PORT EXPANSION PROJECT
PORT OF PHILLIPSBURG
ST. MAARTEN NETHERLANDS ANTILLES

WAVE PENETRATION STUDY

TU Delft
Delft University of Technology

Faculty of Civil Engineering
Hydraulic and Geotechnical Engineering Division
Hydraulic Engineering Group

PORT EXPANSION PROJECT
PORT OF PHILLIPSBURG
ST. MAARTEN NETHERLANDS ANTILLES

WAVE PENETRATION STUDY

V.J.W. Hombergen

Delft, march 1991

Delft University of Technology
Faculty of Civil Engineering
Division: Hydraulic and Geotechnical Engineering
Section: Hydraulics and Off-shore Engineering

Supervised by:
Prof. ir. K. d'Angremond
Dr. ir. L. Holthuijsen
ir. A. Mol

Commissioned by:
Grabowsky&Poort BV
Consulting Engineers
The Hague

ACKNOWLEDGEMENTS

The complete study "PortExpansion Project Port of Phillipsburg, St. Maarten Netherlands Antilles", was under supervision of Prof. ir. K. d'Angremond, Dr. ir. L. Holthuijsen, and ir. A. Mol from Grabowsky&Poort International BV, The Hague.

The present Wave Penetration Study has been performed during my work-emplacement at Grabowsky&Poort. I would like to extend my gratitude to all employees at Grabowsky&Poort, The Hague, for the superb atmosphere I was fortunate to work in.

I would also like to thank Delft Hydraulics for their assistance and advise, especially Dr. ir. G. van Vledder and Mr. D. Hurdle.

Vincent Hombergen.

CONTENTS:

1.0 SUMMARY WAVE PENETRATION STUDY. 1
2.0 INTRODUCTION 2
3.0 OBJECTIVE 2
4.0 THE STUDY 3
4.1 Diffraction 3
4.2 The DIFFRAC-Model 4
5.0 STARTING POINTS AND LIMITATIONS 5
5.1 Starting points 5
5.2 Limitations 6
5.3 The schematisation 7
6.0 THE ALTERNATIVE LAY-OUTS. 8
7.0 DISCUSSION OF RESULTS 9
7.1 Results 0-Alternative 9
7.2 Alternative G 10
7.3 Alternative D2 11
7.4 Shortening of breakwater Alternative D2 13
8.0 CONDITIONS AT BERTHS AND THEIR ESTIMATED DOWN TIME. 17
8.1 Maximum wave height at berth 17
9.0 CONCLUSIONS. 20

LIST OF FIGURES

4.1 Example of diffraction due to a breakwater
7.1 Locations present situations
7.2 Locations alternative G
7.3 Locations alternative D2

LIST OF TABLES

5.1 Calculation input.
7.1 Percentages of incident wave height at quay (present situation).
7.2 Percentages of incident wave height at quay (Alt G, container berth).
7.3 Percentages of incident wave height cruise terminal (Alt G, Cruise terminal).
7.4 Average percentage of incident wave height Grote Kade (Alt G).
7.5 Percentage of incident wave height at quay (Alt D2, Container berth).
7.6 Percentage of incident wave height at quay (Alt D2, Grote Kade).
7.7 Percentages of incident wave height cruise terminal (Alt D2, Cruise terminal East-side).
7.8 Percentages of incident wave height cruise terminal (Alt D2, cruise terminal West side).
7.9 Shortened breakwater (Alt D2).
8.1 Summary diffraction parameters in percentages.
8.2 Summary per mille exceedance of max. wave height, plus total down time period(d.t.p) in per mille.
8.3 Shortened breakwater, down time period in per mille.

APPENDICES

A Diffraction study, lay-outs.
B Diffraction study, Colour plots potential alternatives.
C Mathematical description Diffraction study.
D Diffraction study, Results computations.
E References.

1.0 SUMMARY WAVE PENETRATION STUDY.

The Sint Maarten Ports Authority (SMPA) wishes to expand the present port facilities of the Port of Phillipsburg. They have therefore commissioned Grabowsky&Poort International BV as the main consultants for the port development.
The present wave penetration study has been performed, to be used as a tool for preliminary designs and the feasibility study for this project.

With the aid of the computer model DIFFRAC, provided by Delft Hydraulics de Voorst, a study has been carried out on wave penetration in the designed alternatives presented in Appendix A.

During the course of the study, alternative D2 and alternative G, resulted from extensive examination and consultation, as the preferable designs. These two alternatives are therefore discussed in detail in this report (section 7).

To minimize construction costs, alternative D2 was also tested on diffraction with shortened breakwaters. Shortening of the breakwater in alternative G is not possible. The maximum protection is necessary for this alternative.

The results for computations on alternative D2 and G are presented in section 7, and are plotted in Appendix B. The results for all computations are presented in Appendix D.

2.0 INTRODUCTION

As a result of a significant increase in cargo throughput and calls of cruise vessels in the Port of Phillipsburg, the St. Maarten Ports Authority (SMPA) is planning to further expand the port with a cruise terminal and a multi-purpose container terminal. The SMPA has appointed Grabowsky&Poort International BV, as their main consultants for the port development.

In the port lay-out study, Grabowsky&Poort presented a number of alternative lay-outs according to requirements established by the Client and general harbour design criteria. The criteria have been discussed in previous reports.
An important criterium for the port design is that vessels must be able to enter the harbour without problems and to moor and remain safely along the berths. The presence of waves is an important factor with respect to this point.

3.0 OBJECTIVE

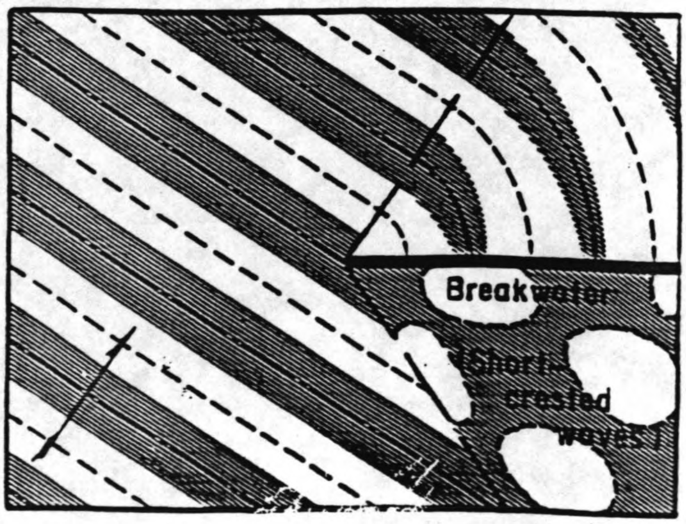
The purpose of this study is to determine the wave penetration into the harbour for the different alternatives. The results will be used as a selection criterium for the port lay-outs, and to further optimization of required breakwater length.

4.0 THE STUDY

4.1 Diffraction

A wave train which meets an obstacle such as a breakwater or an offshore platform may be reflected backward and in lateral directions, but the crests can also bend around the obstacle and thus penetrate into the lee of the obstacle. This phenomenon is called diffraction. Figure 4.1 shows the diffraction around an obstacle (breakwater).

The extent of this wave penetration can numerically be determined by the DIFFRAC-model.



WAVE PENETRATION STUDY | **FIGURE 4.1**

Example of diffraction due to a breakwater

4.2 The DIFFRAC-Model

The alternative harbour lay-outs are presented in Appendix A. In the report "Port Lay-out and Breakwater design", a brief elaboration will be made on the accomplishment of these alternatives.

The alternative harbour lay-outs must first be schematised on a x,y-grid (section 5.3). In this way, an alternative is divided in a series of lines ('edges') between grid coordinates. The contours are divided into wave lengths. The number of points per wave length along a reflecting edge in the computations is set (optional) to the minimum allowed for accuracy, five. DIFFRAC defines these points on the contour of the alternative, as sources. The strength of these sources is determined by the reflection coefficient of the edges. The computational points are the points on the edges and the grid points in the rest of the computational area. Each point in the calculated area, is influenced by its neighbouring point. DIFFRAC generates a matrix of equations for all these points (as defined in Appendix C), and with a Gausian elimination, the wave heights at each point in the computation area is determined.

The wave penetration computations give the results for monochromatic long crested waves. This means that each computation gives the results for waves with one phase, frequency (monochromatic), and one wave direction (long crested parallel waves), while nonlinear effects like wave breaking and bottom friction, are not accounted for. In reality the incident wave field consists of many waves with several frequencies and from a range of directions. This irregularity and short-crestedness must be taken into consideration in the interpretation of the results. In practice however, the results for computations with regular waves, are a good guide to the behaviour of random waves [ref.: 7].

5.0 STARTING POINTS AND LIMITATIONS

5.1 Starting points

- Only the alternatives which have the potential of being chosen as the future port of Phillipsburg were analyzed with DIFFRAC. In the course of the study, some of the alternatives were abandoned after extensive evaluations. This resulted in the alternatives A,C,D,G and D2 in Appendix A.

- Wave directions at open sea, used as input for the diffraction study are derived from the Wave Climate Study. For more information refer to the report "Wave Climate Study" [ref.: 3].

- As discussed in section 4, the model approaches the random wave field as a linear monochromatic uni-directional wave field. The linearity allows to use a standard wave height of 1 meter. Values generated by the model are then in percentages of incident wave height, and can later be multiplied directly with the "actual" incident wave height (significant wave height), which resulted from the wave climate study.

- All of the alternatives were analyzed with a wave period of T = 8 seconds. In the course of the study, the alternatives G and D2, appeared the most favourable (based on nautical and lay-out criteria). These two alternatives were subsequently tested with a wave period of 5 and 12 seconds (see table 5.1). The wave period T = 8 sec., was found to be an intermediate wave period for this particular wave climate. The period could be used as an indication for the prevailing wave period of 5 sec., as well as for the wave period of T = 12 sec., which occurs during hurricane conditions, and swells.

Direction	Wave period		
	T = 5 s.	T = 8 s.	T = 12 s.
90°N	X	X	
135°N	X	X	
180°N		X	X
225°N		X	X

Table 5.1: Calculation input.

The directions 90°N and 135°N were the most probable wave directions for normal weather conditions (T = 5 sec.). Directions 180°N and 225°N hardly occur but are important for the estimation of the design wave height, during hurricane conditions (T = 12 sec.) [ref.: 3].

It is therefore believed that the above distribution of wave period and directions as input for the calculations can give a sufficient indication on the problem of wave penetration.

5.2 Limitations

Not all structures can be schematised in the DIFFRAC-model, only closed edges with a certain reflection coefficient. This is why the cruise terminal, designed in some alternatives as a structure on piles, can not be found on the output plots.

Some of the computations gave such large output files that accurate contour and colour plotting of the results was not possible. This was the case for the alternative D2. The resulting plots are less reliable in the area just behind the breakwater, and a too high value is shown. Therefore the interpretation was made on basis of the numerical output (before adapting for colour and contour plotting), which can be interpreted as reliable (appendix D).

The larger the total lengths of the harbour contour, the more potential points are introduced in the matrix (section 4.2).

This DIFFRAC-model is limited to only 300 potential points in the matrix. This is why for large alternatives, areas with little influence on the output, or areas of little interest, are left out of the calculation. This adaption was also necessary for the wave period of 5 seconds. Small wave periods give smaller wave lengths. This results in more "wave lengths" along an edge and subsequently in more computation points per edge and in the computation grid.

5.3 The schematisation

The alternatives of the harbour contour must be defined in an x,y-grid. Between the defined coordinates of the harbour contour the edges (lines) between these coordinates must be specified on their reflection coefficient (closed edges), or as open edges.
Reflection coefficients used in the schematisation were:

* 10% to 30% for gravel and rock edges.
* 90% for vertical quays.
* 4% for sand beaches/slopes.

After the harbour contour is specified with the reflection coefficients, the open edges where the wave field can enter the computation area must be defined. The incident wave parameters (as described in section 5.1) must then be defined.

The proposed port is to be dredged to an uniform depth of 12 meter. In the model (which calculates on an uniform depth), this depth is used both in the harbour schematisation and in the area outside the port. DIFFRAC does not account for refraction.

6.0 THE ALTERNATIVE LAY-OUTS.

Analyzed lay-outs are presented in Appendix A.
For the zero-alternative (present situation) and alternatives D2 and G, colour plots are made. These can be found in Appendix B.

Each colour plot in Appendix B represents a certain interval as indicated in the legend. Areas with little wave penetration (yellow) can quickly be distinguished from areas where the wave amplification is high (red).

The results of the computations can be found in appendix D. These are not all the results of the presented alternatives in appendix A. Only for the present situation, alternative G and alternative D2. The values in the plots indicate the wave height amplification, which is the computed wave height expressed as percentages of incident wave height.

It must once more be stressed that all values given in the tables and plots are the results computed for monochromatic long crested waves. In practice the wave field is irregular. The wave height amplifications will therefore in reality be some weighted average of the amplification factors for a large number of different periods and directions.

7.0 DISCUSSION OF RESULTS

In this section the potential alternatives will be discussed on basis of results presented in Appendix D.

7.1 Results 0-Alternative

To get a reasonable insight on the extent of the changes of the wave penetration in Great Bay, due to the construction of the port, first the 0-Alternative (= present situation), must be calculated. The locations of given values in the tables for the present situation is shown in figure 7.1.

Some values at the present Ro-Ro berth (Grote Kade, at the north of the A.C. Wathey pier) are extracted from the plots to give an indication of the wave penetration near the quay. Most of the specified output points are close to the quay. (approximately one ship,s beam). In front of the high reflection quay, node and anti-node patterns may often occur. Taking the result from just one computational point for the spot value at a location would therefore lead to random results, as a small shift of the requested location, could give a completely different wave height amplification. This was avoided by using the results of all grid points near the quay in an area of one to two wave lengths, which is an area large enough to contain both node and anti-node. The values in this area were averaged by computing the quadratic mean of the wave height amplification along the quay. This is usually done when determining the significant wave height in a wave field. (Root mean square).
The results are collected in the following table:

Grote Kade (present situation)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	1.5	3.5	
135°N	7.3	7.4	
180°N		91.5	100
225°N		100.0	100

Table 7.1: Percentages of incident wave height at the Grote Kade.

Conclusions:

The figures confirm the present situation, that for the directions 90°N and 135°N the quay is well protected by Point Blanche Hill (figure 7.1). Between directions 180°N and 225°N the waves hardly experience any obstruction, and port operations must be ceased when waves from these directions exceed

7.2 Alternative G

The approximation of the wave amplification along the quays is done in the same way as in the 0-alternative. For the cruise terminal the quadratic mean of the whole area around the open pier structure is calculated.
The container berth is the large rectangular area in the lay-out. See figure 7.2.

Alternative G (Container Berth)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	4.3	5.0	
135°N	8.3	9.5	
180°N		79.3	54.6
225°N		162.6	138.9

Table 7.2: Percentages of incident wave height at quay.

Alternative G (Cruise terminal)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	10.2	8.7	
135°N	13.9	17.1	
180°N		66.1	54.7
225°N		106.6	101.0

Table 7.3: Percentages of incident wave height cruise terminal.

The "Grote Kade" (present situation) is included as a comparison to the present situation. This quay is situated at the north of the container terminal.

Alternative G (Grote kade)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	1.0	1.0	
135°N	1.0	1.0	
180°N		5.0	7.0
225°N		25.0	40.0

Table 7.4: Average percentages of incident wave height Grote Kade in alternative G.

Conclusions:
Comparing the results with the 'Grote Kade' in the present situation, it is found that the wave penetration is large, for the important directions 90°N and 135°N. This is mainly due to the fact that reflected waves can hardly exit the port area, which results in an increase of wave energy level in the port area.
Comparing the "Grote kade" in alternative G with the same quay in the present situation, shows the reduction on wave amplitude due to the container terminal (acting as a breakwater). The energy in this area is dissipated in the rubble mount jetty at the north of the harbour.

7.3 Alternative D2

The following tables were generated for this alternative: The container terminal is situated at the East-side of the port. See figure 7.3.

Alternative D2 (Container terminal)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	2.2	8.9	
135°N	9.5	11.9	
180°N		27.3	42.8
225°N		84.3	81.9

Table 7.5: Percentages of incident wave height at quay.

Alternative D2 (Grote Kade)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	2.1	7.2	
135°N	9.7	10.1	
180°N		28.1	31.1
225°N		105.8	81.9

Table 7.6: Percentages of incident wave height at quay.

The following values are for the inside of the cruise terminal, (the 700 meter long quay).

Alternative D2 (Cruise terminal)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	3.8	10.8	
135°N	12.7	16.4	
180°N		48.3	42.2
225°N		≈80.0	92.2

Table 7.7: Percentages of incident wave height cruise terminal (inside).

The following values are for the outside of the cruise terminal.

Alternative D2 (Cruise terminal West-side)			
Direction	T = 5 s.	T = 8 s.	T = 12 s.
90°N	1.6	4.9	
135°N	8.5	10.8	
180°N		77.9	67.3
225°N		≈90.0	115.3

Table 7.8: Percentages of incident wave height cruise terminal (West = outside).

Conclusions:

The effect of a "second breakwater" (the cruise terminal), for the directions 180°N and 225°N is noticeable. The container terminal is much better protected compared to Alternative G. The higher values compared to the present situation are also due to the introduction of reflecting edges.

7.4 Shortening of breakwater Alternative D2

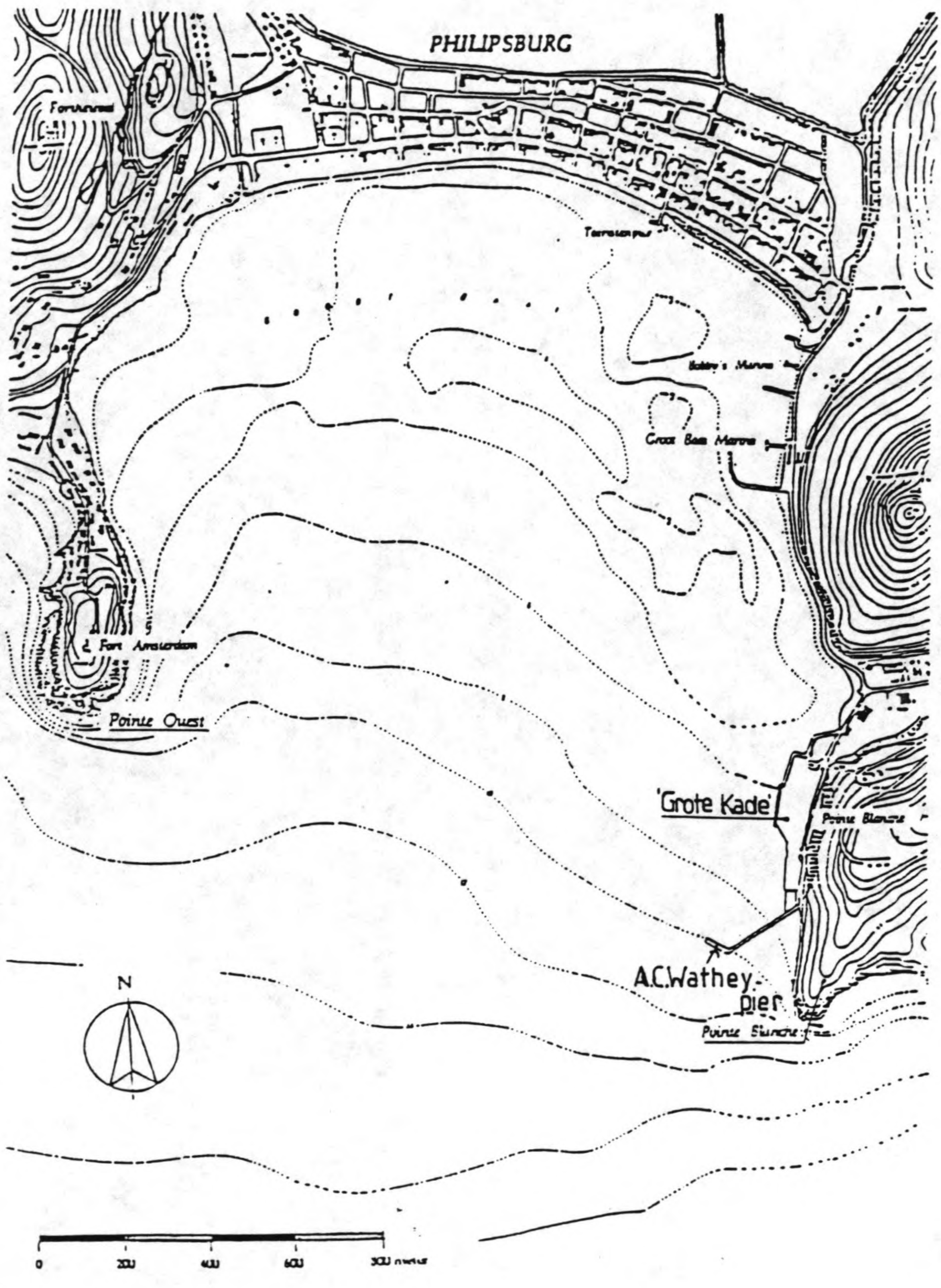
An extra calculation is made to determine the effect of a shorter breakwater. A shorter breakwater would reduce construction costs. The calculations were only performed for the two prevailing direction 90°N and 135°N, which are the wave directions during at least 85% of the time. The breakwater in Alternative D2 was shortened in two steps, resulting in the following diffraction parameters.

