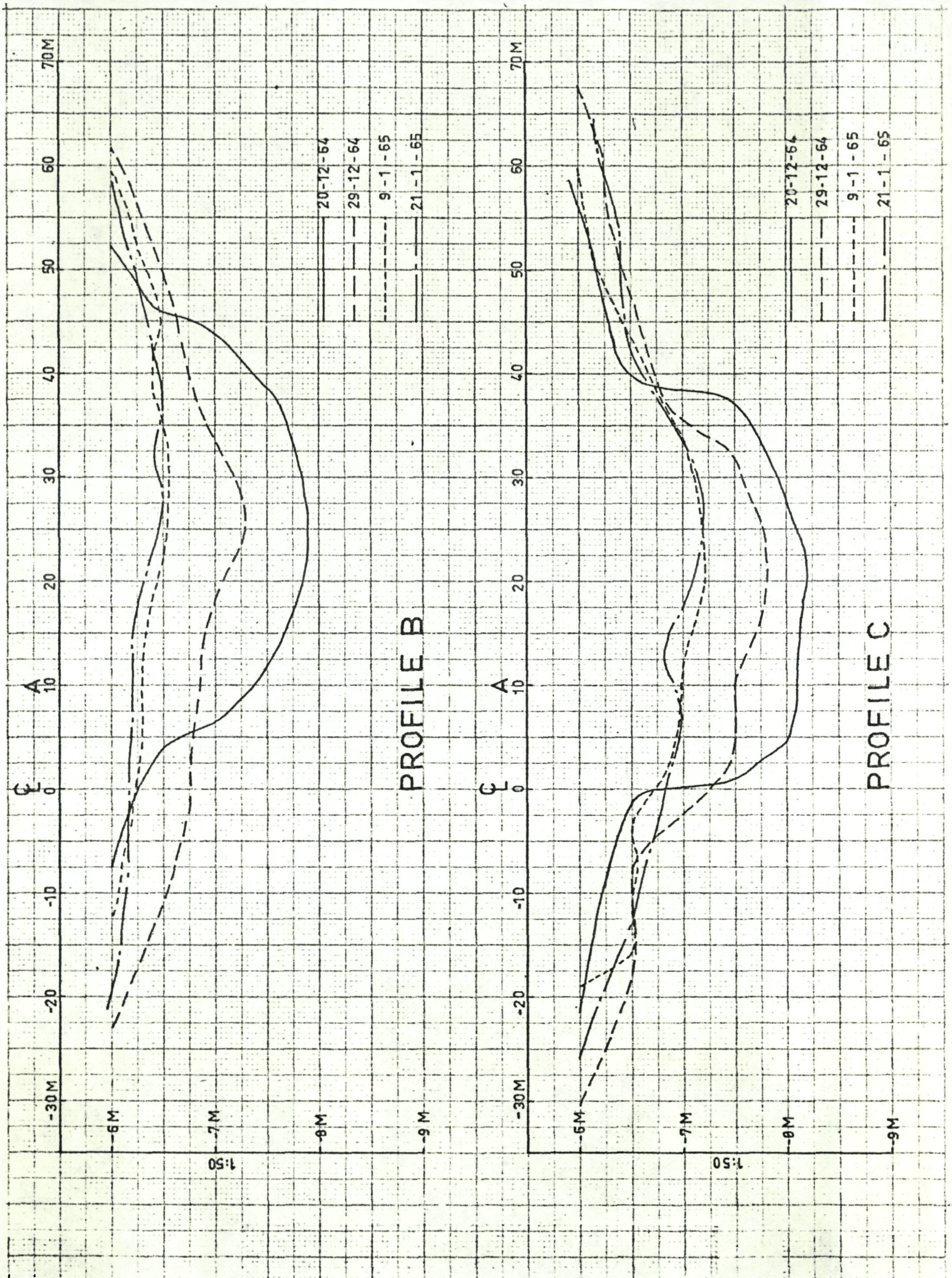
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	GRAIN SIZES OF SEDIMENT IN TRENCH (CALCULATED)	PLAN 124
SCALE.			



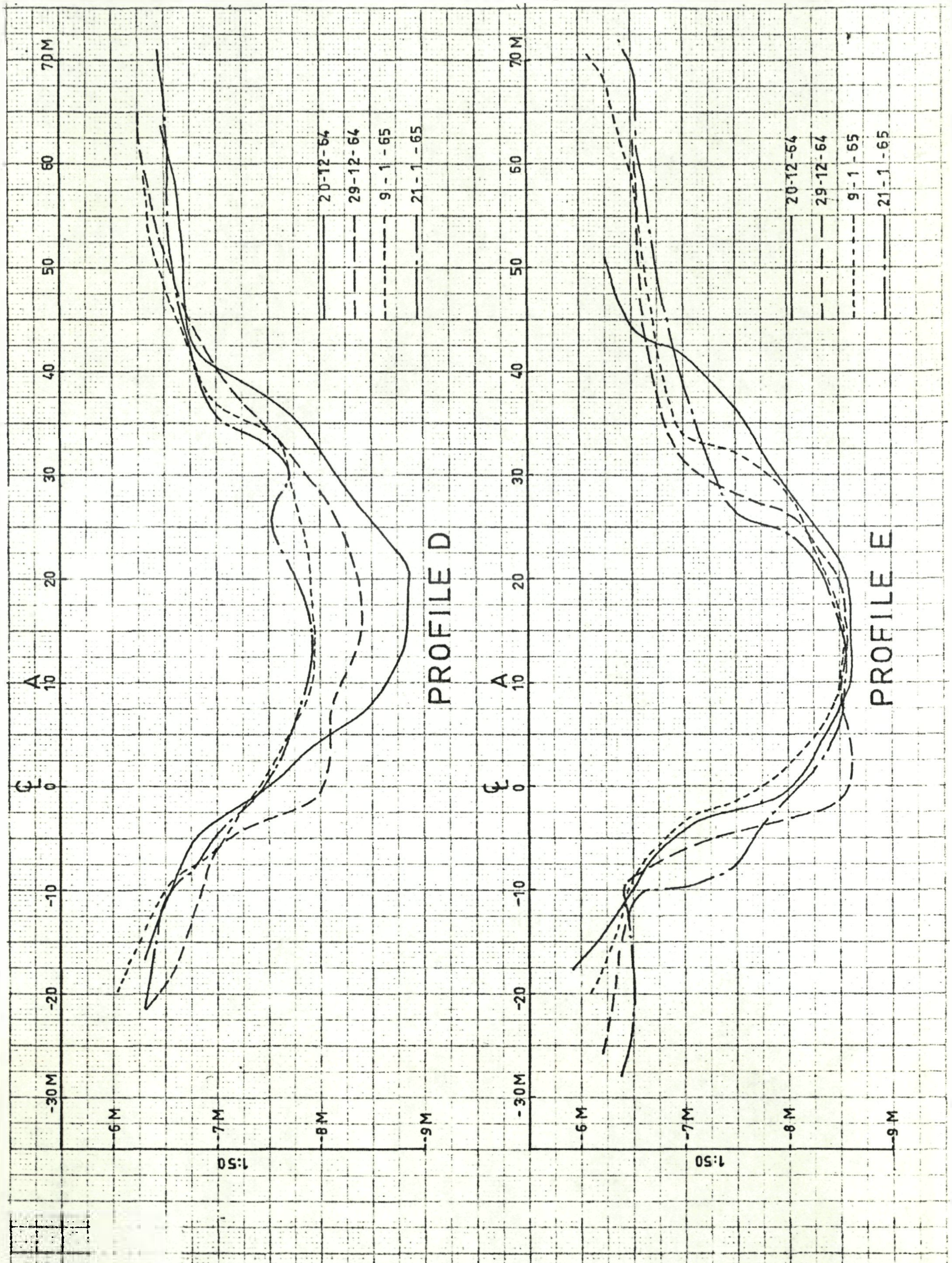
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE 64-1	DATE 20-4-65	LOCATION OF TEST PITS	PLAN 151
SCALE 1:2500			



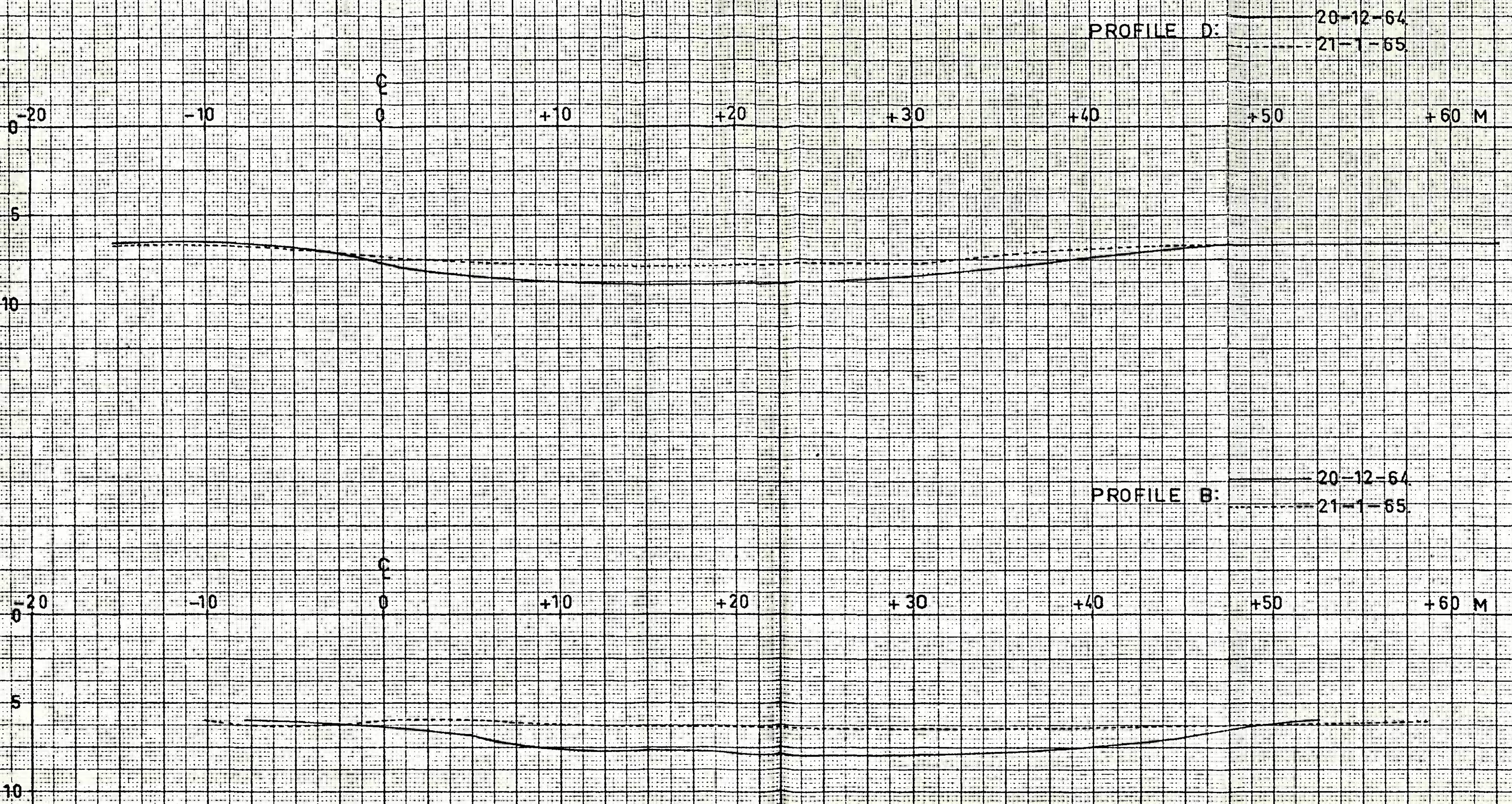
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	PIT P2. POSITION OF SECTIONS AND PROFILE A	PLAN 152
SCALE: 1:500			



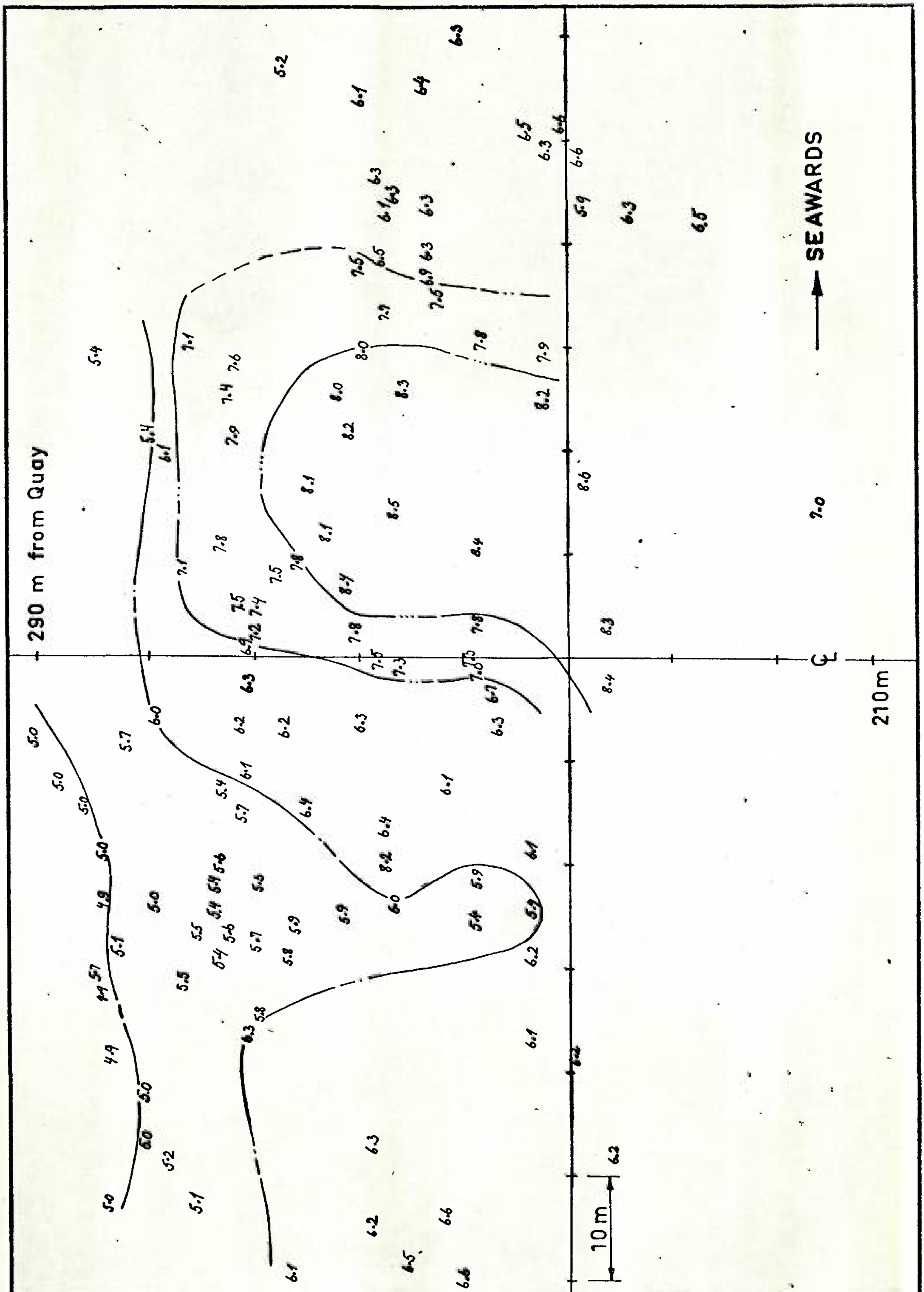
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-64	PROFILES B AND C PIT P2	PLAN 153
SCALE: 1:500			