Alt D2 Shortening of breakwater				
		reductions		
T = 8 sec.	dir.	0m.	100m.	180m.
Cruise term. East side	135°N 180°N	16.4 48.3	24.4 69.6	30.0 142.1
Cruise term. West side	135°N 180°N	10.8 77.9	14.5 95.2	20.9 92.2
Container Berth	135°N 180°N	12.4 30.2	18.6 55.4	126.7 57.3

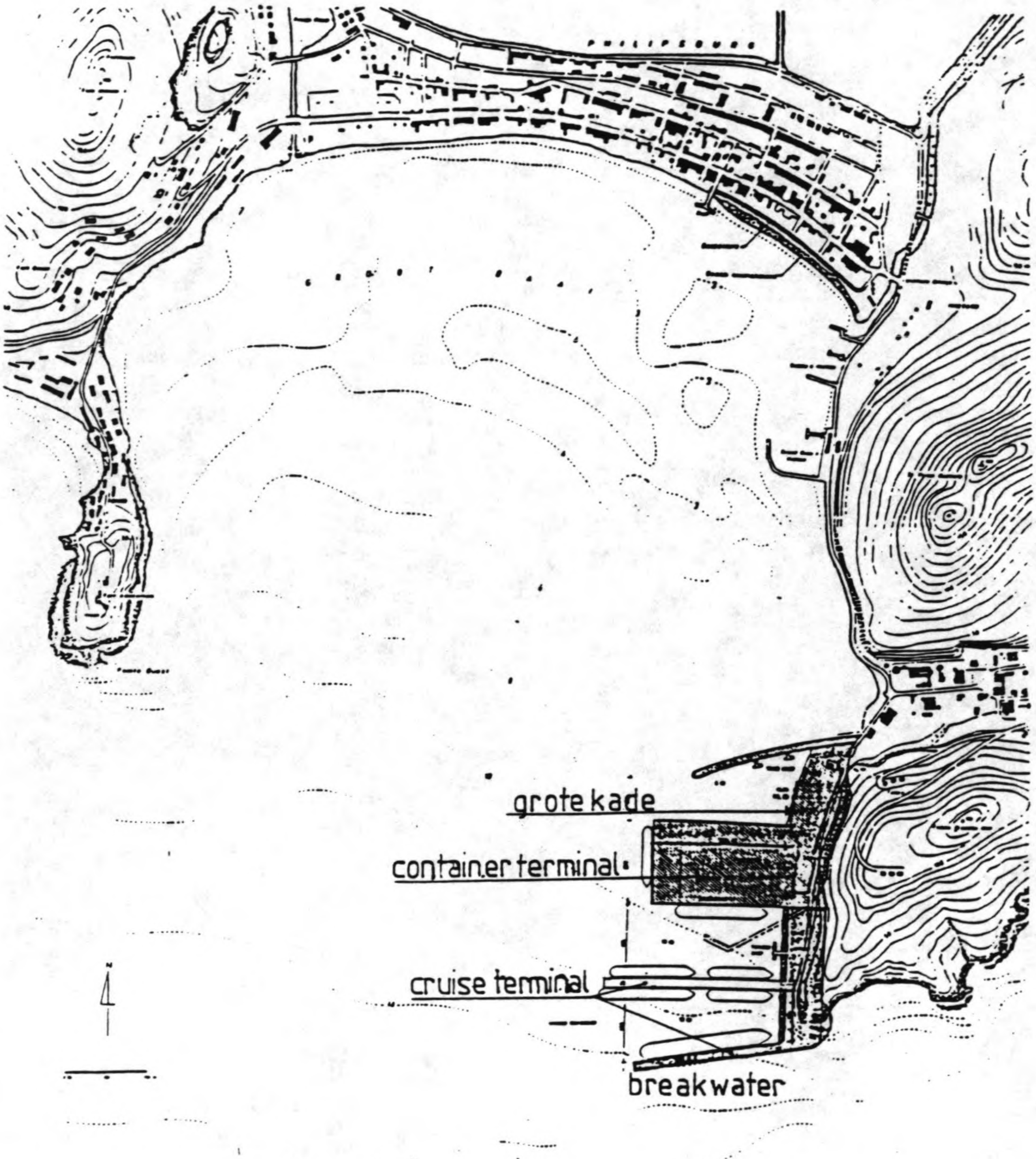
Table 7.9 Shortened breakwater.

Conclusion:

The necessity of the breakwater is now noticeable. The values in the table 7.9 are higher than in the tables 7.5 to 7.8, though a 100m. reduction of breakwater length is possible.

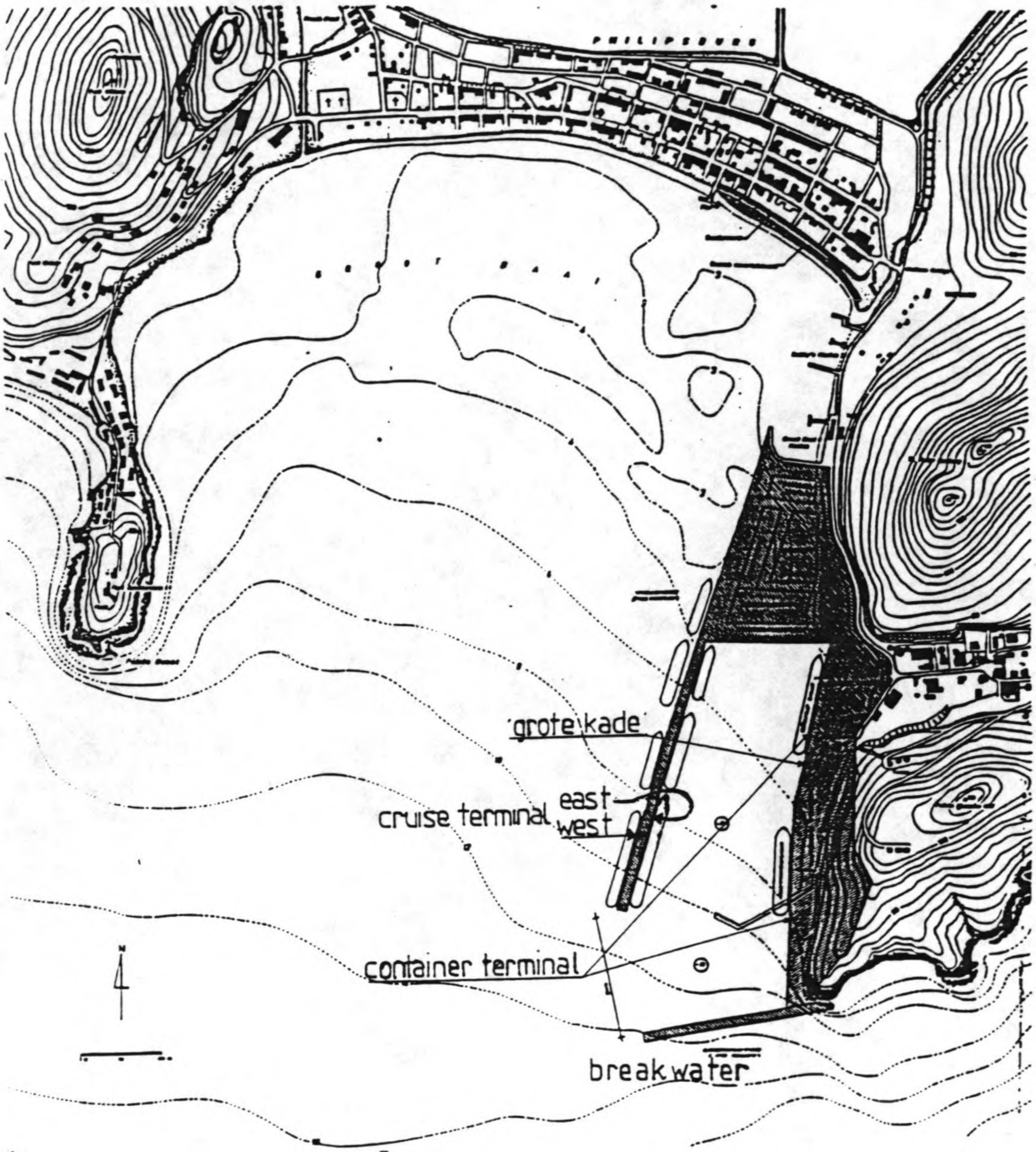


WAVE PENETRATION STUDY	FIGURE 7.1
Locations present situation	



WAVE PENETRATION STUDY | FIGURE 7.2

Locations alternative G



WAVE PENETRATION STUDY

FIGURE 7.3

Locations alternative D2

8.0 CONDITIONS AT BERTHS AND THEIR ESTIMATED DOWN TIME.

8.1 Maximum wave height at berth

An overall table is made as tool for the comparison. The table is based on the computations for the representative wave period of 8 seconds.

Alternative		pres. sit.	Alt D2		Alt G
location	dir.				
Grote kade	90°N 135°N 180°N 225°N	3.5 7.4 91.5 100.0	7.2 10.1 28.1 105.8		1.0 1.0 5.0 25.0
			East	West	
Cruise terminal	90°N 135°N 180°N 225°N	not relevant	10.8 16.4 48.3 80.0	4.9 10.8 77.9 90.0	8.7 17.1 66.1 106.6
Container terminal	90°N 135°N 180°N 225°N	not relevant	8.9 11.9 27.3 84.3		5.0 9.5 79.3 162.6

Table 8.1: Summary diffraction parameters in percentages.

The maximum allowed wave height at the berths for safe and efficient cargo handling is assumed to be 0,4 meter.
With this assumption a backward calculation was carried out, to find the maximum wave height allowed at the 12 meter depth contour. This calculation was carried out by dividing 0,4 meter by the diffraction parameter, giving the significant wave height "allowed" at the port entrance (depth: 12 meter). Using the tables in the Wave Climate Study (based on Snell's Law section 7), the frequency of exceedence (per mille) of this wave height was found. This can be seen as the expected down time (d.t.) of the alternatives (table 8.2) during normal weather conditions. The down time of a port is the time in which port activities are ceased because safe berthing or container handling is not possible. The comparison is made excluding hurricane conditions. For all alternatives applies the assumption of an empty port during

severe weather conditions. In co-operation with Miami (USA) and Puerto Rico, St. Maarten has a perfect 'Hurricane Watch', which dispatches warnings, days before the hurricane may reach the island, so that ample measures can be taken.

<table>
<tr><td colspan="2">Alternative:</td><td>pres. sit.</td><td colspan="2">Alt D2</td><td>Alt G</td></tr>
<tr><td>location</td><td>dir.</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>Grote kade</td><td>90°N
135°N
180°N
225°N</td><td>-
-
8
4</td><td colspan="2">-
1
7
4</td><td>-
-
8
4</td></tr>
<tr><td colspan="2">total down time</td><td>12</td><td colspan="2">12</td><td>12</td></tr>
<tr><td>Cruise terminal</td><td>90°N
135°N
180°N
225°N</td><td>not relevant</td><td>East
-
2
7
4</td><td>West
-
-
7
4</td><td>1
2
7
4</td></tr>
<tr><td colspan="2">total down time</td><td>-</td><td>13</td><td>11</td><td>14</td></tr>
<tr><td>Container terminal</td><td>90°N
135°N
180°N
225°N</td><td>not relevant</td><td colspan="2">-
1
7
4</td><td>-
-
8
4</td></tr>
<tr><td colspan="2">total down time</td><td>-</td><td colspan="2">12</td><td>12</td></tr>
</table>

Table 8.2: Summary of exceedance of max. wave height, and total down time (d.t.) in per mille during normal weather conditions.

The same is done for shortened breakwater in alternative D2.

Alt D2 Shortening of breakwater				
		reductions		
T = 8 sec.	dir.	0m.	100m.	180m.
Cruise term. East side	135°N 180°N	2 7	40 2	130 11
total down time		9	42	141
Cruise term. West side	135°N 180°N	- 7	4 11	5 11
total down time		7	15	16
Container Berth	135°N 180°N	1 7	16 7	151 7
total down time		8	23	158

Table 8.3: Shortened breakwater, down time in per mille during normal weather conditions.

9.0 CONCLUSIONS.

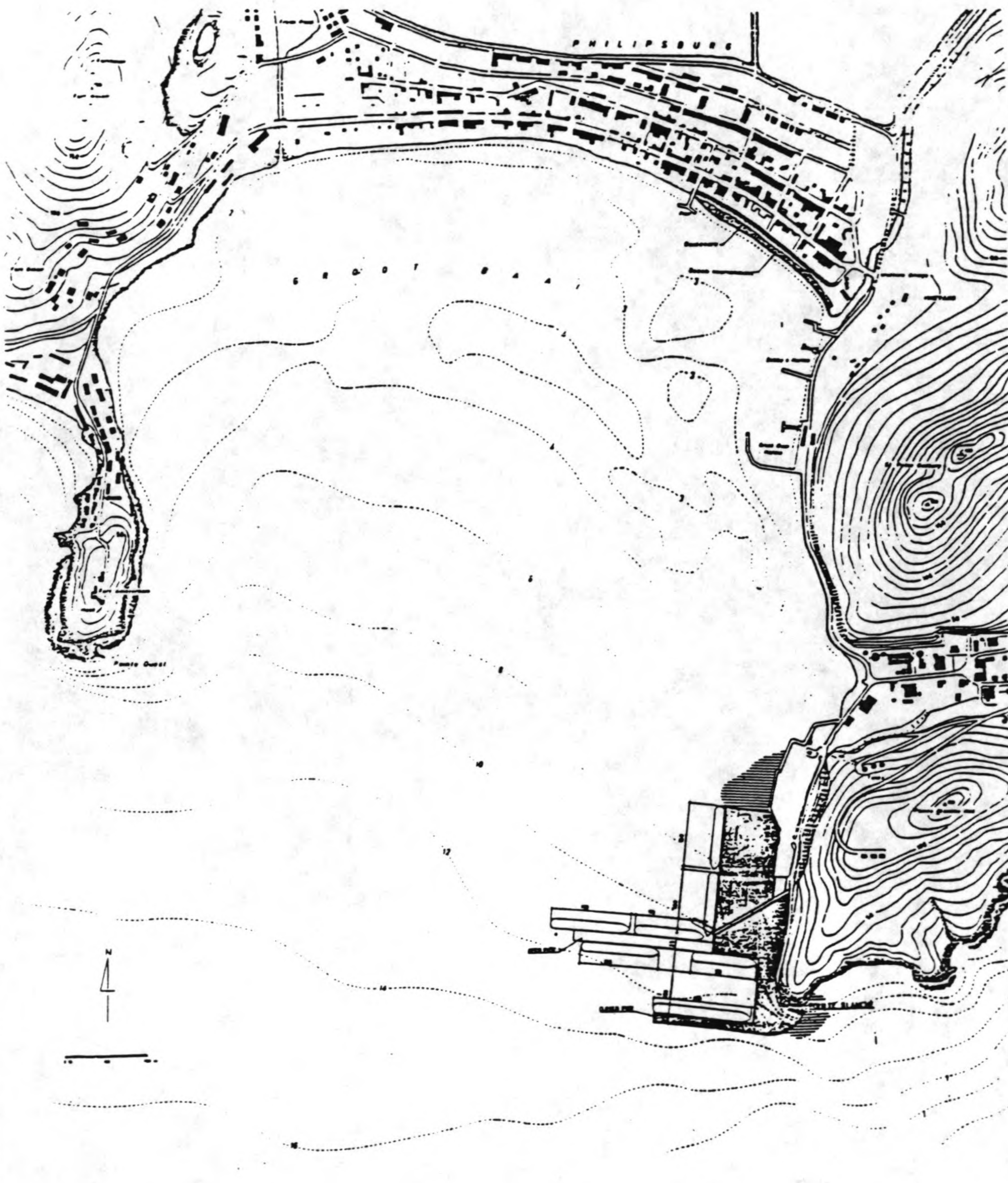
Next to what has already been stated in section 7 the following can also be concluded.

- In literature on diffraction is found that the wave penetration is also strongly dependent of the entrance-width/wave-length ratio. If the B/L (width/wave length) is smaller than 5 [ref.: 5], the waves will also be influenced by the other edge of the port entrance. This can also be seen in the tables in section 7. For more sheltering the port entrance should be narrowed. This is not possible because the entrance width is designed on the minimum width necessary for the design vessel.
- Values in table 8.1 show a lower value for the diffraction parameters for the present situation compared to the values for both alternatives. This is mainly because of the vertical reflecting quays to be constructed in alternatives where no energy dissipation takes place, compared to the gravel and rock which exists in the present situation.
- The down time (d.t.) for alternative D2 and G is the same. This is due to the fact that the port is open to waves from the west in both alternatives. For the same reason there is no difference with the present situation. The down time is thus only dependent on the recurrence of severe weather conditions. The port however, will be evacuated on time, and port operations will be ceased during these conditions. The diffraction parameters for these directions (180°N and 225°N) will be used to determine the design conditions for the port structures.
- Reduction of the breakwater length of approximately 100 meter is possible for Alternative D2, resulting in a maximum down time at the Eastern side of the cruise terminal of 4.2%. More reduction results in a higher d.t. than 4.2 (+/- 15 days), which is not acceptable. This can not be done for Alternative G. For this alternative the maximum protection is necessary.
- Results from the computations give no significant

preference for the selection of the lay-outs based on the down time. One could consider Alternative D2 preferable as it provides for better expansion possibilities.

APPENDIX A

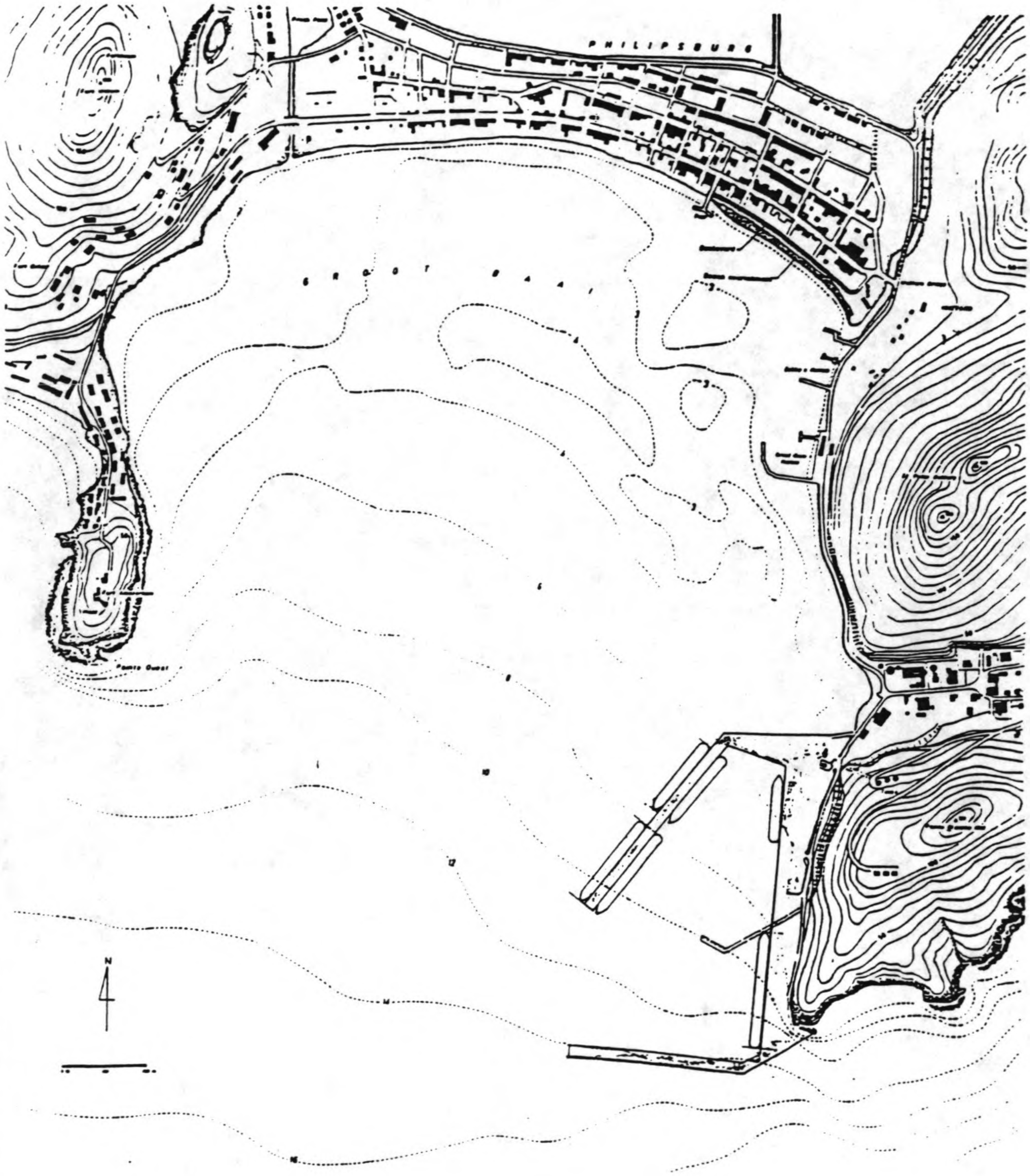
DIFFRACTION STUDY, LAY-OUTS.



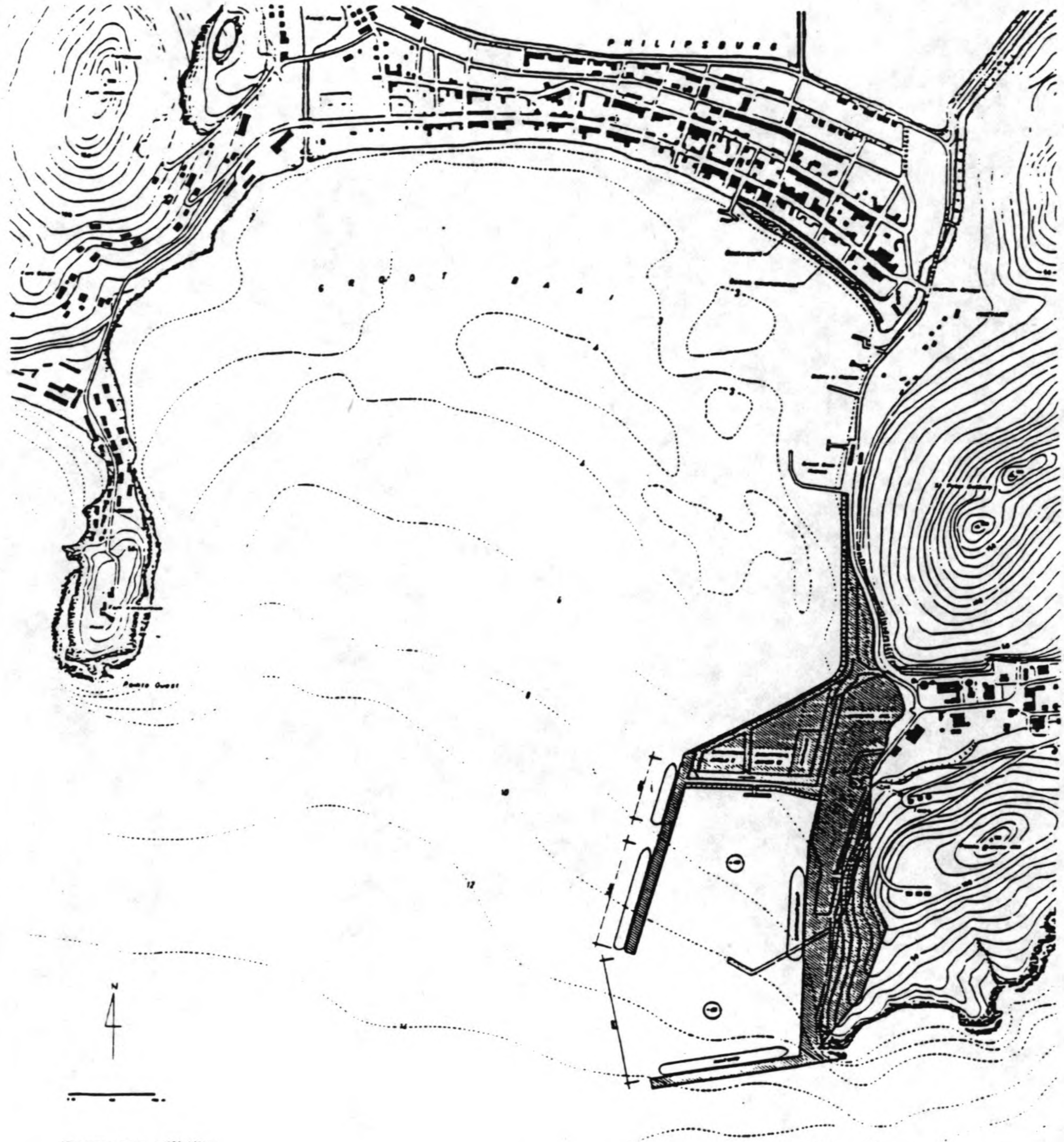
ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE A

SCALE: DISTORTED

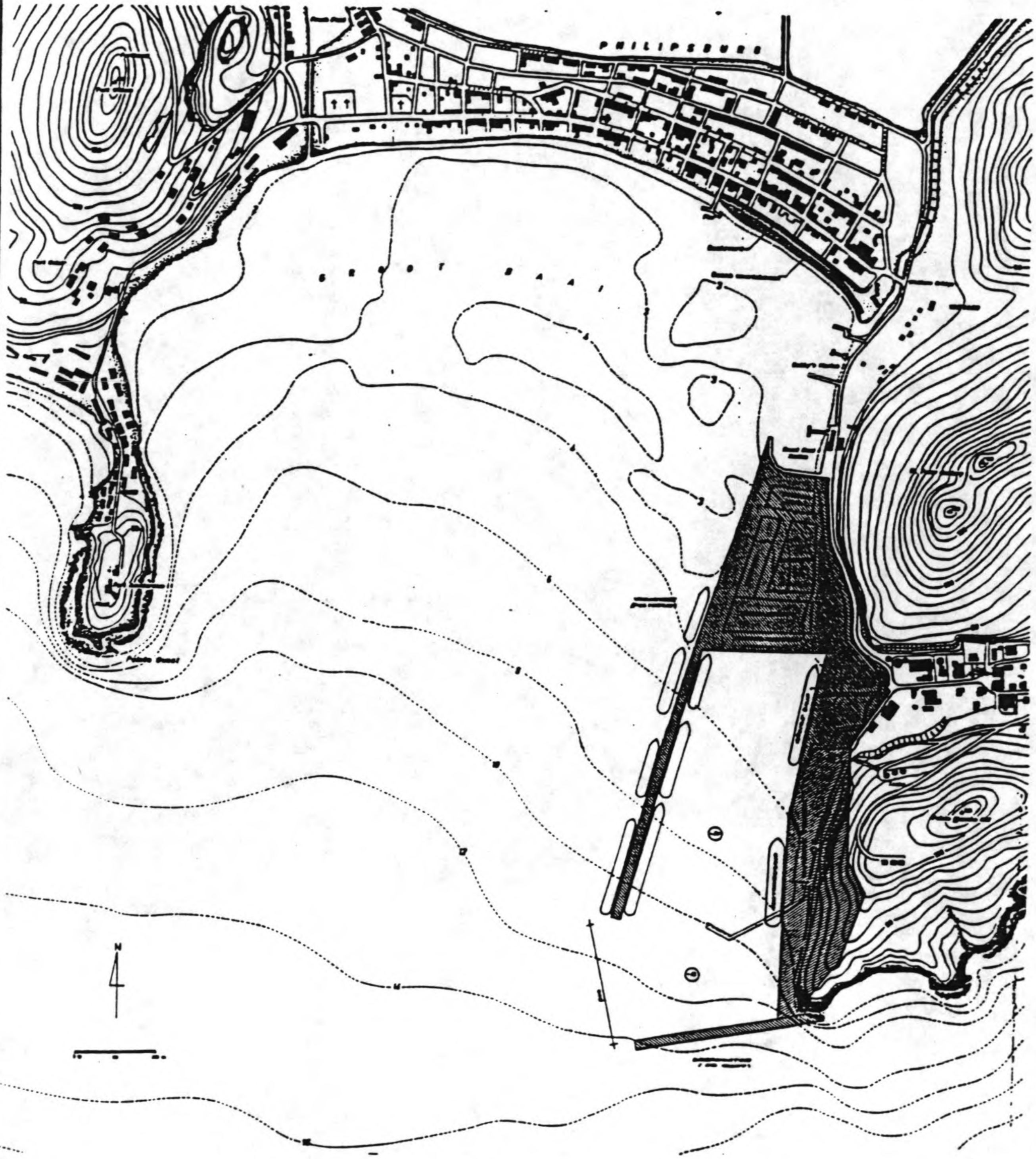
Grabowsky&Poort BV, Consulting Engineers | 7810.2 | FIG.



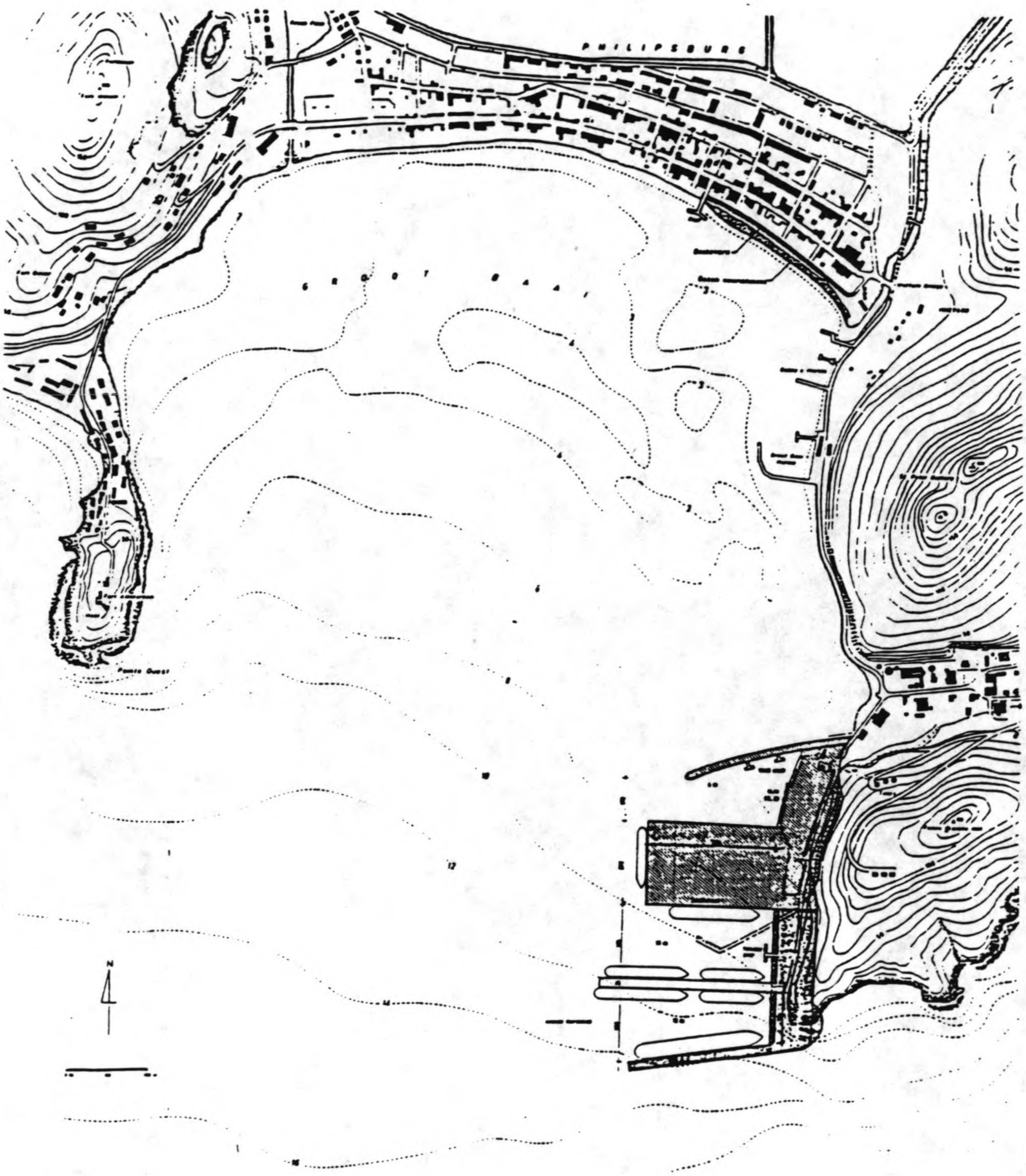
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE C	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG.



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D		
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG.



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2		
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG.



ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE G

SCALE: DISTORTED

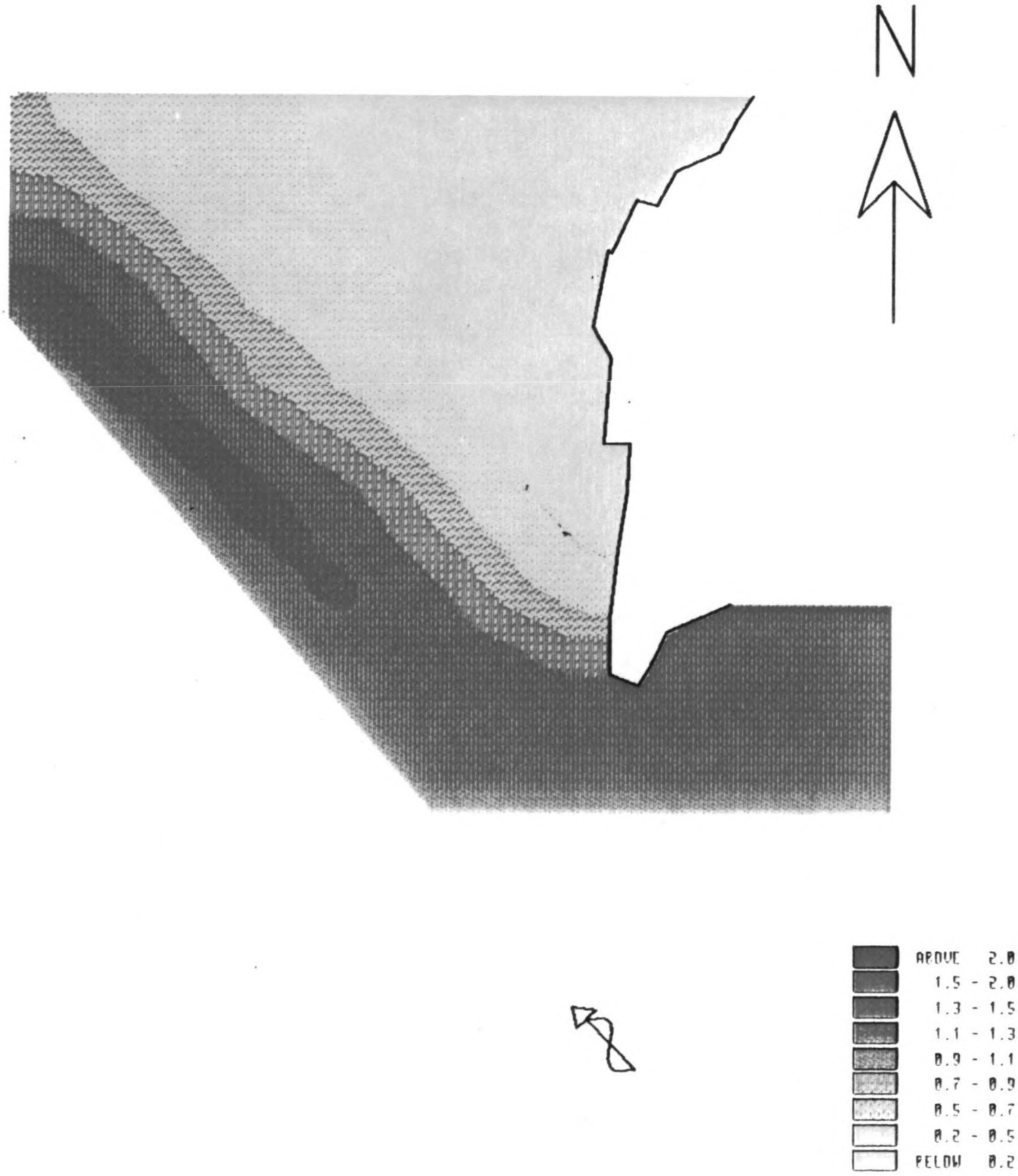
Grabowsky&Poort BV, Consulting Engineers

7810.2

FIG.