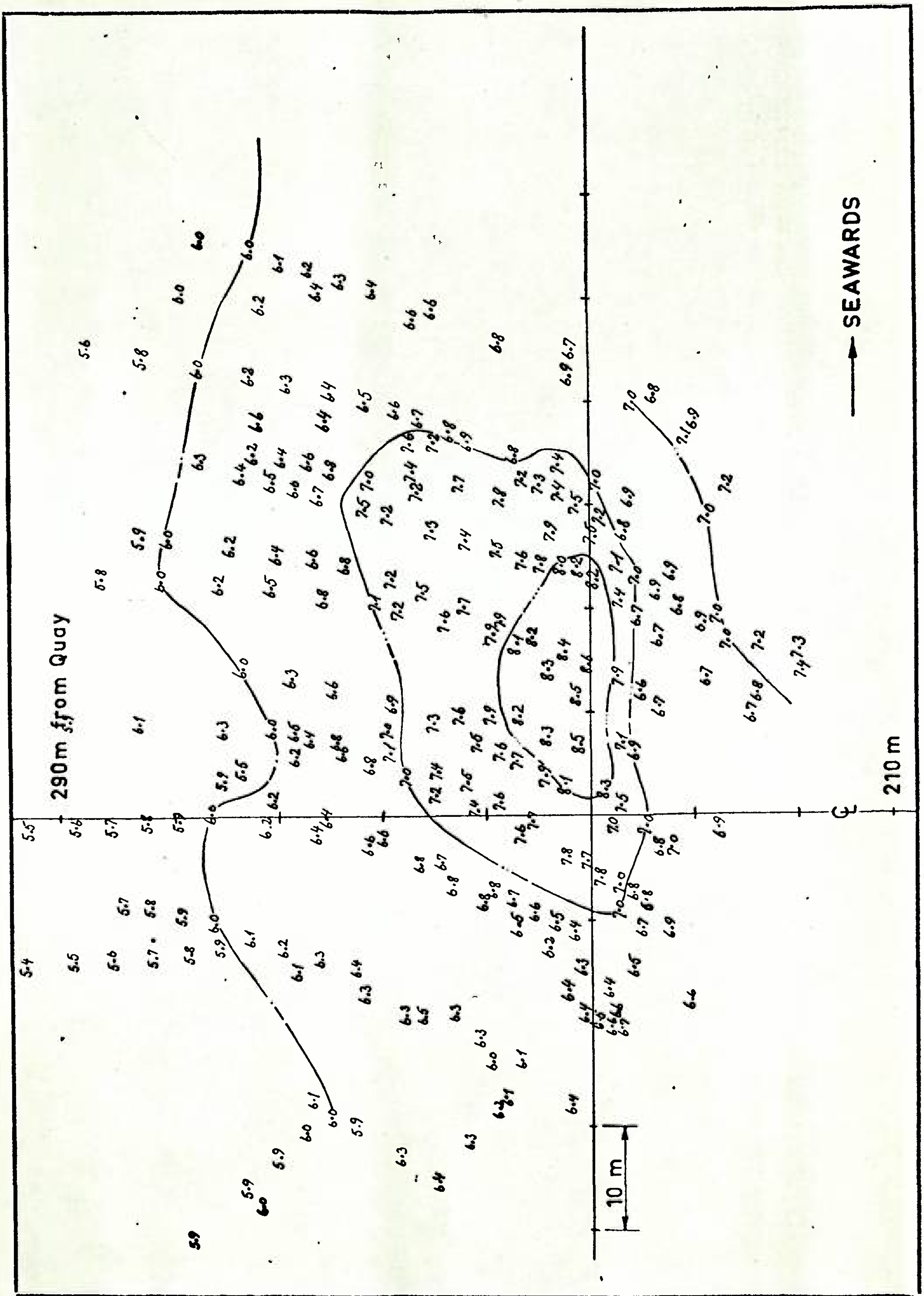
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	PROFILES D AND E PIT P2	PLAN 154
SCALE: 1:500			



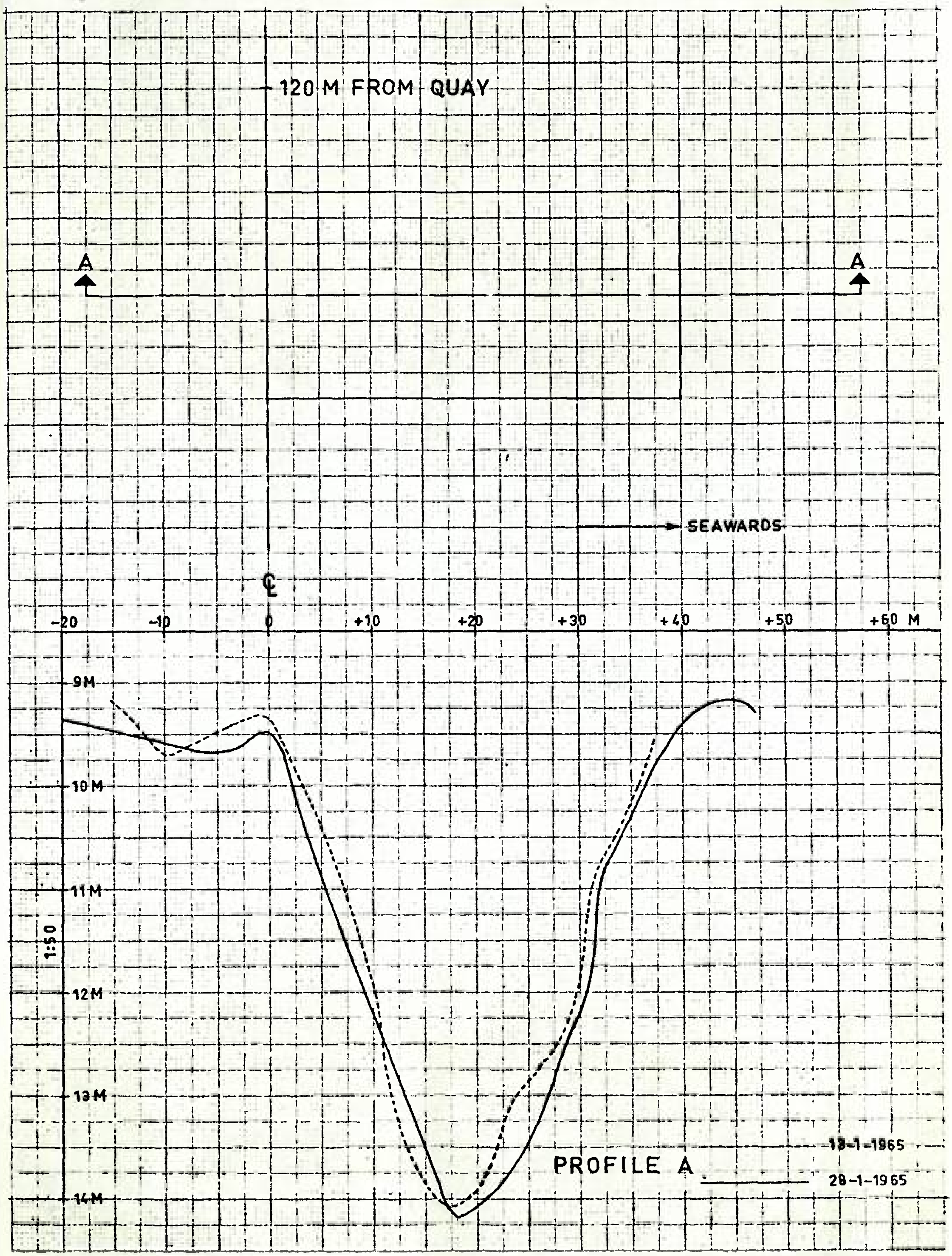
DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 27-4-65	PROFILES B AND D PIT P2	PLAN 155
SCALE: 1:250	MP		