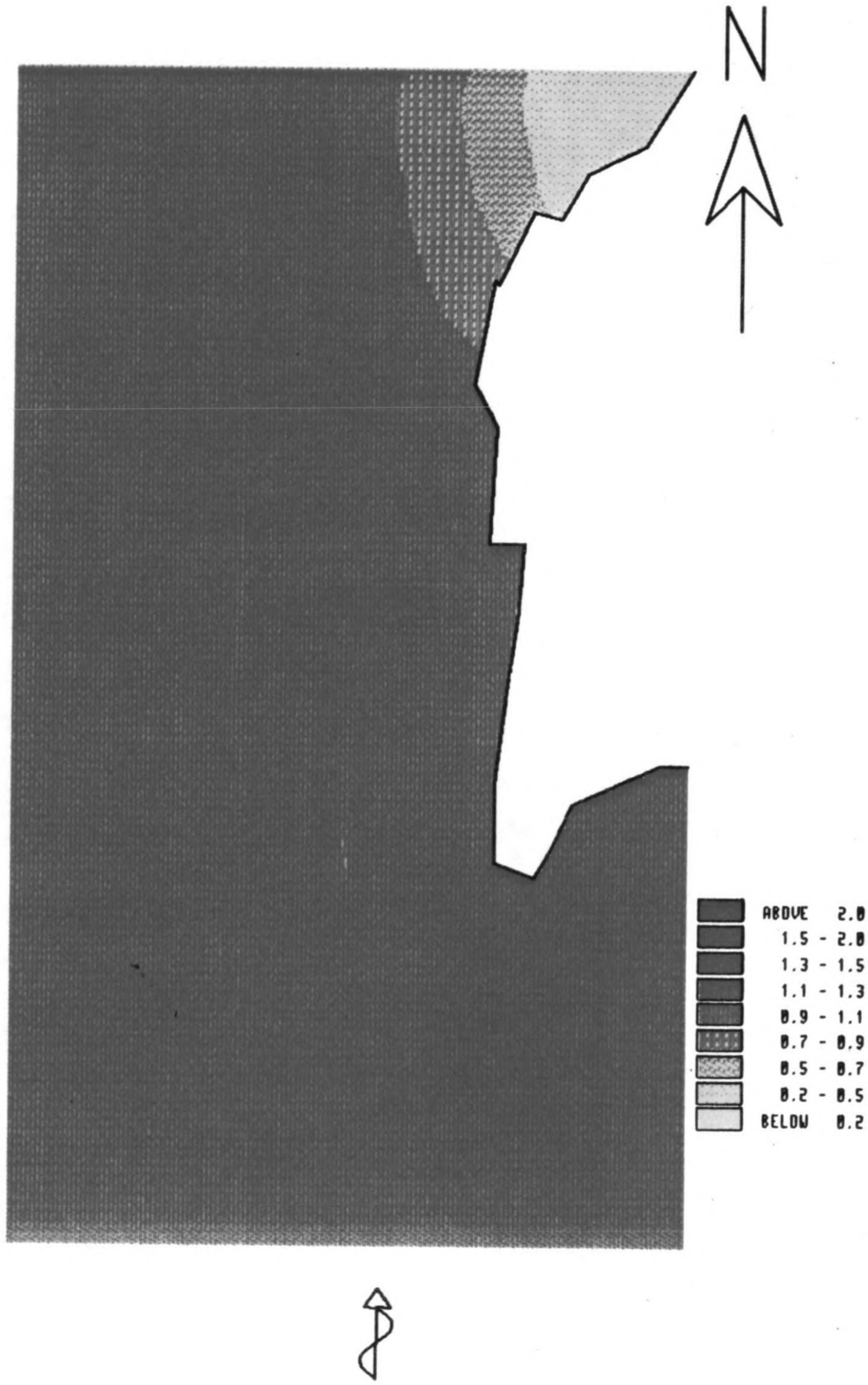
APPENDIX B

DIFFRACTION STUDY, COLOUR PLOTS, POTENTIAL ALTERNATIVES.



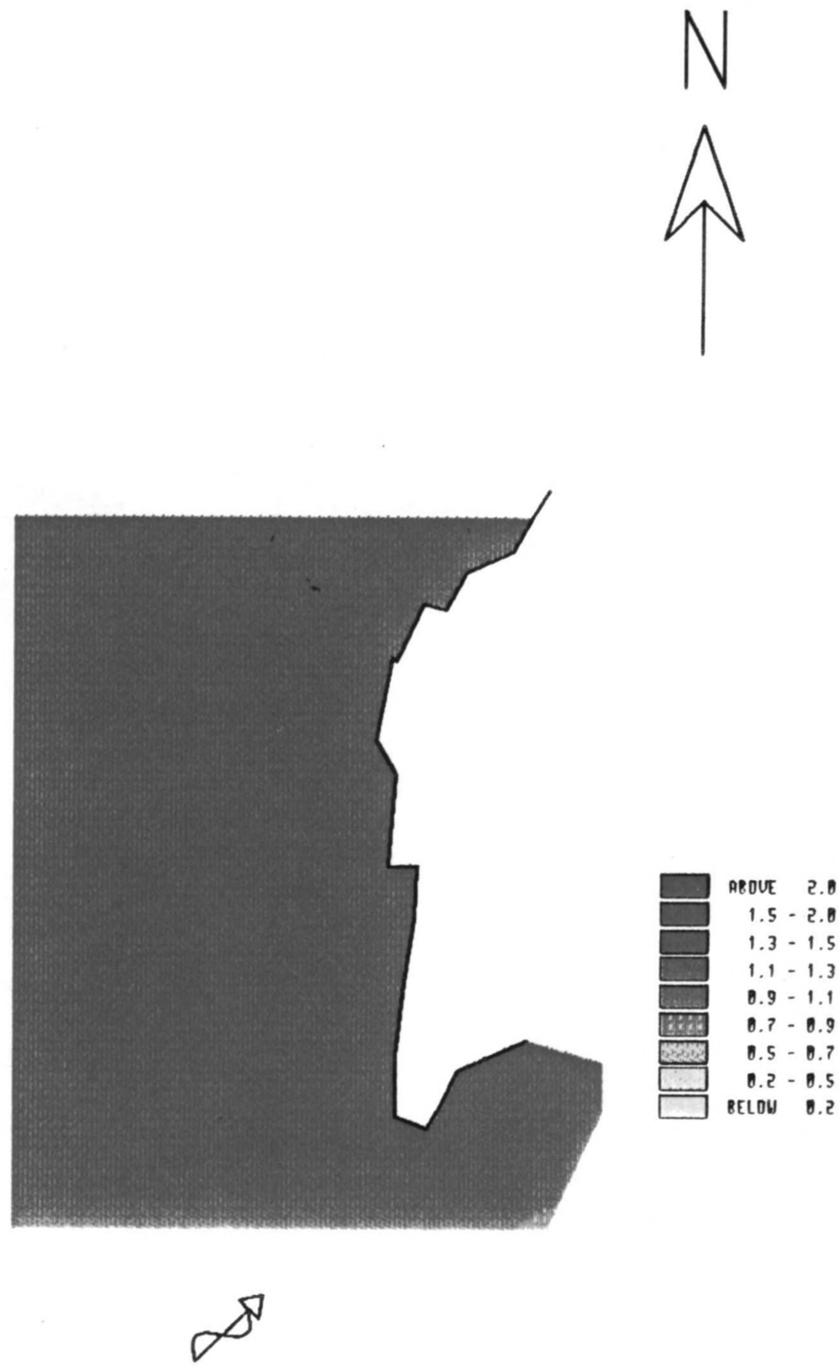
Diffraction study proposed port St. Maarten NA	DIR = 135N
0-Alternative (present situation)	Scale 1 : 10000
Grabowsky & Poort BV	504N

G-01 31/10/90 13.13



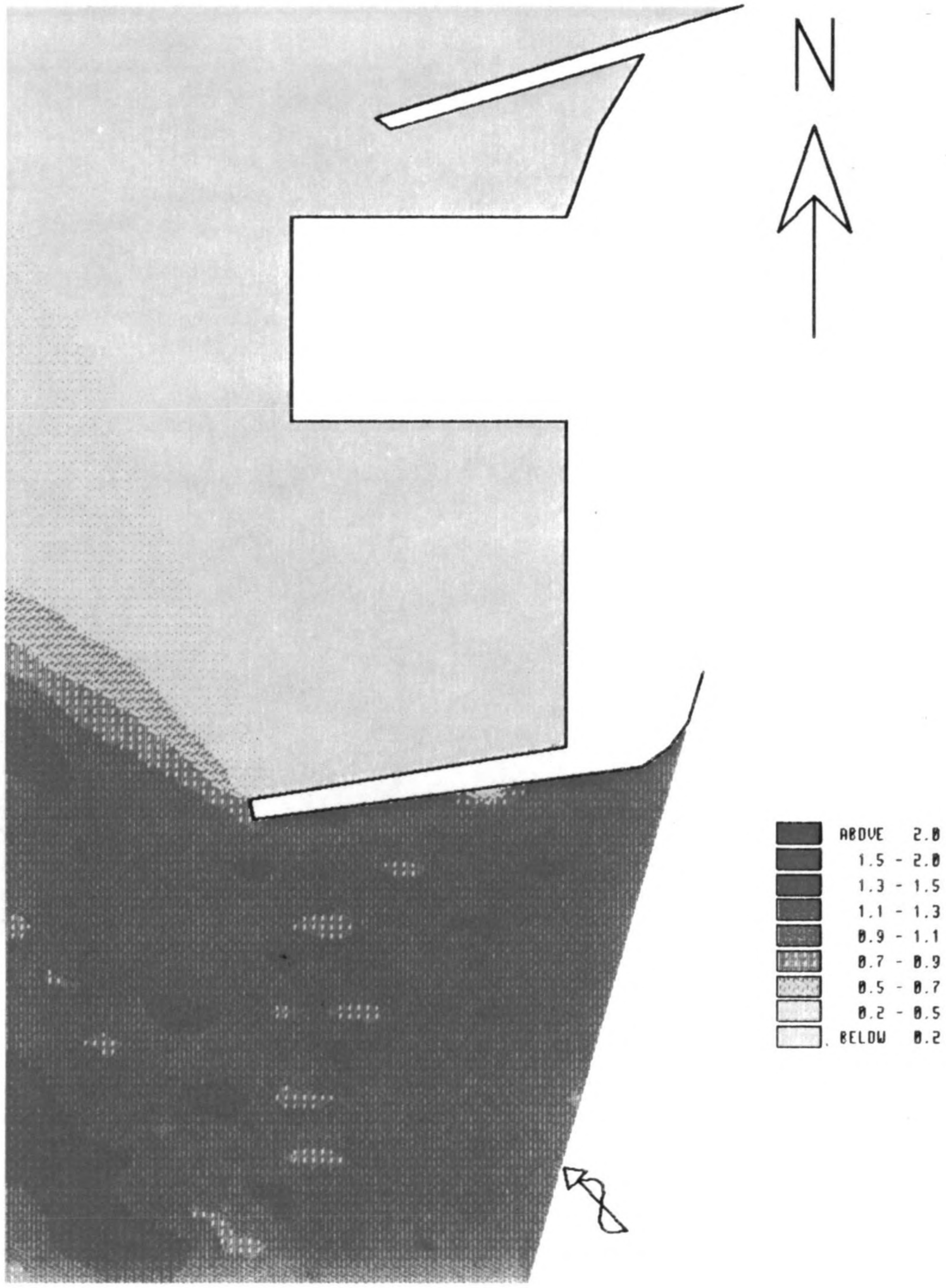
Diffraction study proposed port St. Maarten NA	DIR = 180N
0-Alternative (present situation)	Scale 1 : 7500
Grabowsky & Poort BV	5018

G-03 01/11/90 16.24



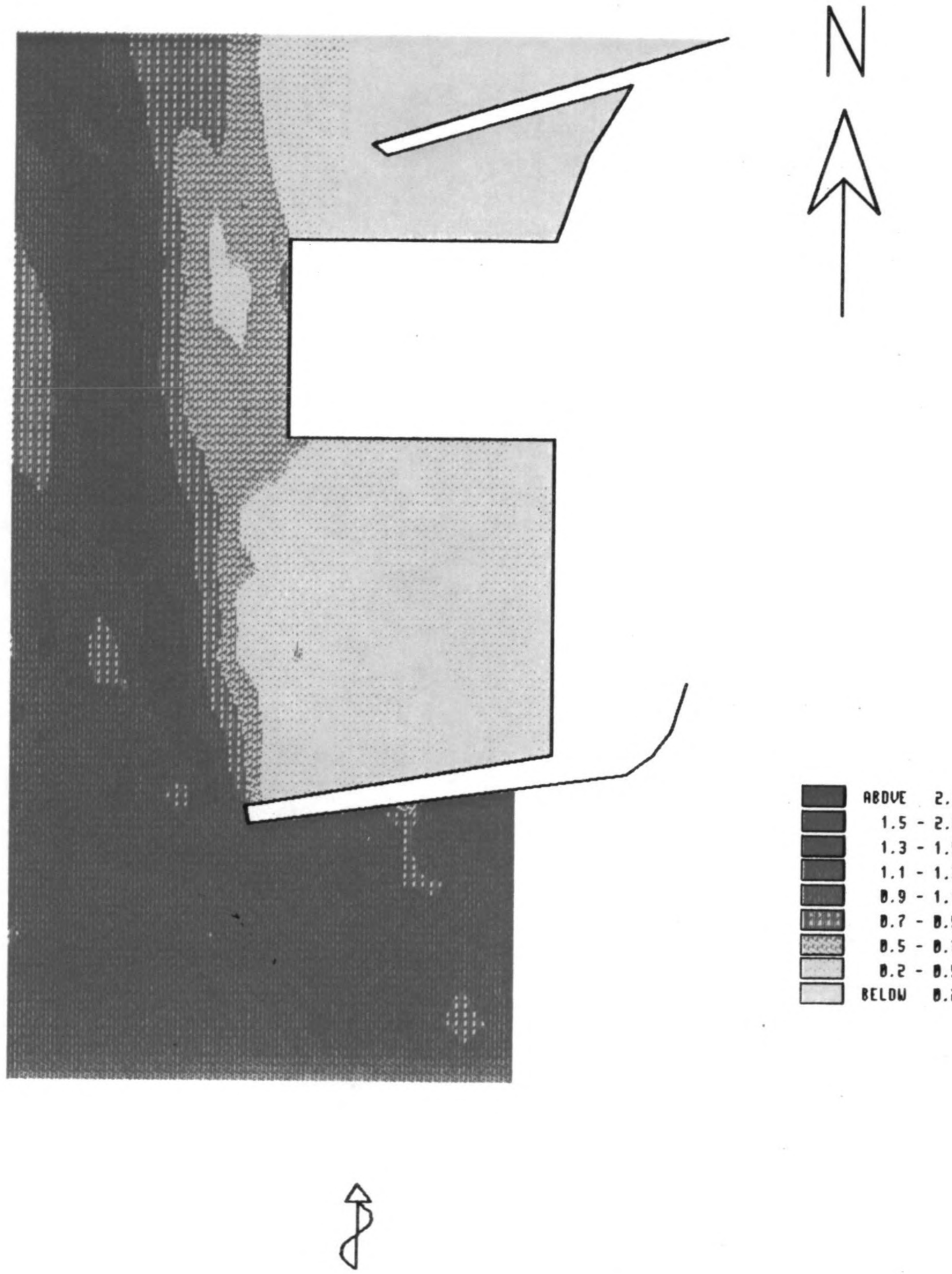
Diffraction study proposed port St. Maarten NA	DIR = 225N	
0-Alternative (present situation)	Scale 1 : 10000	
Grabowsky & Poort BV	50225	

G-04 31/10/90 15.05



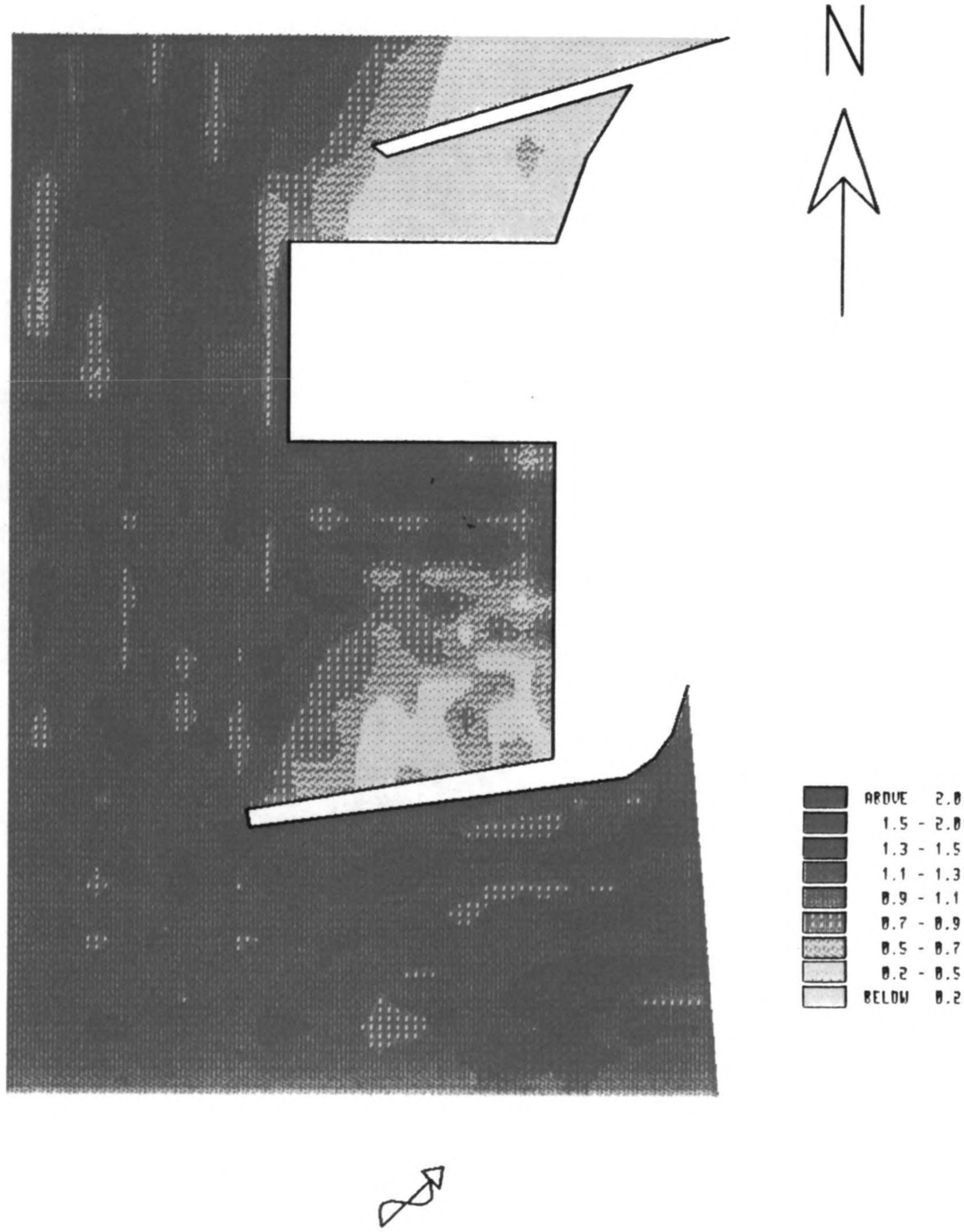
Diffraction study proposed port St. Maarten NA	DIR = 135N	
Alternative G	Scale 1 : 7500	
Grabowsky & Poort BV	534	

G-09 31/10/90 13.35



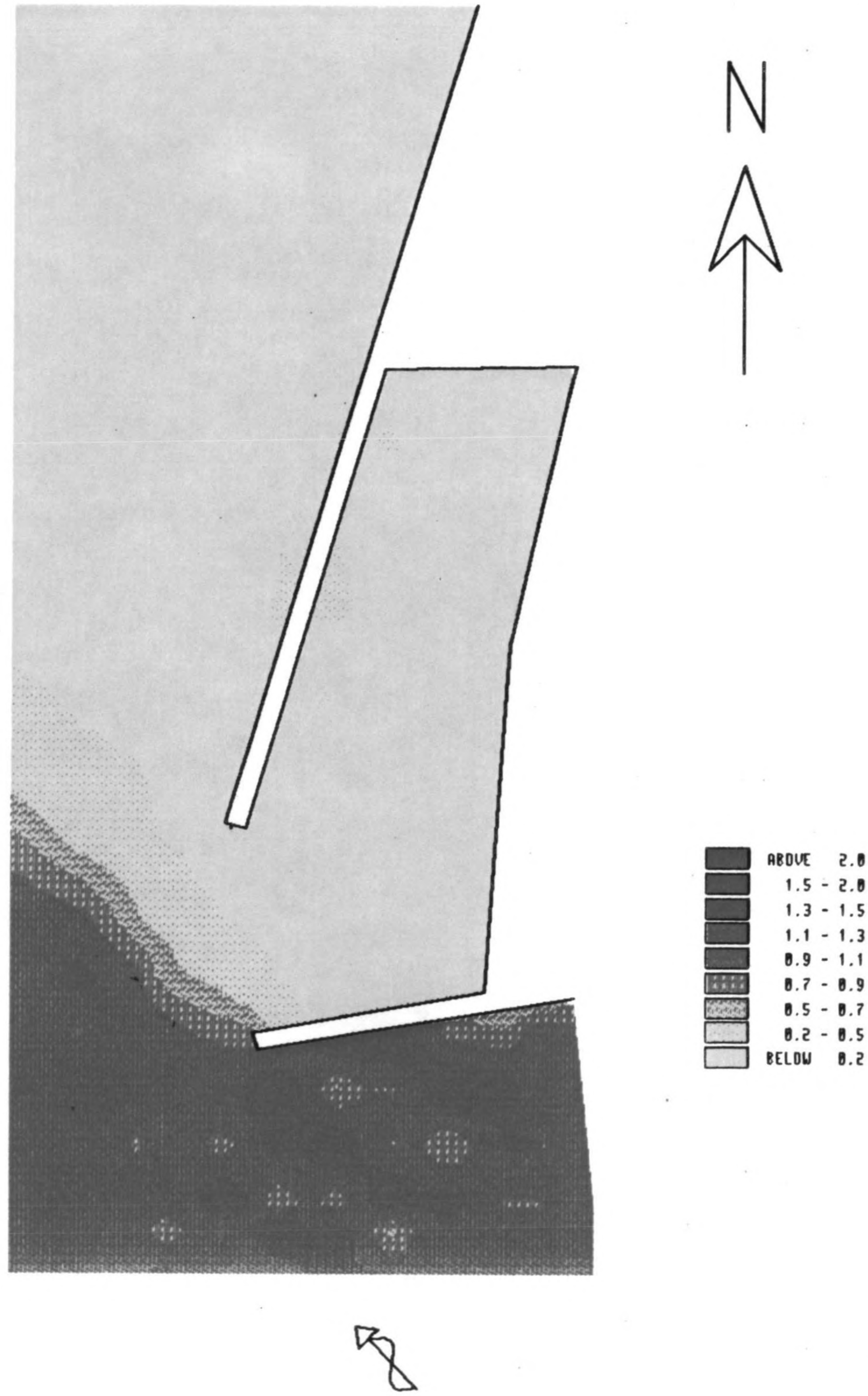
Diffraction study proposed port St. Maarten NA	DIR = 180N
Alternative G	Scale 1 : 7500
Grabowsky & Poort BV	S318

G-11 01/11/90 17.48



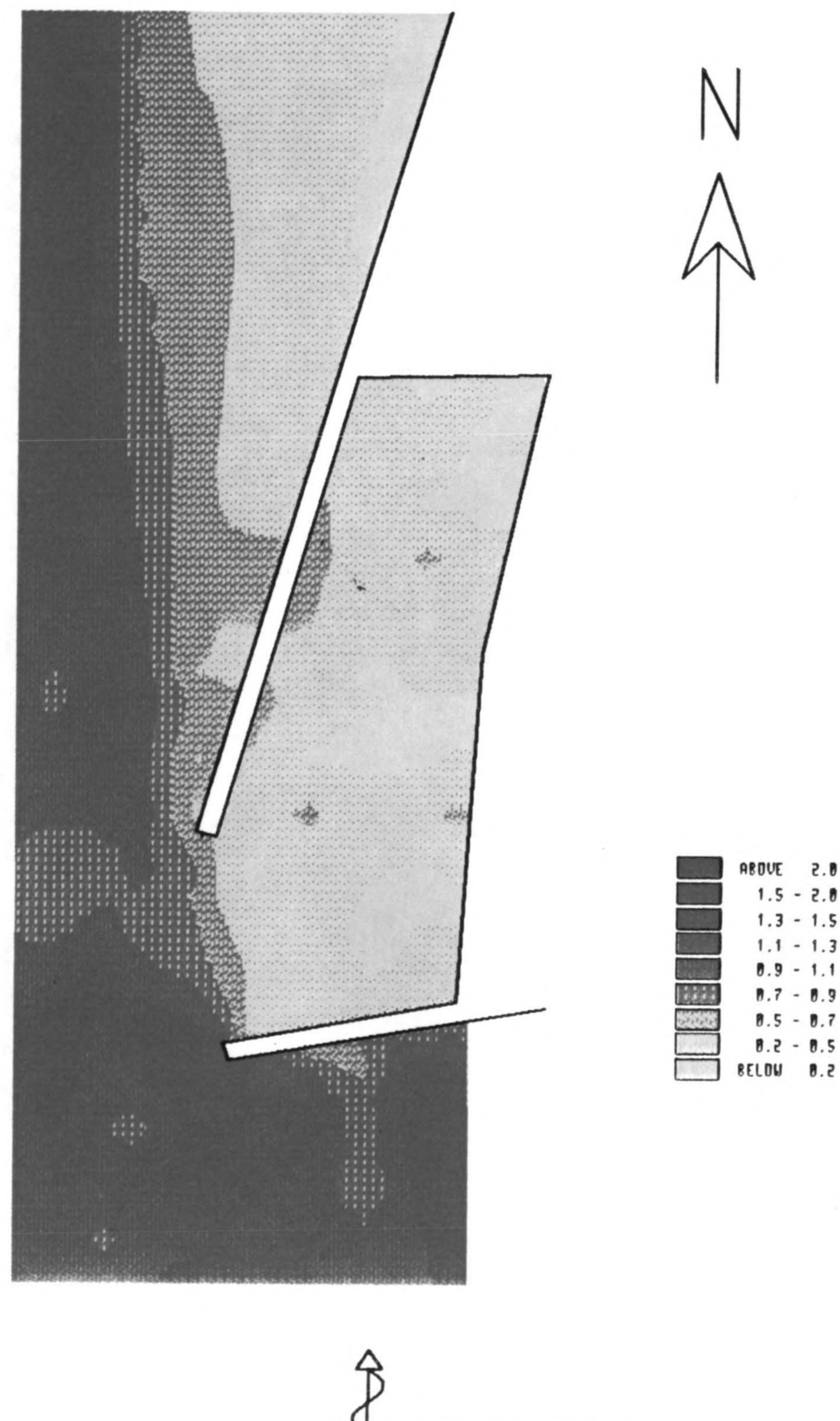
Diffraction study proposed port St. Maarten NA	DIR = 225N
Alternative G	Scale 1 : 7500
Grabowsky & Poort BV	53225

G-12 31/10/90 10.35

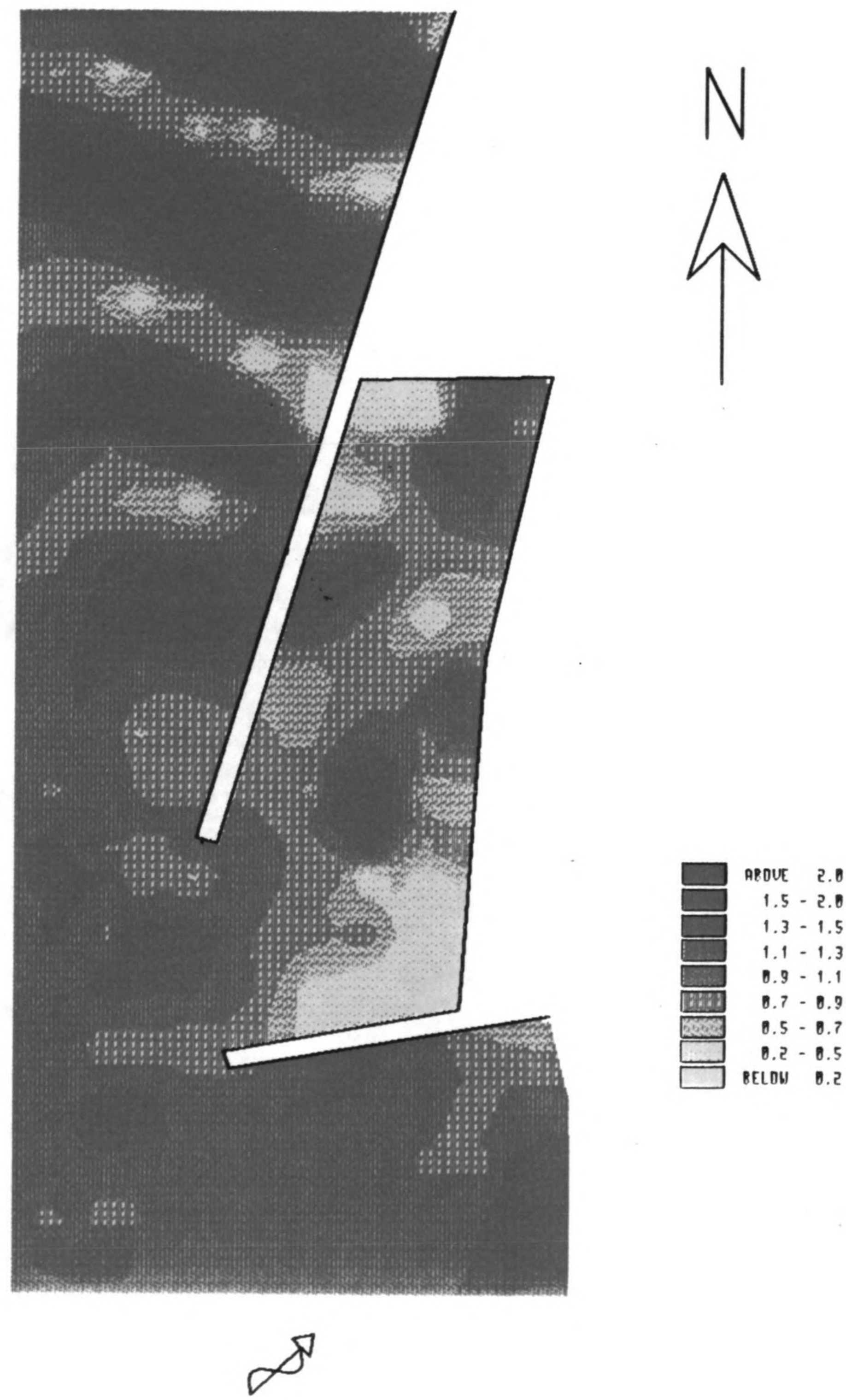


Diffraction study proposed port St. Maarten NA	DIR = 225N
Alternative D2	Scale 1 : 10000
Grabowsky & Poort BV	554

X-17 01/11/90 14.39



Diffraction study proposed port St. Maarten NA	DIR = 180N	
Alternative D2	Scale 1 : 10000	
Grabowsky & Poort BV	5518	



Diffraction study proposed port St. Maarten NA Alternative D2	DIR = 225N	
	Scale 1 : 10000	
Grabowski & Poort BV	55225	

X-20 01/11/90 15.06

APPENDIX C

MATHEMATICAL DESCRIPTION DIFFRACTION STUDY.

C.1 METHODOLOGY

For the mathematical description on the diffrac-model, appendix B from the users guide is enclosed.

The wave penetration computations are based on the phenomenon of diffraction, which is the three dimensional effect resulting from the interruption of a wave train by an obstruction. The wave crests behind the obstruction will be strongly curved and along variation of the wave height will occur, which results in a transfer of energy along the wave crest.

The mathematical model for the computations of wave penetration in areas with an arbitrary shape is based on the linear theory of harmonic water waves. The simplifications made in the mathematical formulation are:

1. The fluid is ideal, no viscosity or turbulence effects are taken into account.
2. The fluid motion is irrotational, so a potential formulation can be used (Laplace).
3. There is no energy dissipation in the area of propagation, no wave breaking and no bottom friction.
4. The formulation is linearised so only small amplitude water waves (small wave steepness) can be considered (no breaking).
5. The wave motion is harmonic in time (regular waves).
6. Over the area of propagation the water depth must be constant. Boundaries of the domain must be schematised as vertical, but they may have partial reflection properties.

With these assumptions, the problem can be formulated mathematically as the determination of the wave potential function $\Phi(x,y,z,)$, which must satisfy the Laplace equation:

$$\frac{\delta^2\phi}{\delta x^2}+\frac{\delta^2\phi}{\delta y^2}+\frac{\delta^2\phi}{\delta z^2}=0 \tag{1}$$

in which:
Φ = three dimensional potential (complex).
x,y = horizontal coordinates.
z = vertical coordinates.

In vertical direction the solution domain has the boundaries z=0, which is the mean water level, and z= -h, which is the constant bottom plane. At these boundaries the following conditions are given:

$$\frac{\delta\phi}{\delta z}-\frac{\omega^2}{g}.\phi=0 \tag{2}$$

at z = 0

$$\frac{\delta\phi}{\delta z}=0 \tag{3}$$

at z = -h

with:
omega = angular frequency of the wave motion.
g = gravitational acceleration.
h = water depth.

Due to the constant water depth a separation of variables is possible, resulting in the formulation:

$$\phi=-\frac{g}{\omega}i\phi\left(\frac{\cosh[k(z+h)]}{\cosh(kh)}\right) \tag{4}$$

in which:
i = -√-1, and k must satisfy the dispersion relation:

$$\omega^2=gk\cdot\tanh(kh) \tag{5}$$

Substitution of equation (3) in the Laplace equation results in the Helmholtz equation:

$$\frac{\delta^2\phi}{\delta x^2}+\frac{\delta^2\phi}{\delta y^2}+k^2=0 \qquad (6)$$

with:
Φ = two-dimensional potential (complex).
L = wave length.
k = wave number ($=2\pi/L$).

The boundary conditions in the horizontal plane are given by:

$$\frac{\delta\phi}{\delta n}+ka\phi=0 \qquad (7)$$

at fixed partial reflection boundaries by which $\delta/\delta n$ means the normal derivative. The non-dimensional constant "a" indicates the rate of reflection power in terms of amplitude reduction and phase shift. For complete reflection the value for a is 0, and so (7) changes into:

$$\frac{\delta\phi}{\delta n}=0 \qquad (8)$$

At open parts of the boundaries, such as the entrance to the sea, the radiation condition has to be fulfilled. At sea an incident wave field Φ_0 must be given. In general the incident wave is given by the expression:

$$\phi_0=\frac{1}{2}H_0\cdot\exp[ik(x\cdot\cos(\alpha)+y\cdot\sin(\alpha))] \qquad (9)$$

with:
H_0 = wave height of the incident plane wave.
α = angle of incidence.

The solution of the Helmholtz equation (6) for the boundary conditions as described above is as follows. the problem is linear in Φ, and hence the resulting wave pattern can be constructed from a part generated by the incident wave and a part following from partial reflected waves, which can be seen as waves which are generated by the harbour contour.

The boundary conditions (7) and the radiation condition at the harbour entrance result in an integral equation for the source intensity in each point of the contour. once the potential Φ has been computed, the wave height pattern H(x,y) in the solution domain (harbour) can be found by:

$$H_1(x,y) = H_0\sqrt{\Phi_1^2+\Phi_2^2} \tag{10}$$

in which:

Φ_1 = real part of Φ.

Φ_2 = imaginary part of Φ.

C.2 INTEGRAL EQUATIONS

In this paragraph the integral equations are given which define the problem.

For a point P laying at a wall of the harbour schematisation yields the next equation:

$$\mu(P) + \int_C \mu(M)\frac{\delta G(P;M}{\delta\eta}\cdot ds + ka(P)\int_C \mu(M)\,G(P;M)\cdot ds = 0 \tag{11}$$

and a point P laying at the entrance of the harbour,

$$\int_C \mu(M)\,G(P;M)\,ds = \int_{C_0} \mu_0(M')\,G(P;M)\,ds + \phi(P) \tag{12}$$

and

$$\frac{U_e}{k}[\mu(P) + \int_C \mu(M)\frac{\delta G(P;M)}{\delta n}\cdot ds] + \frac{U_{e0}}{k_0}[\mu_0(P) + \frac{\delta\phi}{\delta n_0}(P)] = 0 \tag{13}$$

In which:

μ = source intensity.

G(P;M) = potential in point P due to a source in M.

s = stream variable along the harbour contour.

a = complex reflection coefficient.

k = wave number.

U_e = energy velocity.

Φ = complex potential

$\delta\Phi/\delta n$ = normal derivative of potential.

C = contour of harbour.

The subscript 0 indicates the sea.