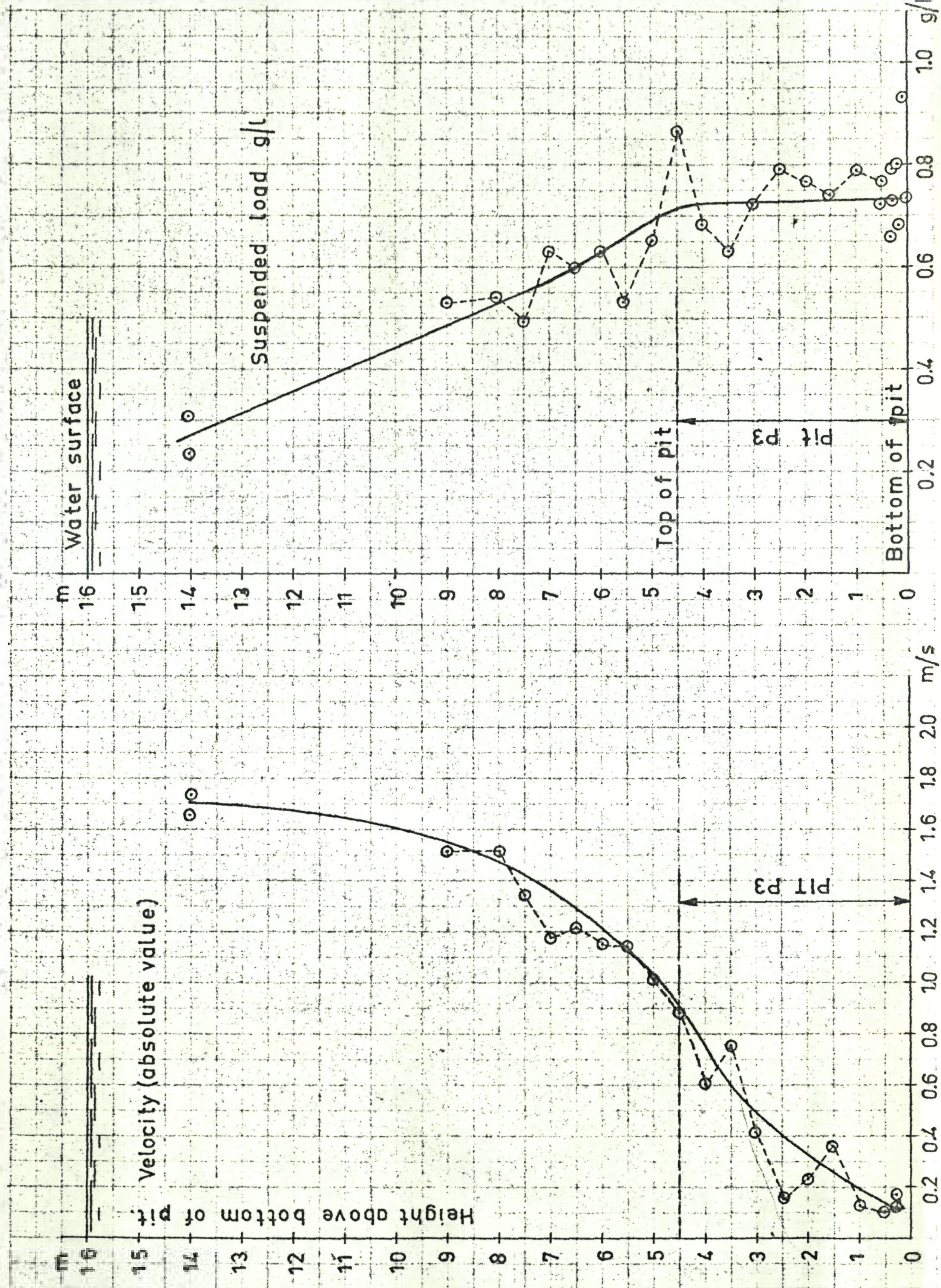
DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 26-4-65	P 2. SOUNDING 20-12-64.	PLAN 156
SCALE: 1:500	MP		



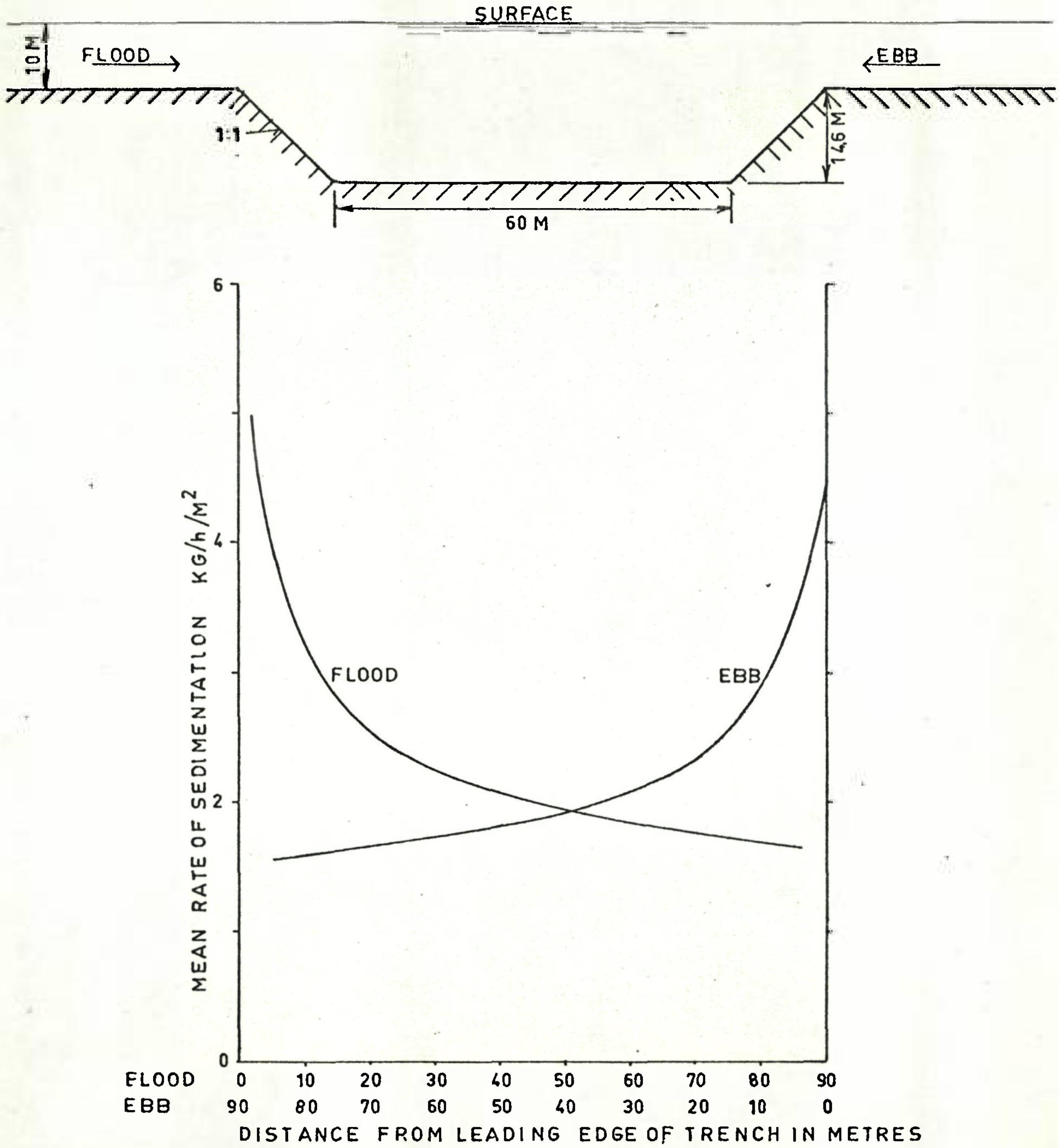
DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 26-4-65	P2. SOUNDING 21-1-65.	PLAN 157
SCALE: 1:500	MP		