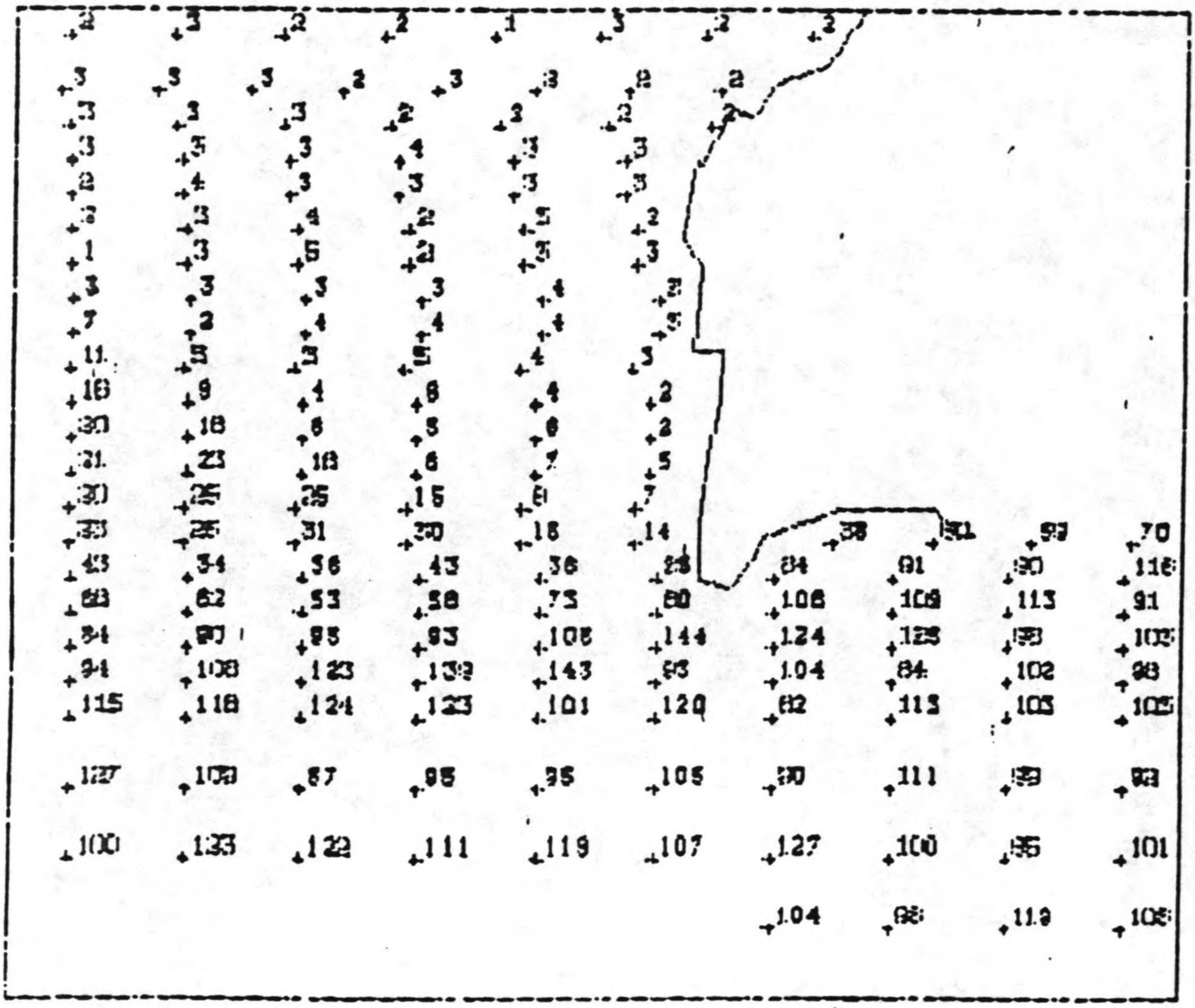
With these integral equations the source intensity functions μ and μ_0 are uniquely defined and can be solved numerically. Once the intensity functions have been found the potential at each point can be computed. For complicated harbours with many basins it is possible to split up the harbour into more areas corresponding to the basin and to express the solution in each area as a source integral over the integral over the boundaries of the area. Requirements of continuity for the normal velocity and wave height at the boundary between two areas create a set of integral equations for the unknown intensity functions μ of all basins.

C.3 SYSTEM OF LINEAR EQUATIONS.

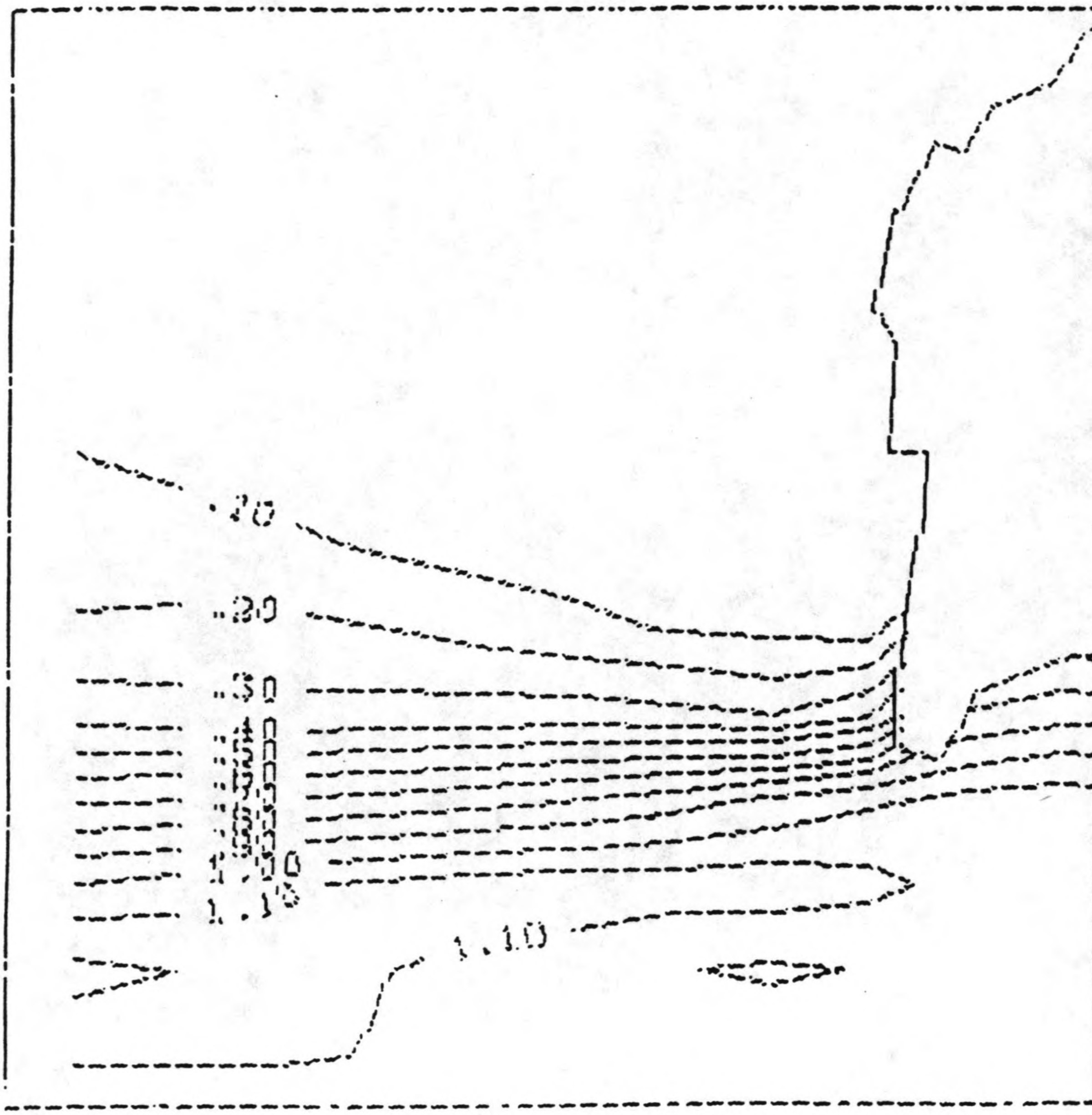
A basin consisting of n computing points at the total harbour contour and m computing points at the entrance delivers a complex system of linear equations of order n. This system is solved by the method of Gaus-elimination. The number of right hand sides of this system of linear equations is equal to the number of incident wave directions.

APPENDIX D

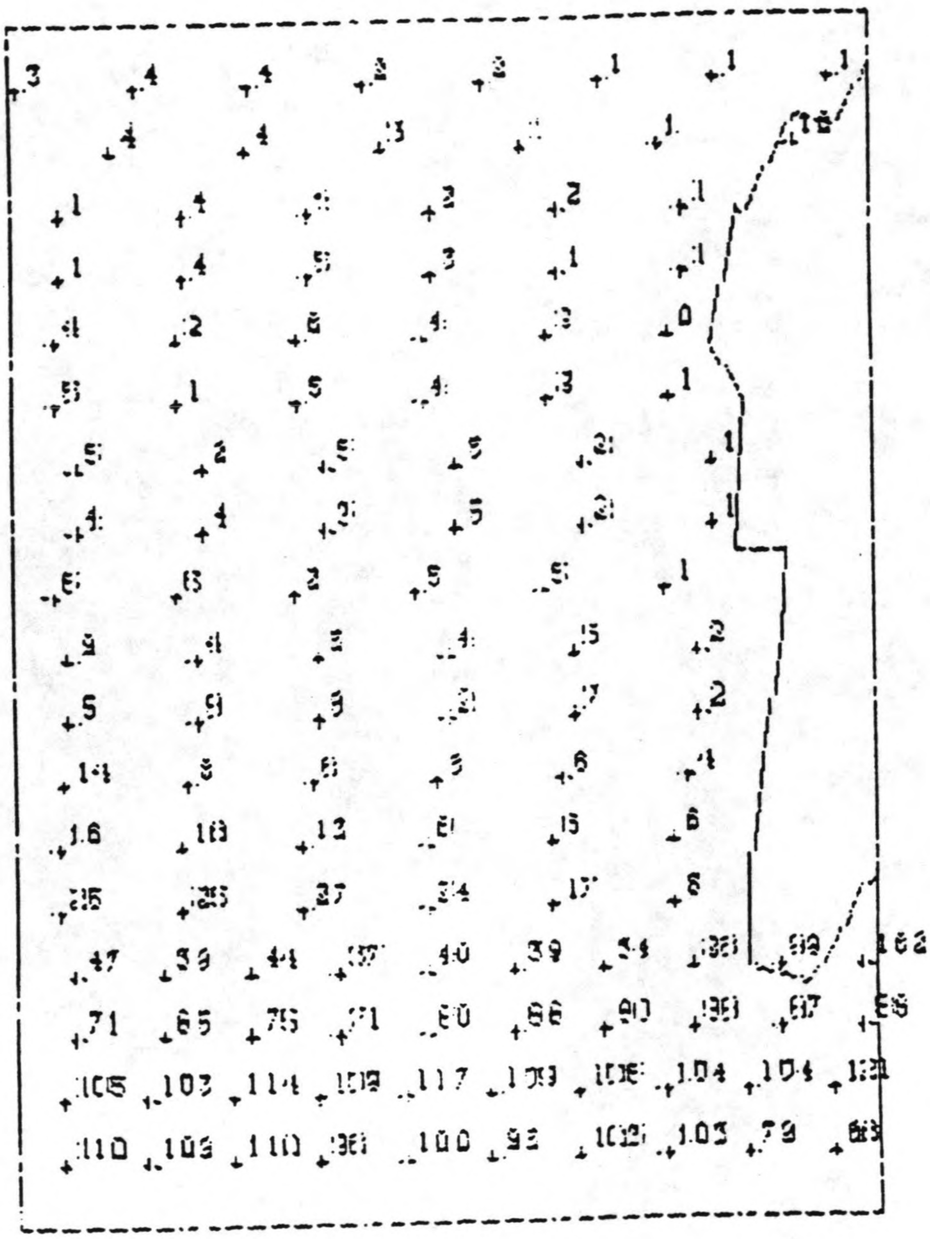
DIFFRACTION STUDY, RESULTS COMPUTATIONS.



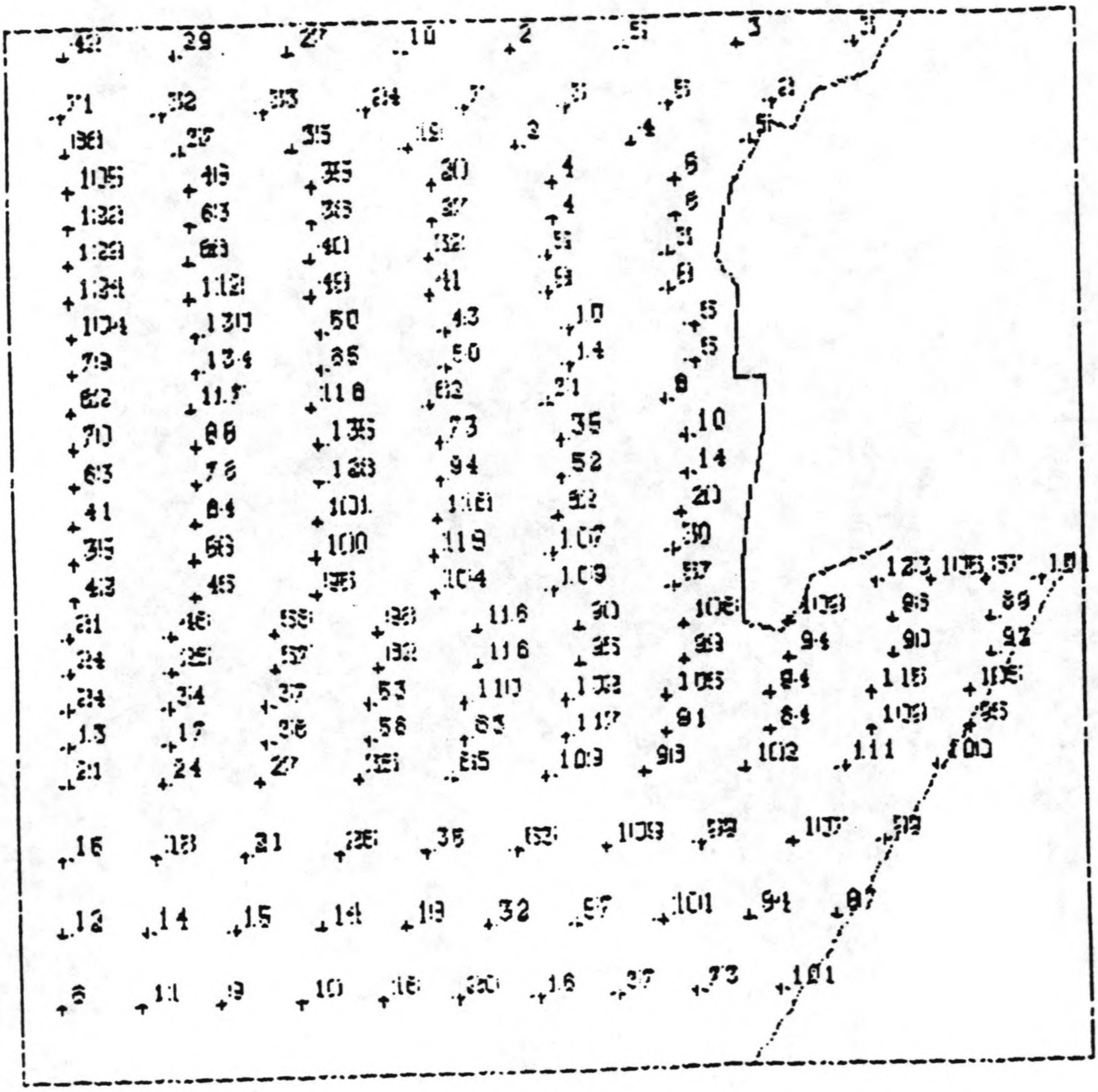
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE *0*	T = *8*	D = *90°*
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. *1*



ST. MAARTEN HARBOUR	T = 8	D = 90
DIFFRACTION STUDY ALTERNATIVE 0	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 2



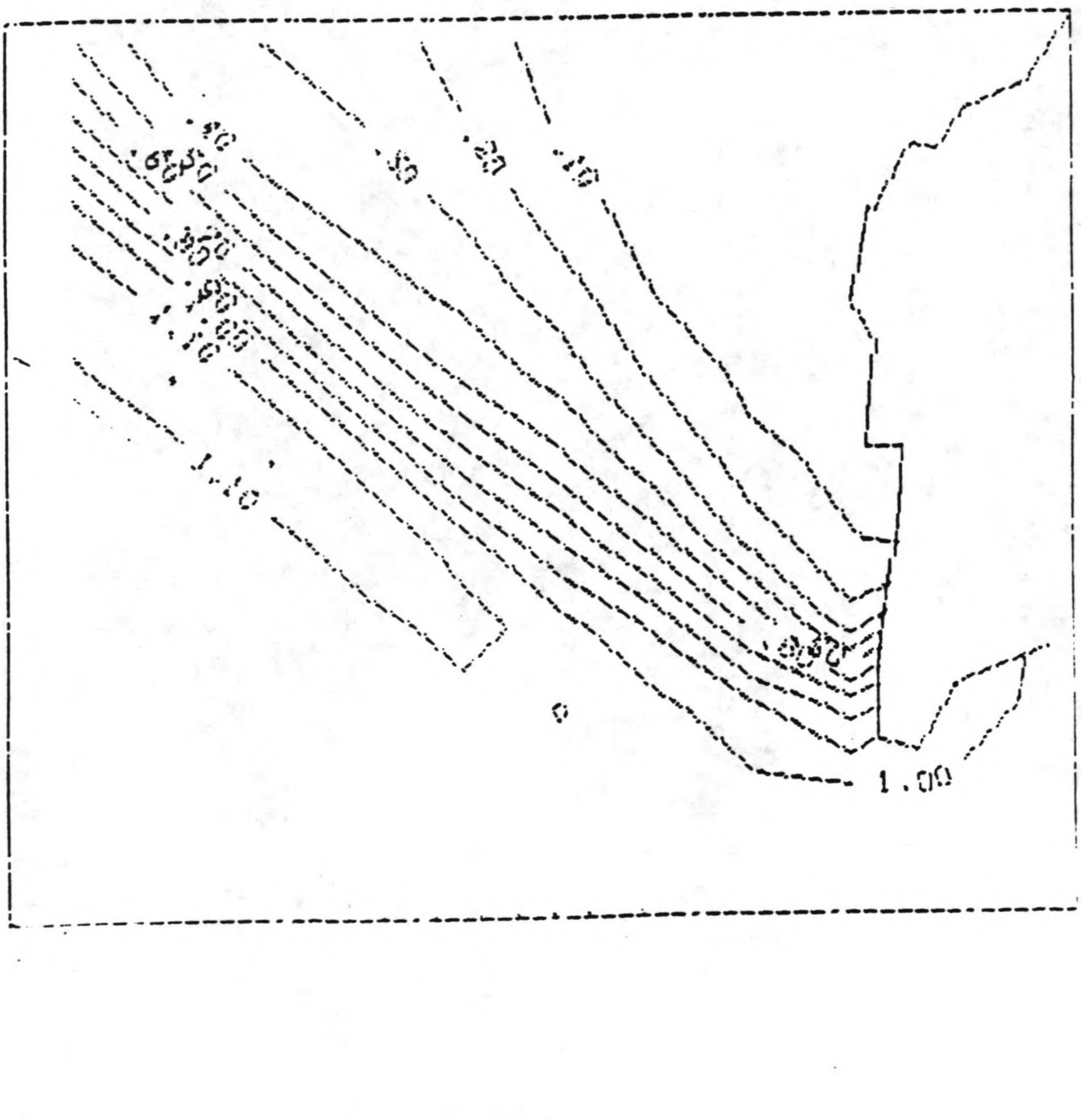
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE O	T = 5	D = 90
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 3



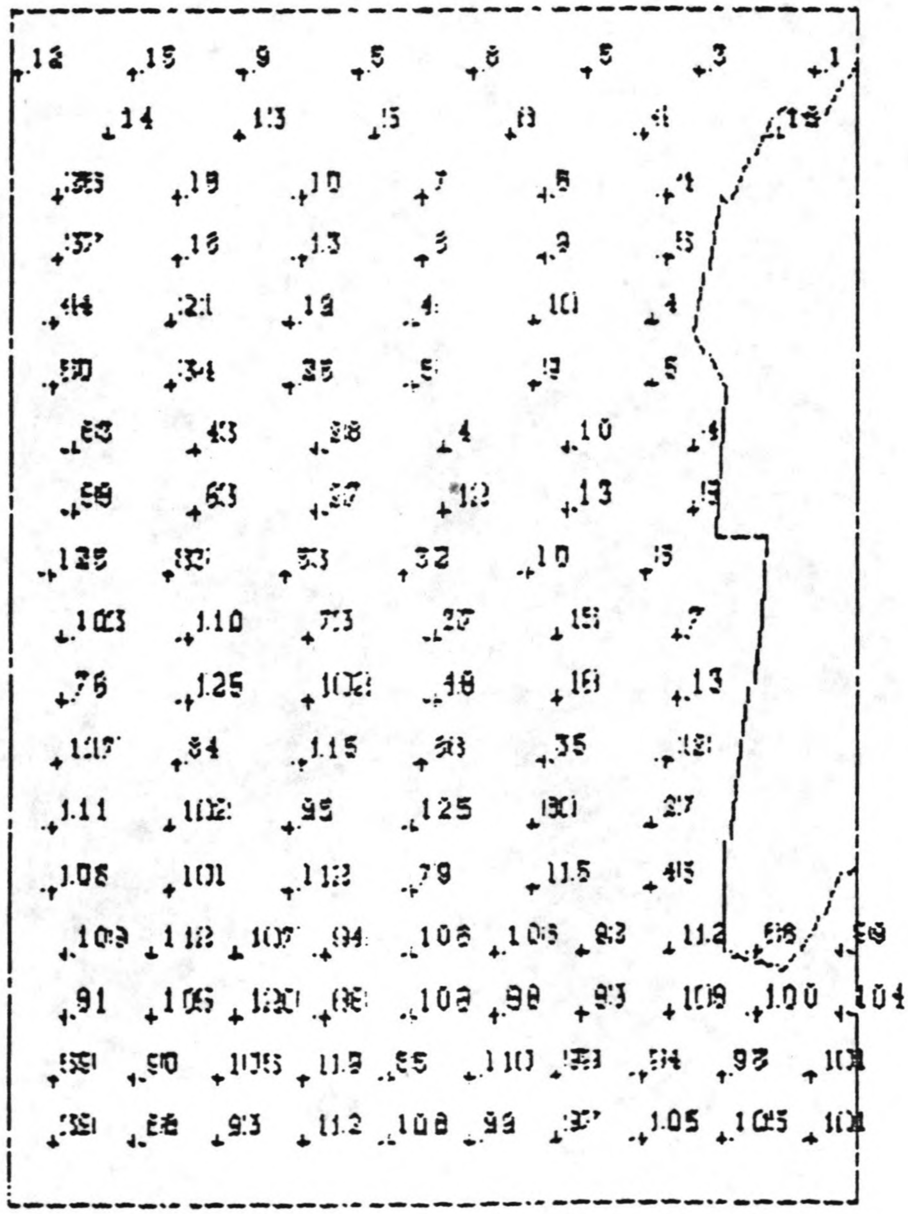
ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE O

T = 8	D = 135
SCALE: DISTORTED	
7810.2	FIG. 4

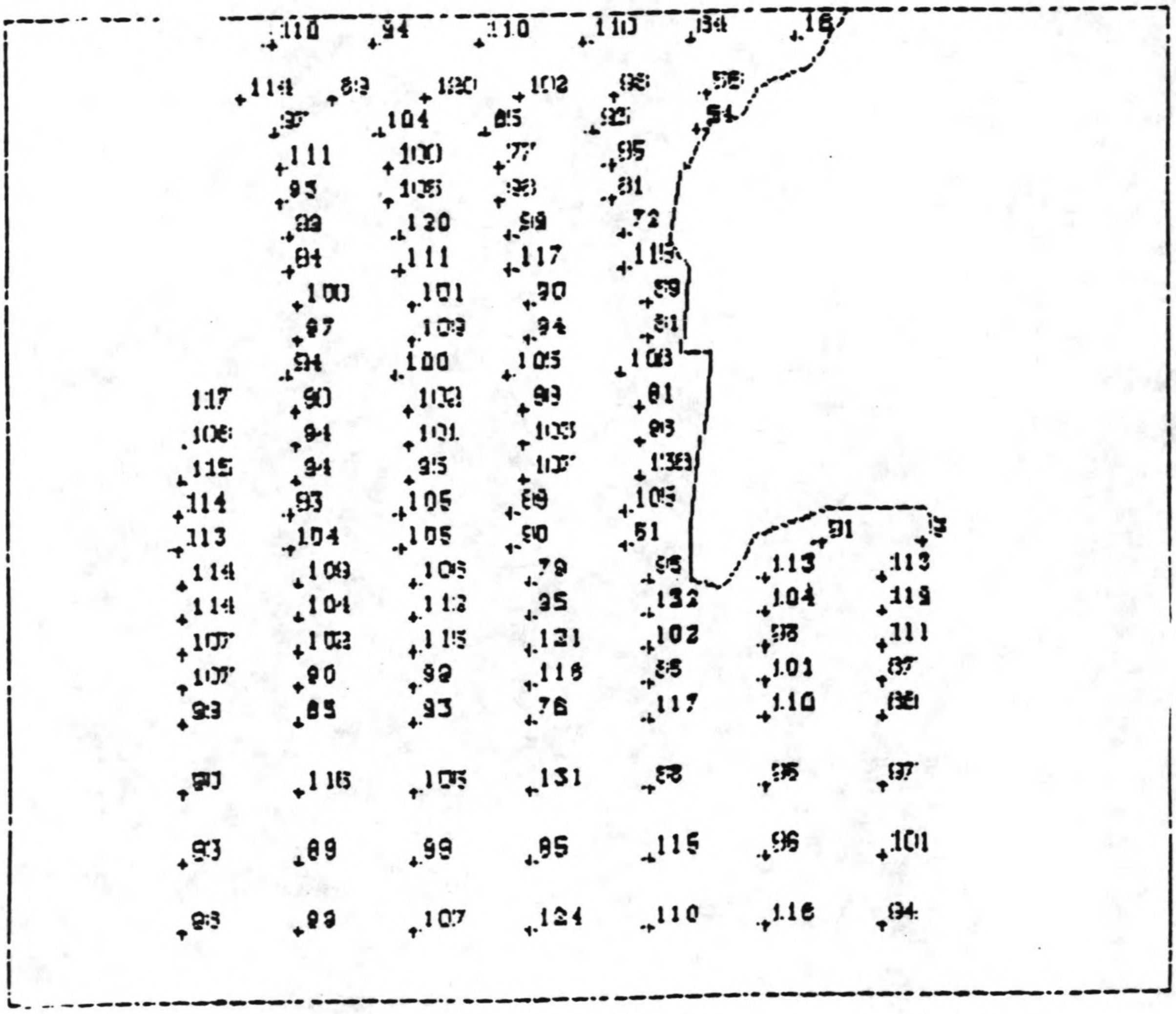
Grabowsky&Poort BV, Consulting Engineers



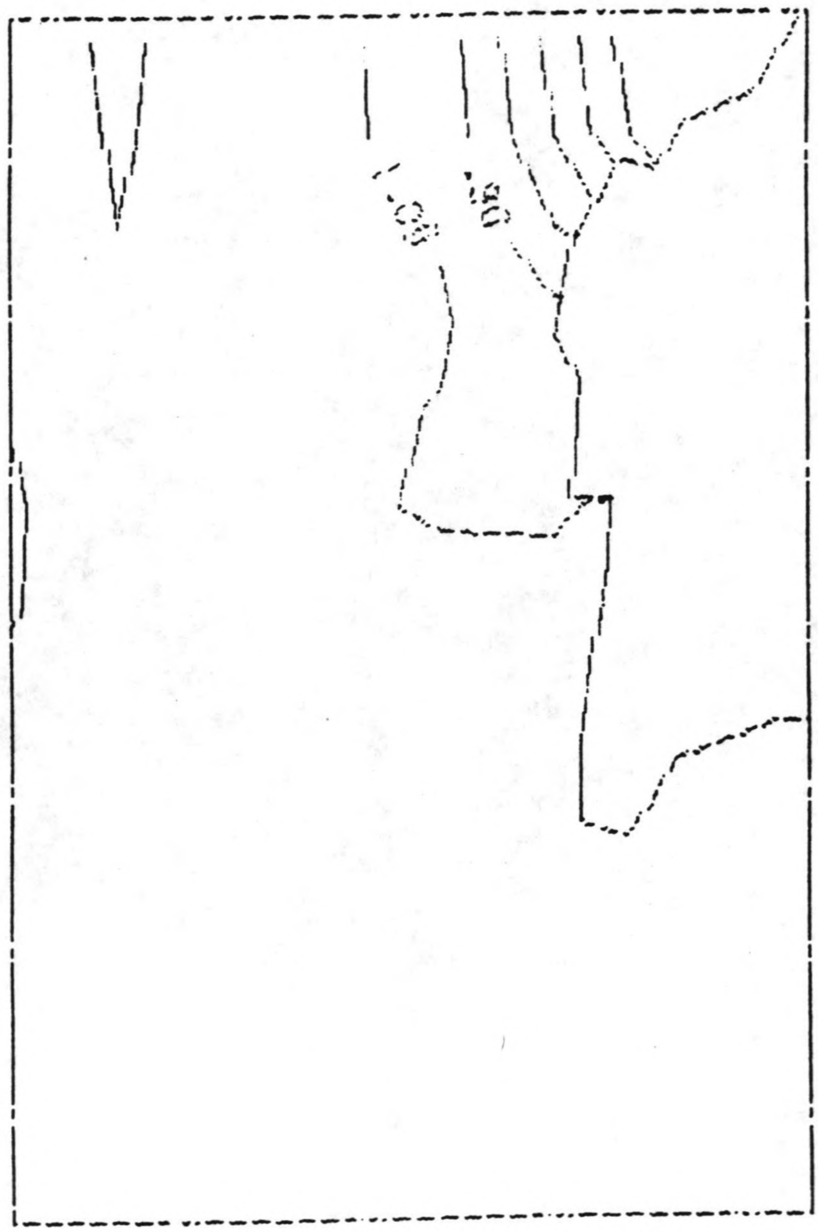
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE O	T = 8	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 5



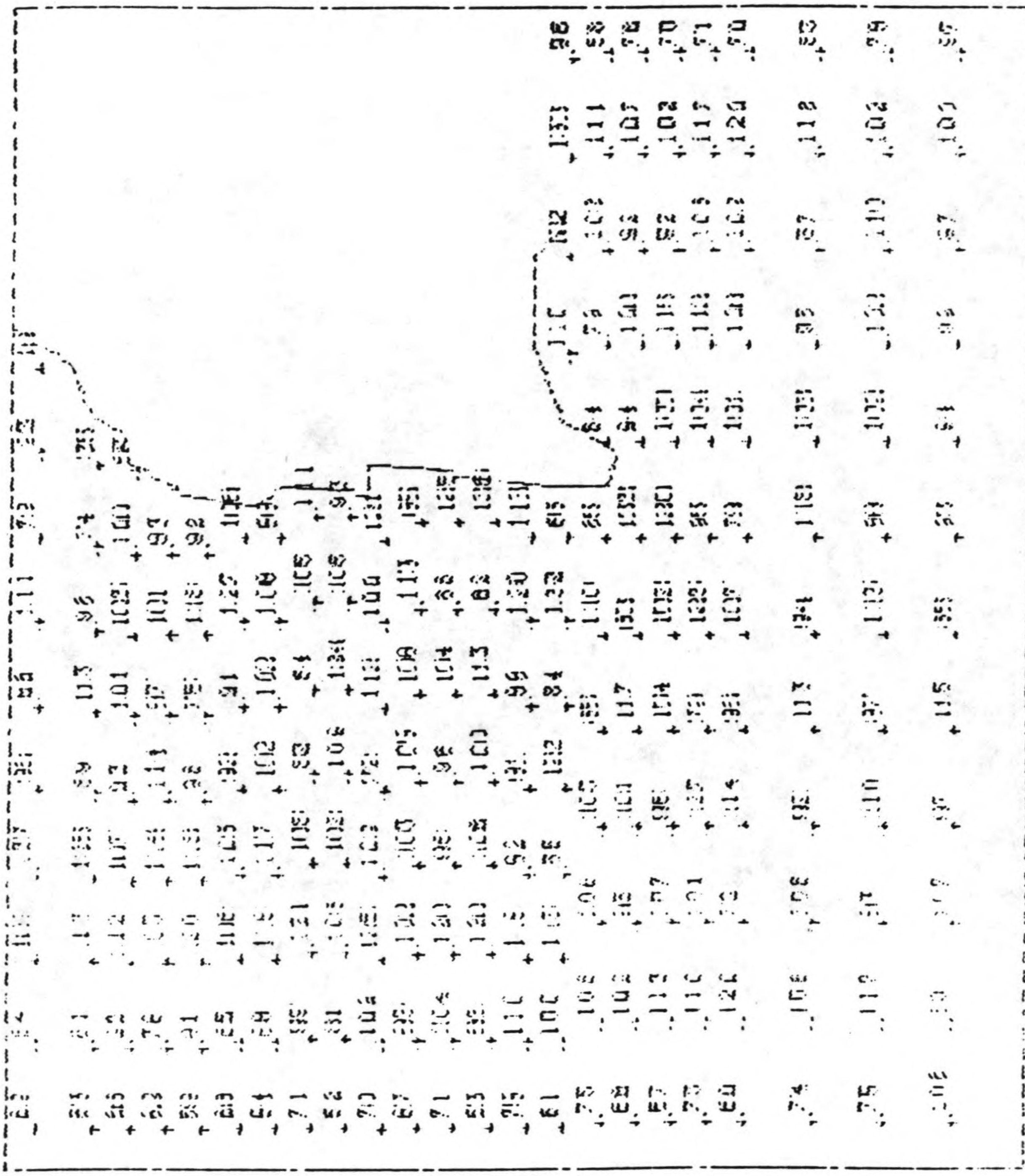
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE O	T = 5	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 6



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE O	T = 8	D = 180°
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 7



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE O	T = 8	D = 180
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 8