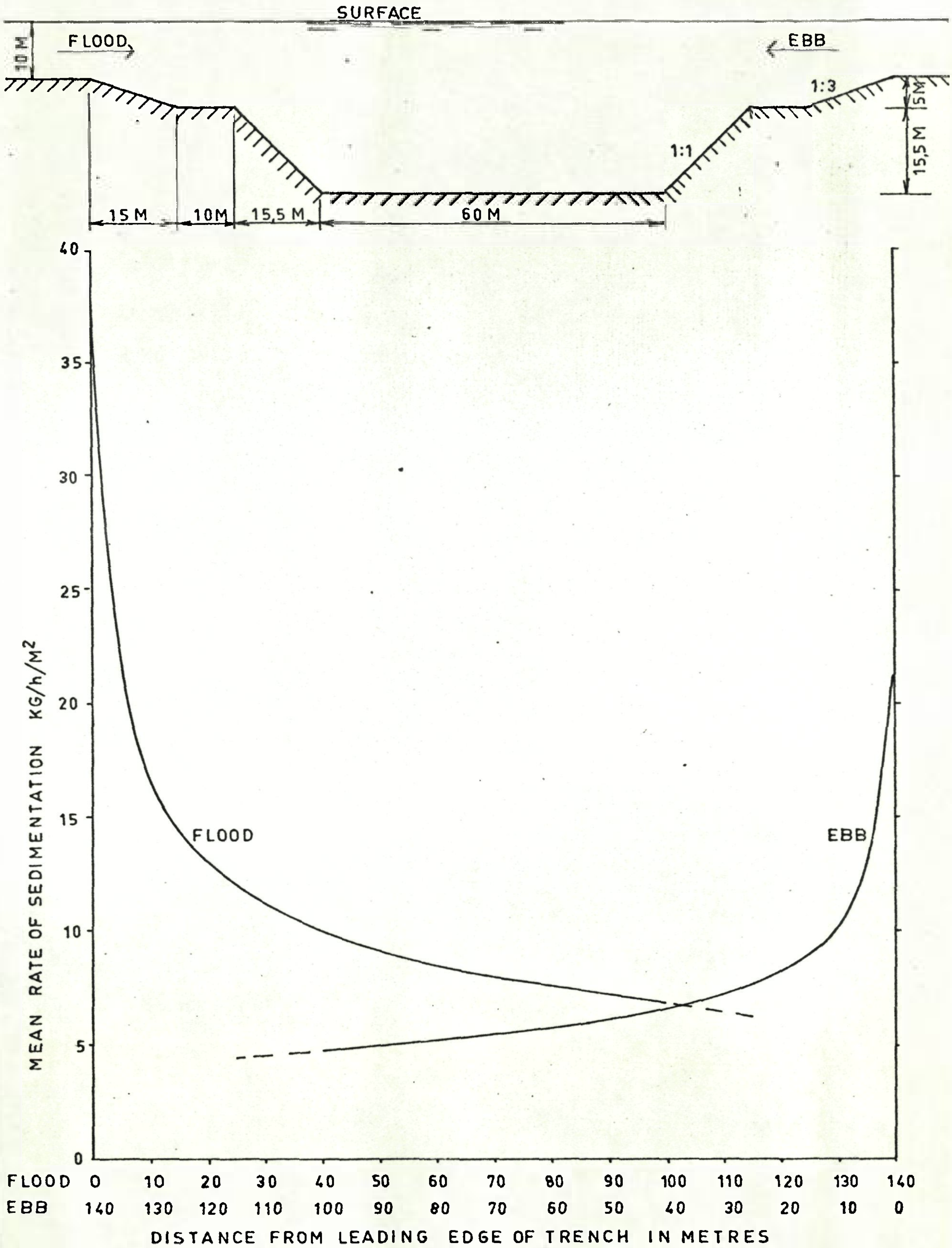
DANISH INSTITUTE OF APPLIED HYDRALICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 26-4-65	PIT P3. PROFILE A	PLAN 158
SCALE: 1:500	MP		



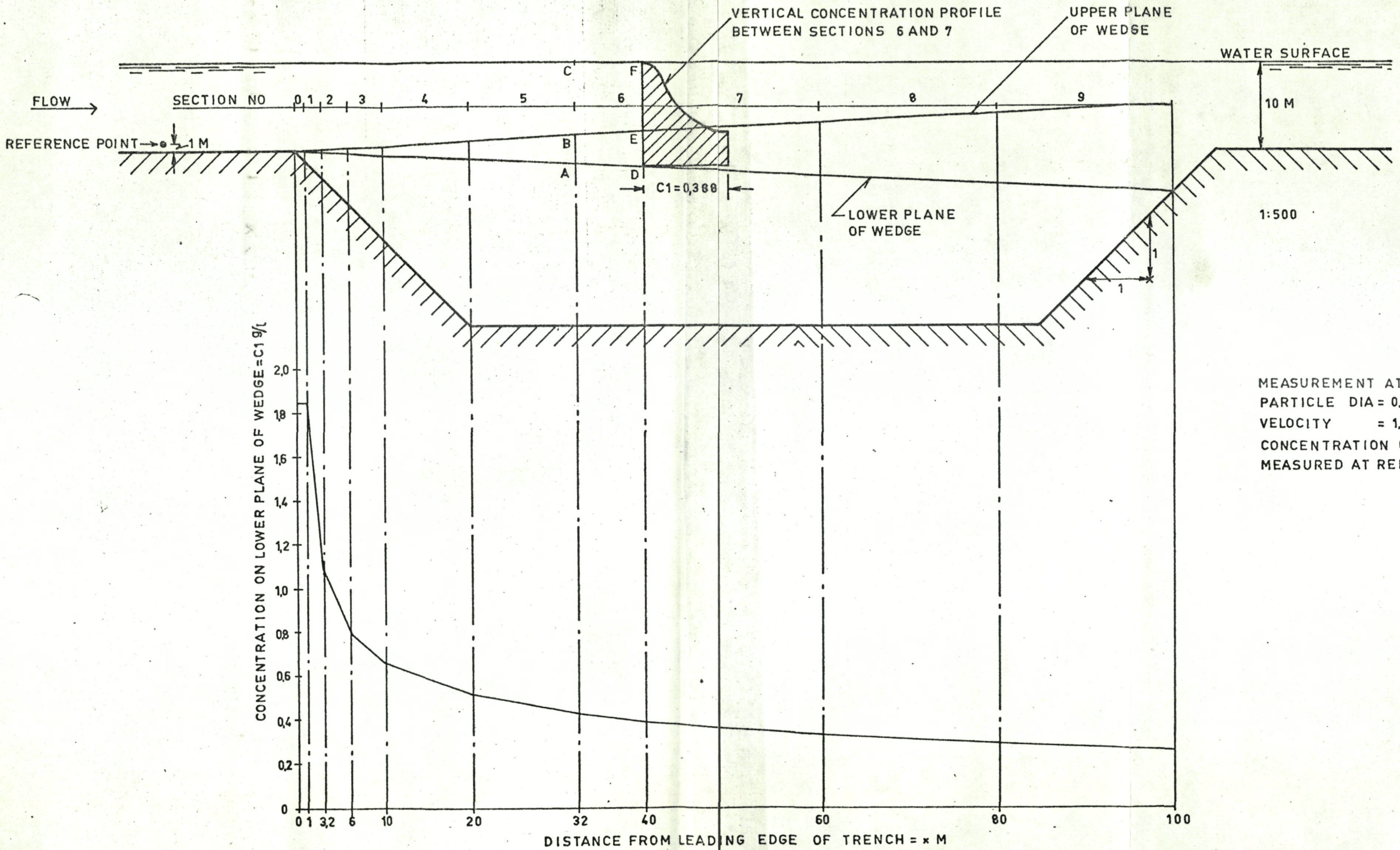
DANISH INSTITUTE OF APPLIED HYDRAULICS		E:3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 7-4-1965	SUSPENDED LOAD AND VELOCITY MEASUREMENT IN PIT P3 20-1-1965	PLAN 159
SCALE:	MP		



DANISH INSTITUTE OF APPLIED HYDRAULICS	E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1 / DATE: 20-4-65 / SCALE:	DISTRIBUTION OF SEDIMENTATION ACROSS TRENCH C3 (NEAP)	PLAN 161

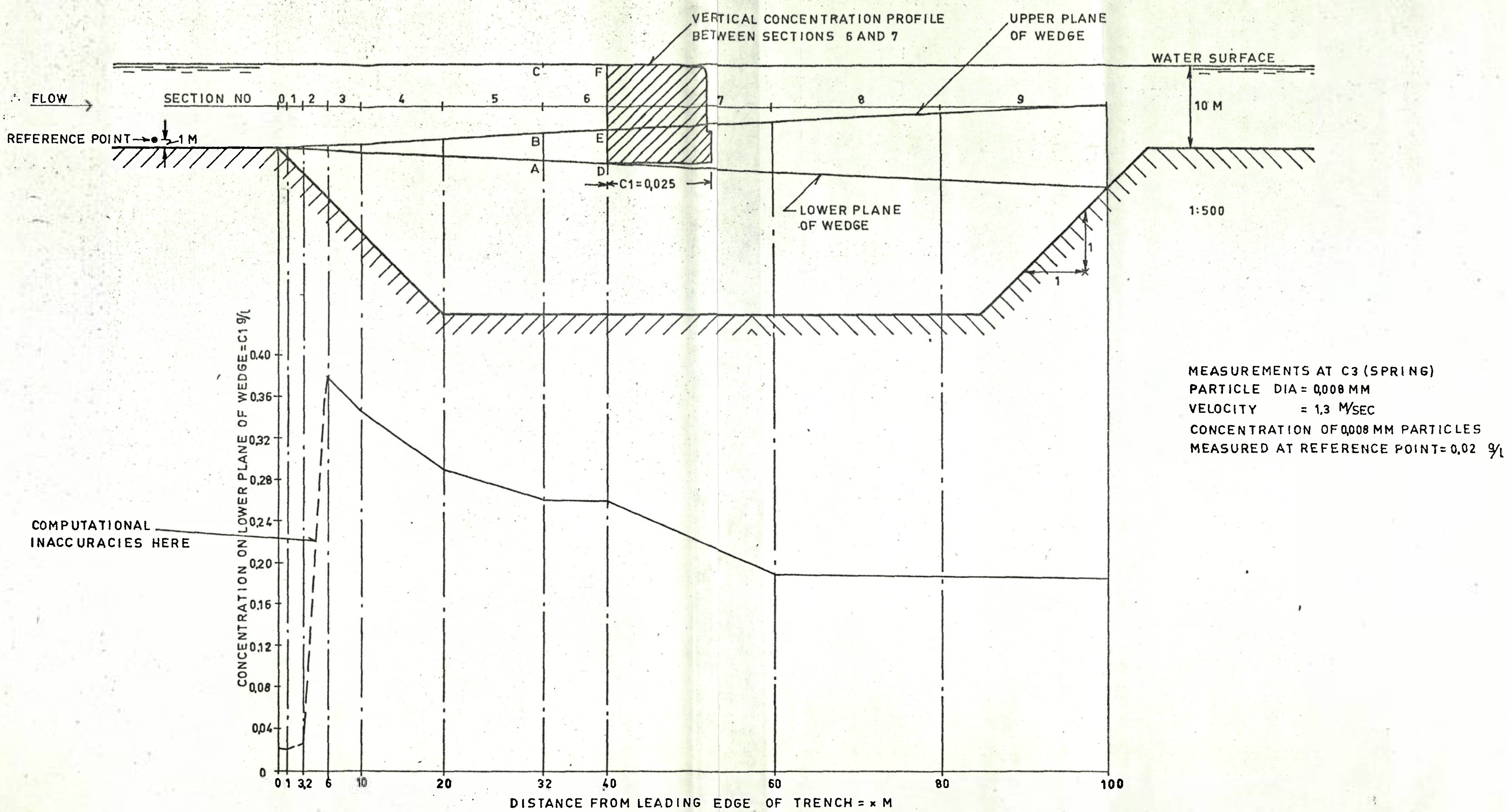


DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	DISTRIBUTION OF SEDIMENTATION ACROSS TRENCH C3 (SPRING)	PLAN 162
SCALE:			

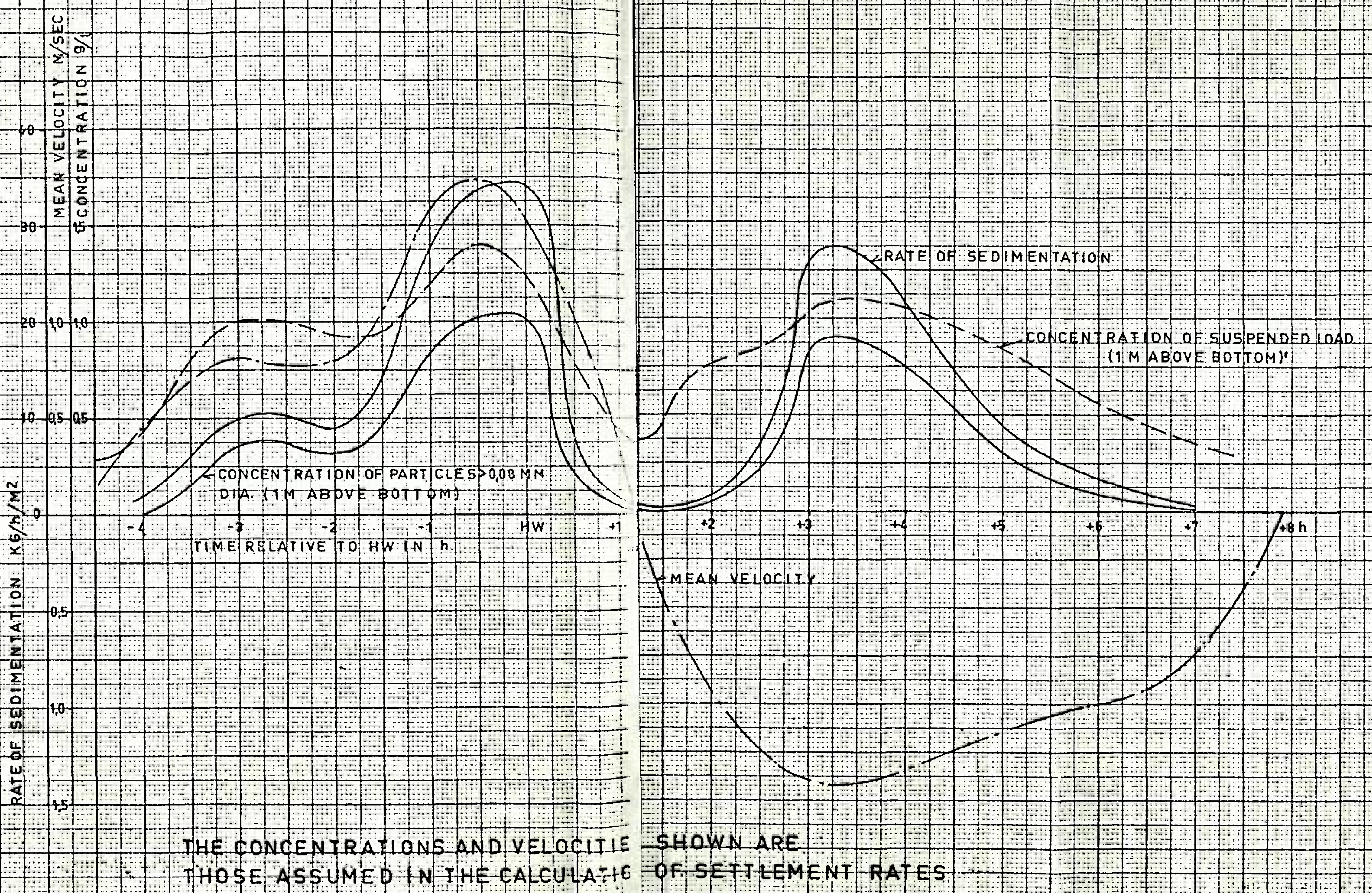


MEASUREMENT AT C3 (SPRING)
PARTICLE DIA = 0,14 MM
VELOCITY = 1,3 M/SEC
CONCENTRATION OF 0,14 MM PARTICLES
MEASURED AT REFERENCE POINT = 0,452 g/l

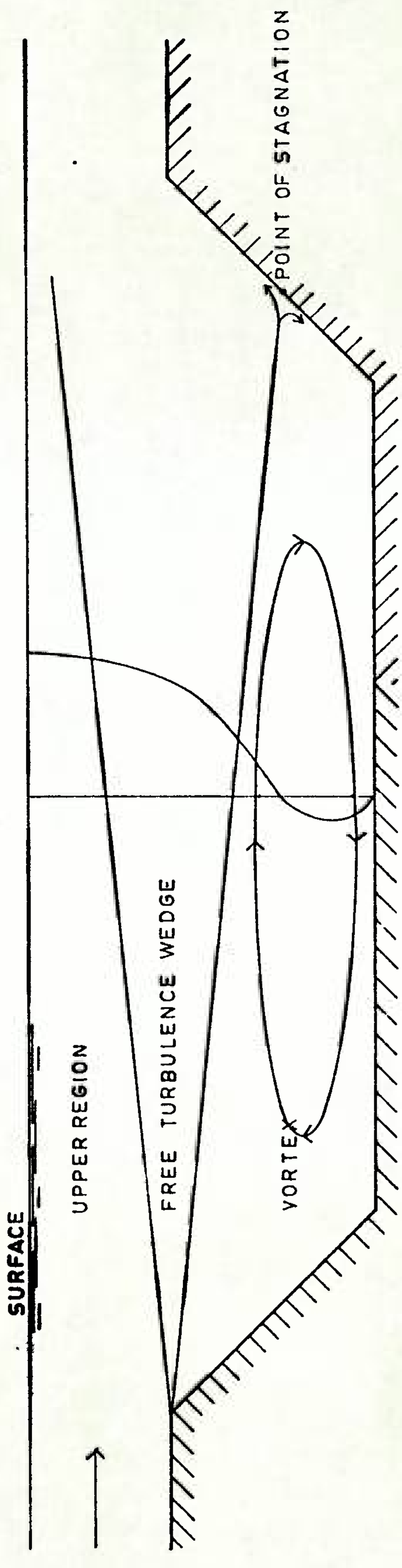
DANISH INSTITUTE OF APPLIED HYDRAULICS		E.3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	SEDIMENTATION IN TRENCH FALLOUT OF 0,14 MM PARTICLES THEORETICAL COMPUTATION	PLAN 163
SCALE.			



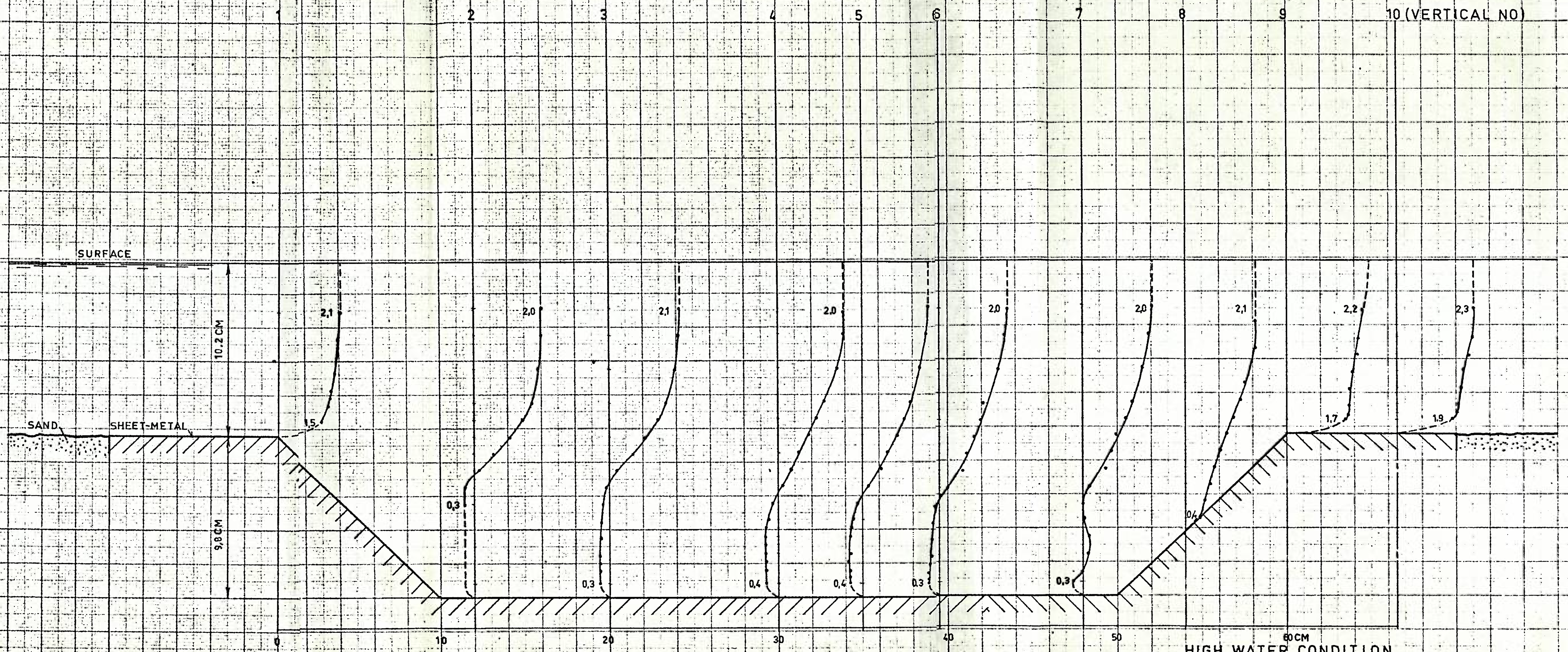
DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	SEDIMENTATION IN TRENCH FALLOUT OF 0,008 MM PARTICLES THEORETICAL COMPUTATION	PLAN 164
SCALE.			



DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	VARIATION OF FALLOUT WITH TIME C3(SPRING) (THEORETICAL CALCULATION)	PLAN 165
SCALE.			

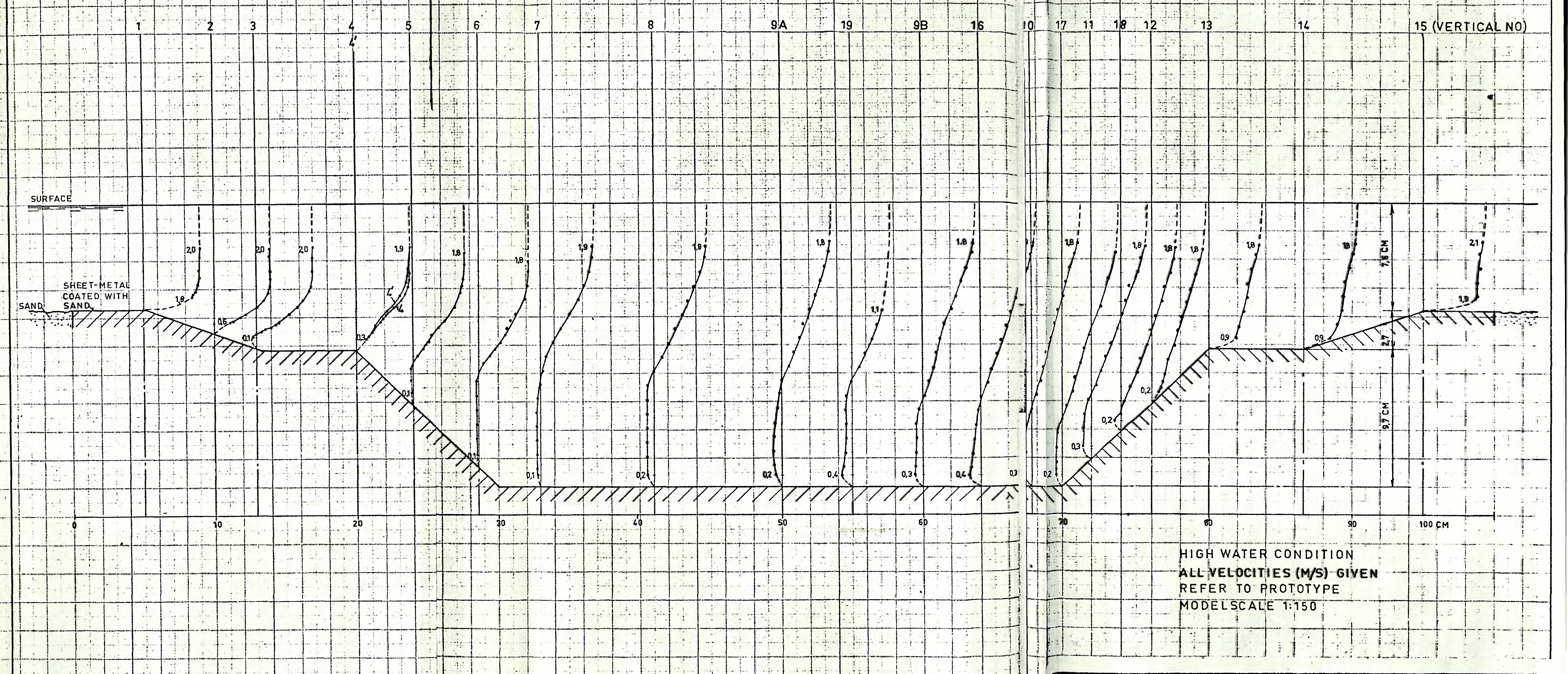


DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	FLOW PATTERN OVER TRENCH	PLAN 170
SCALE.			

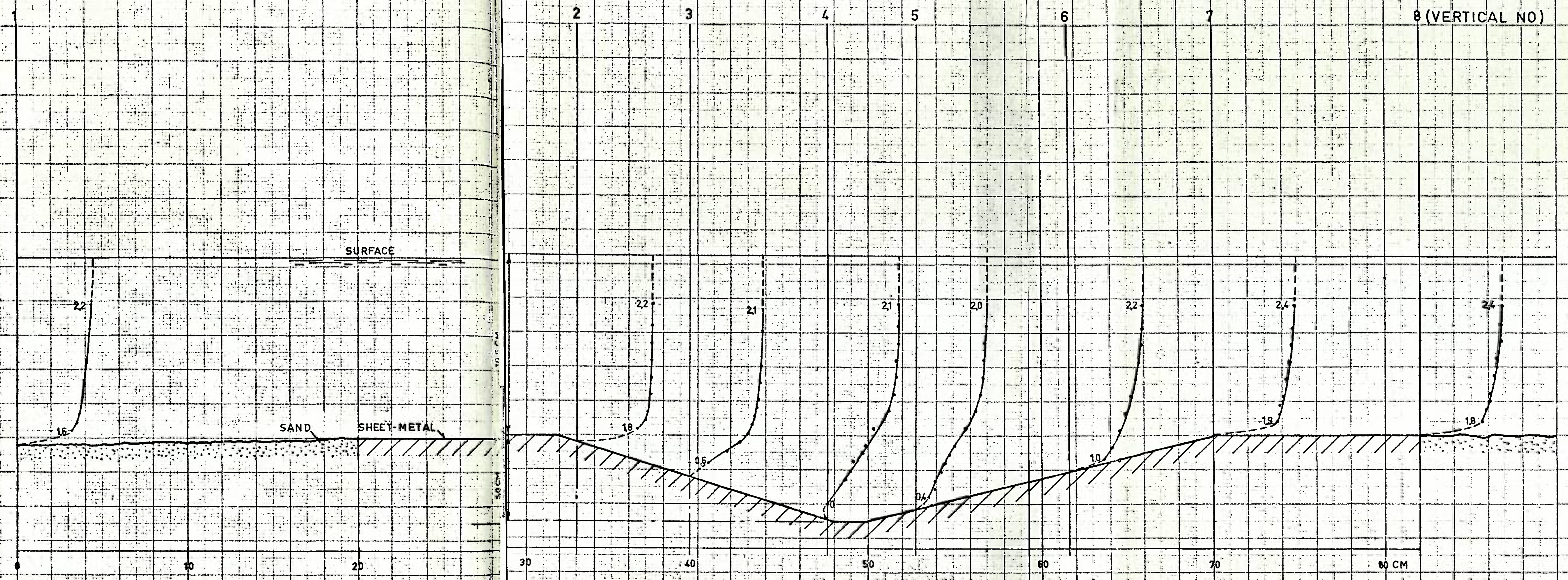


HIGH WATER CONDITION
ALL VELOCITIES (M/S) GIVEN
REFER TO PROTOTYPE
MODELSCALE 1:150

DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	MODEL TEST NO 3 TUNNEL TRENCH	PLAN 171
SCALE: 1:2			



DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	MODEL TEST NO 6 TUNNEL TRENCH	PLAN 172
SCALE: 1:2			



LOW WATER CONDITION
ALL VELOCITIES (M/S) GIVEN
REFER TO PROTOTYPE
MODELSCALE 1:100

DANISH INSTITUTE OF APPLIED HYDRAULICS		E. 3. SCHELDETUNNEL SILTATION INVESTIGATIONS	
FILE: 64-1	DATE: 20-4-65	MODEL TEST PIT P3	PLAN 173
SCALE. 1: 2			