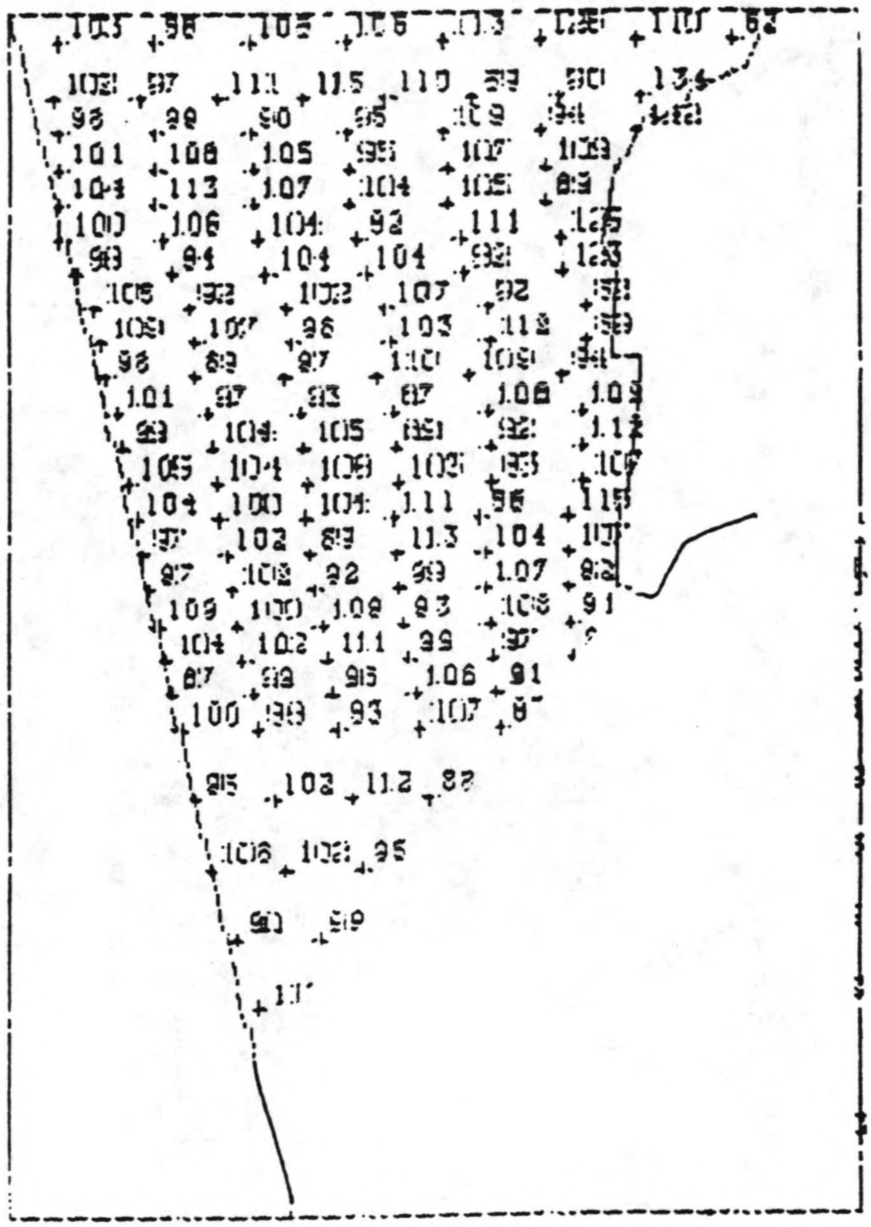


ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE O

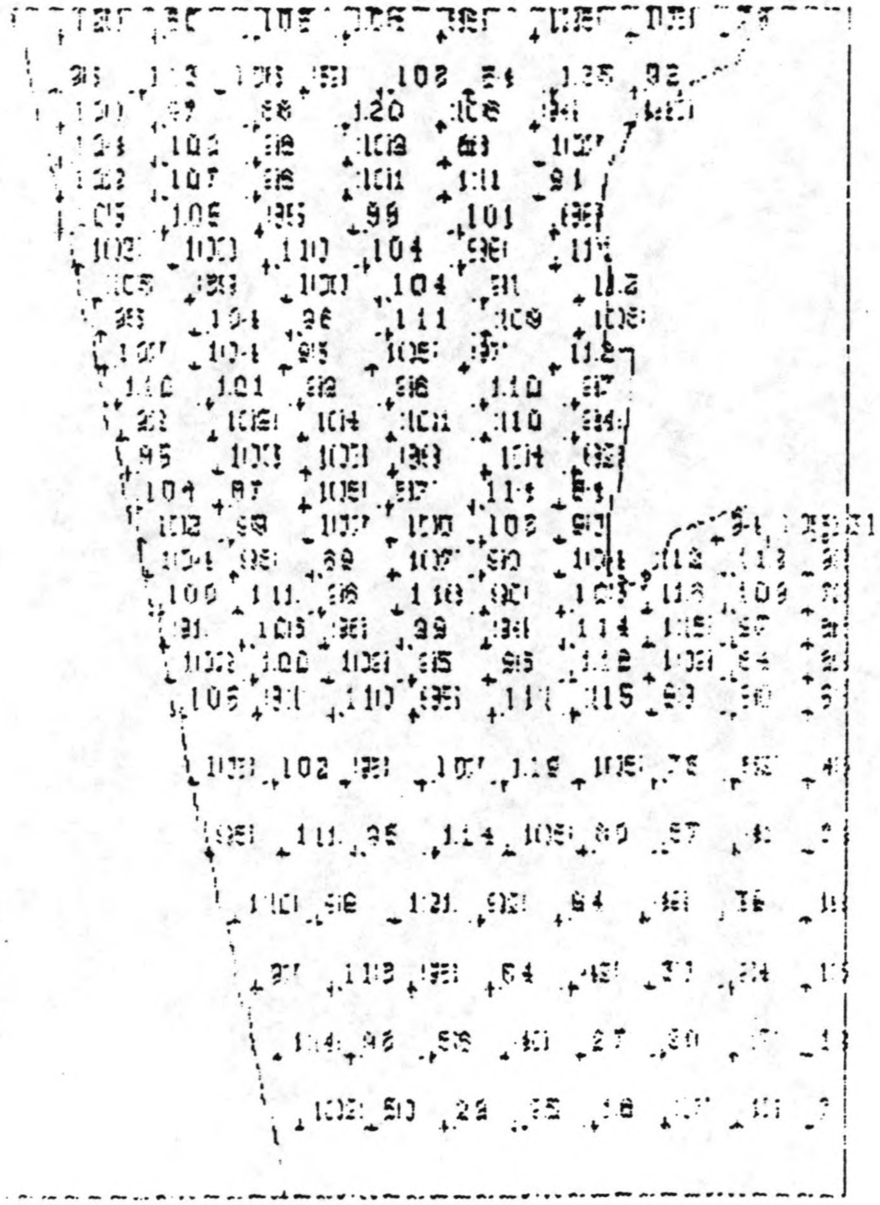
T = 12 | D = 180

SCALE: DISTORTED

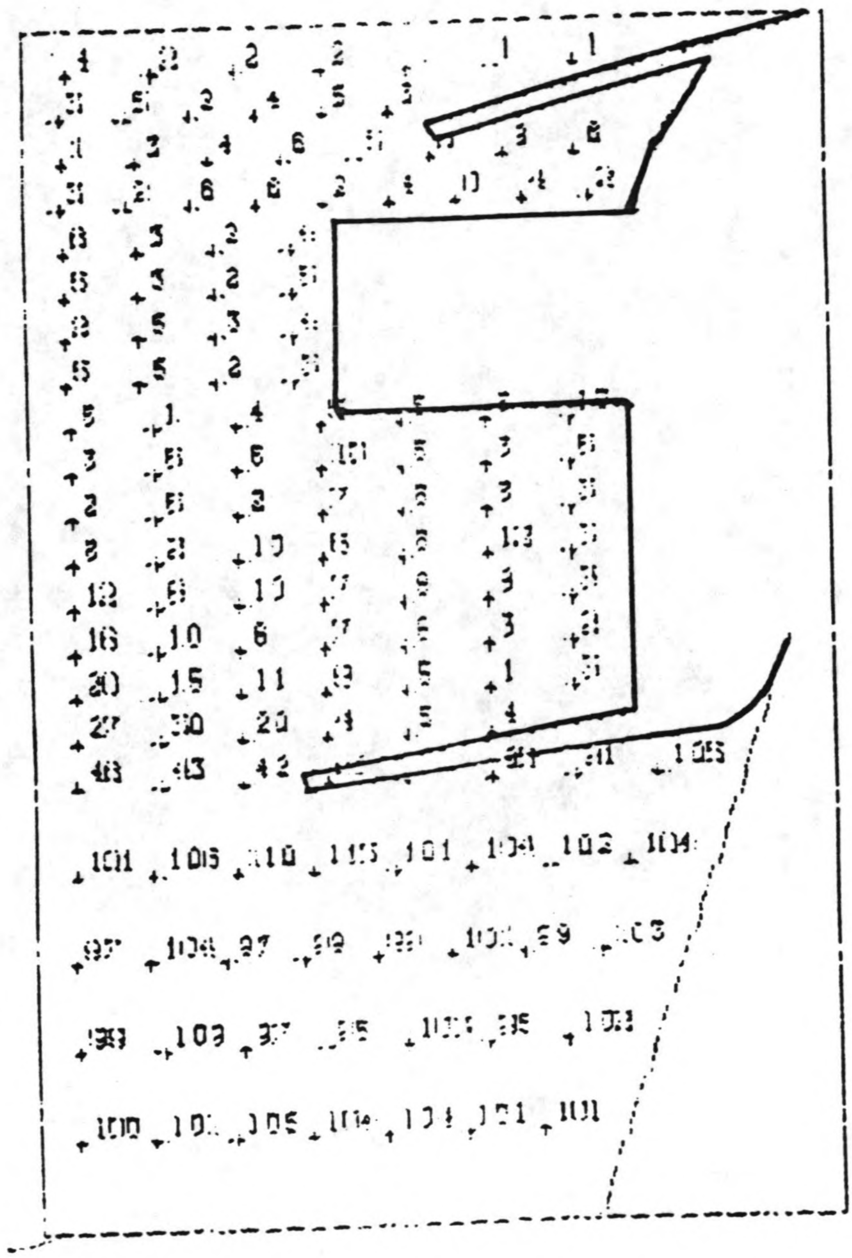
Grabowsky&Poort BV, Consulting Engineers | 7810.2 | FIG. 9



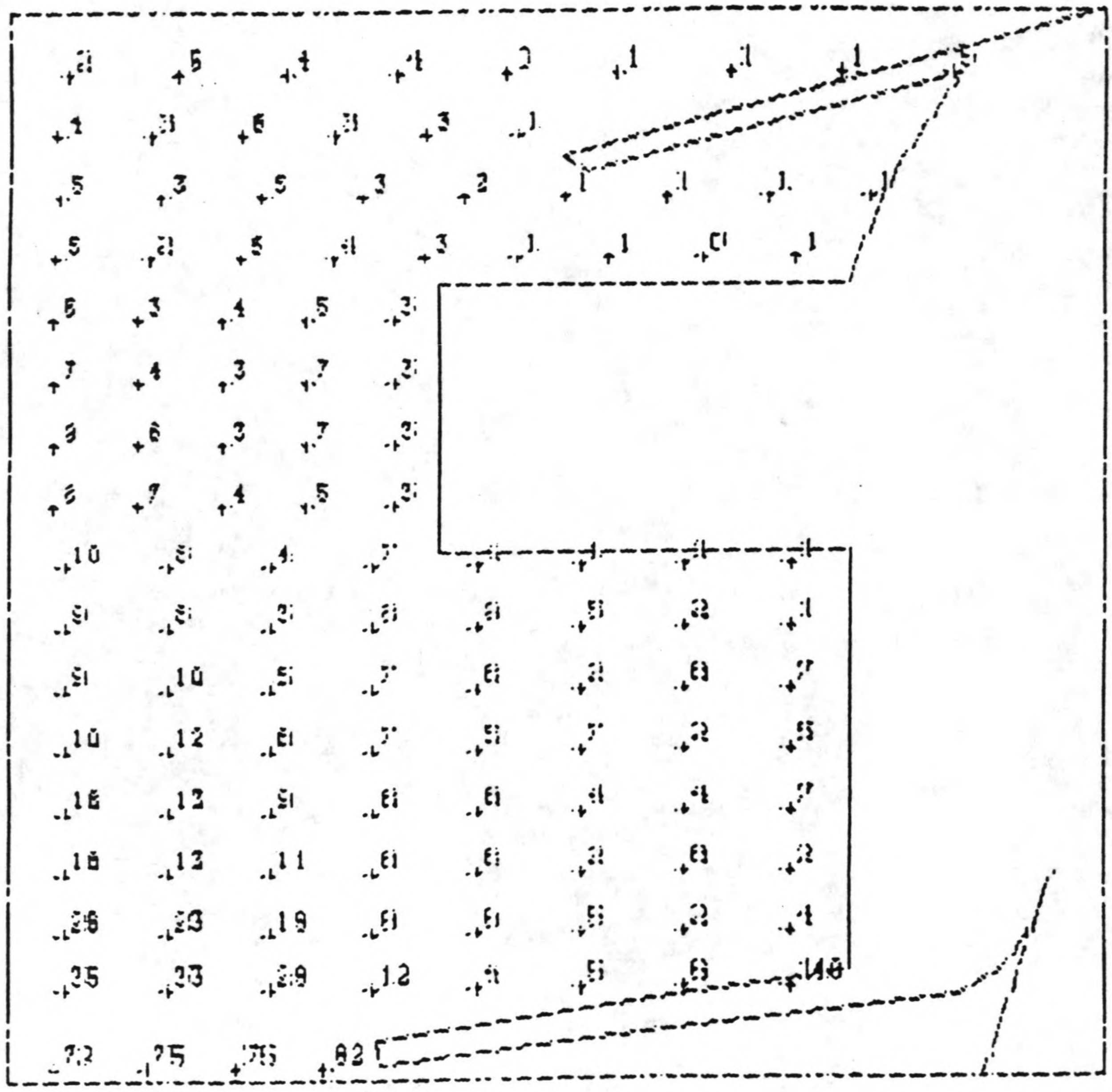
ST. MAARTEN HARBOUR	T = 9	D = 225
DIFFRACTION STUDY ALTERNATIVE 0	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 10



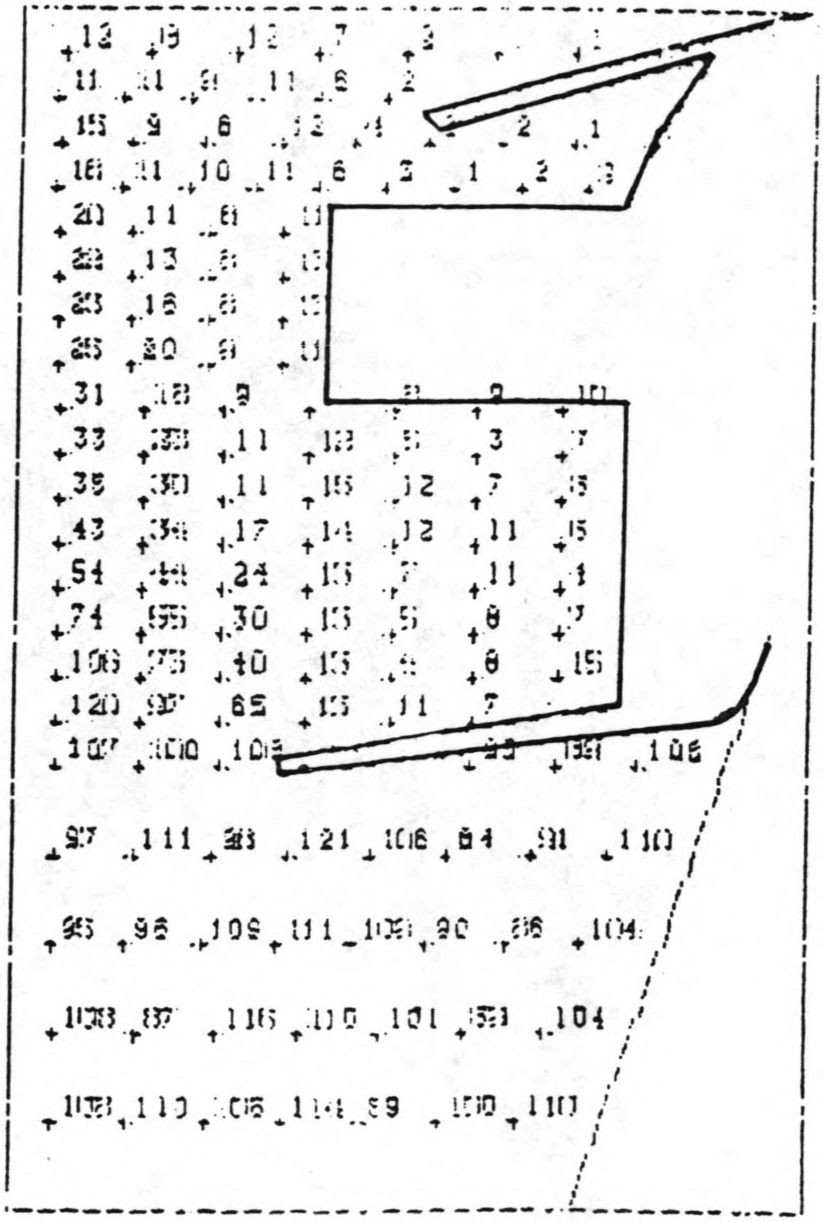
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE 0	T = 12	D = 225
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 11



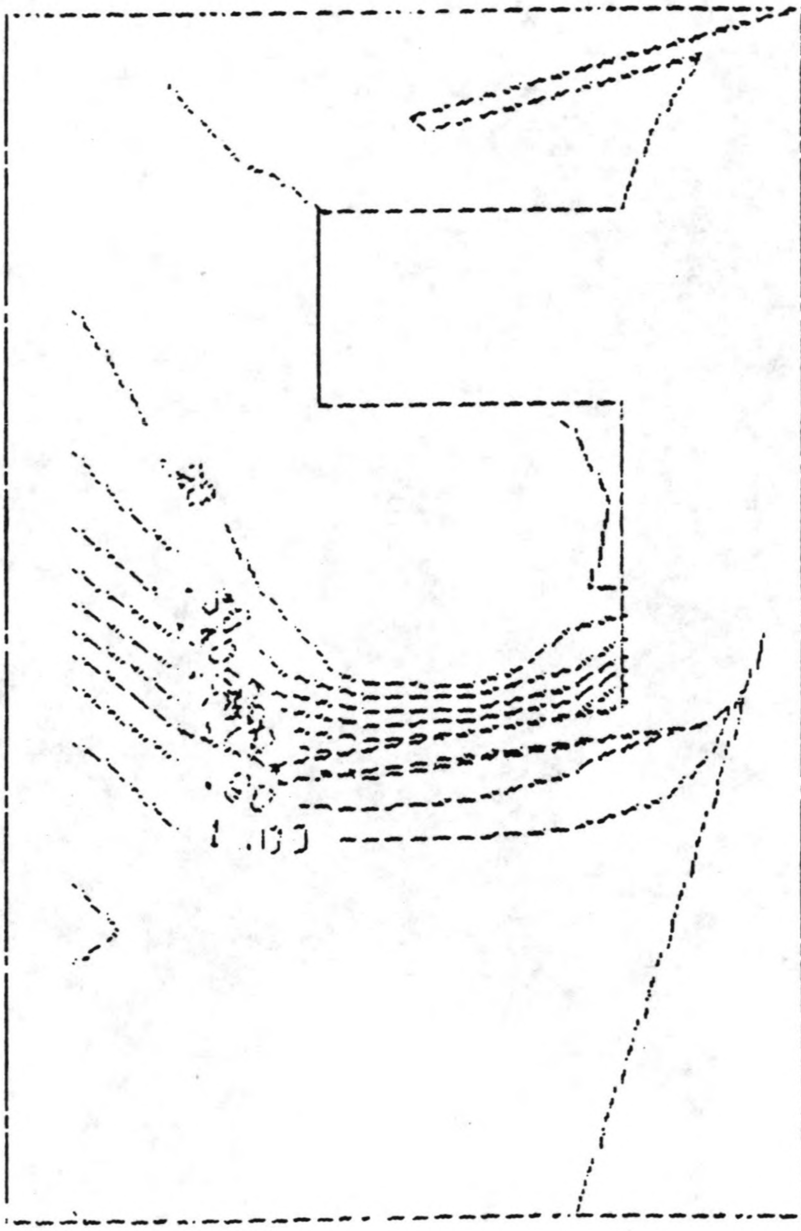
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 8	D = 90
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 31.



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 5	D = 90
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 32



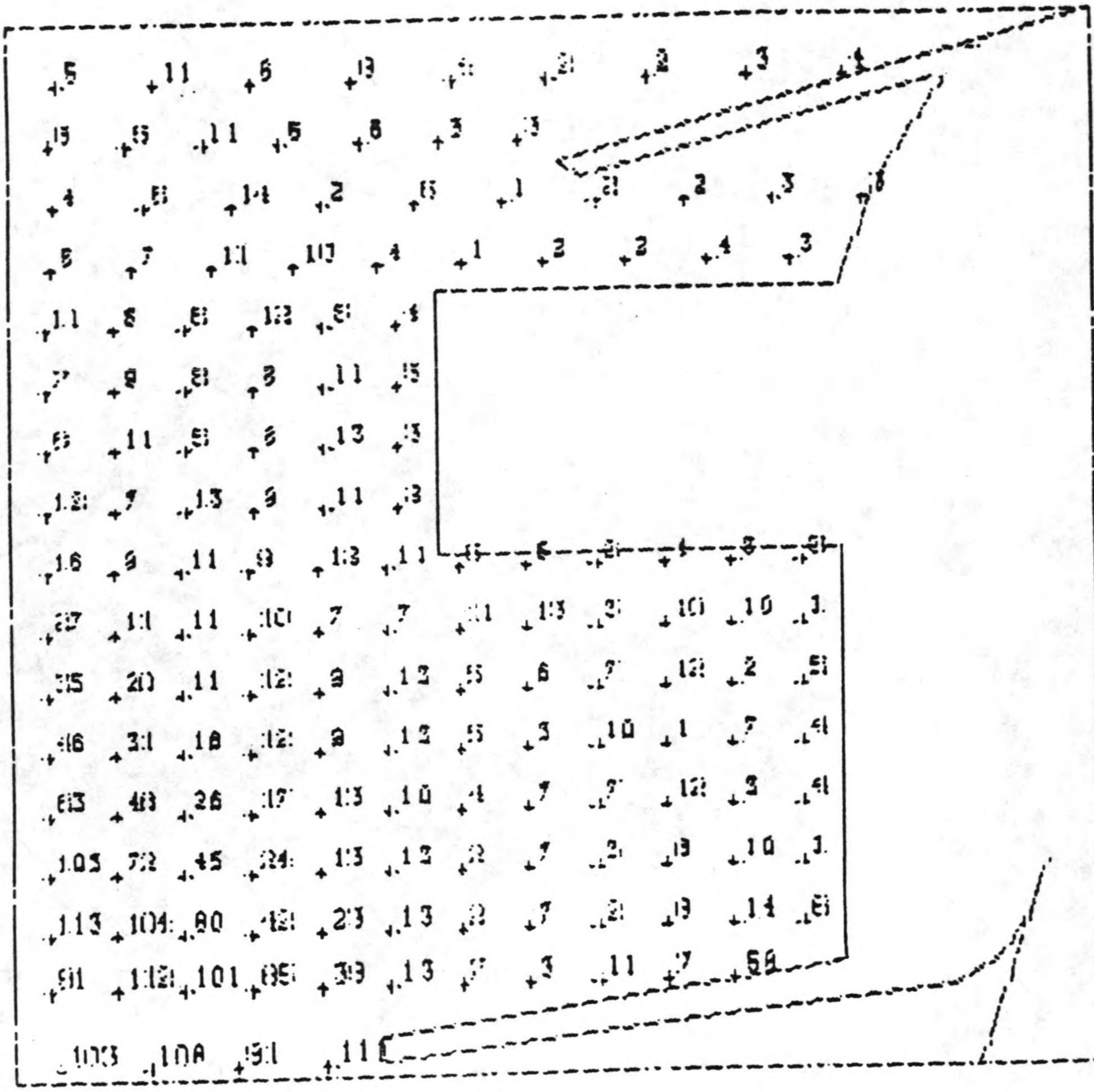
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 8	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 33



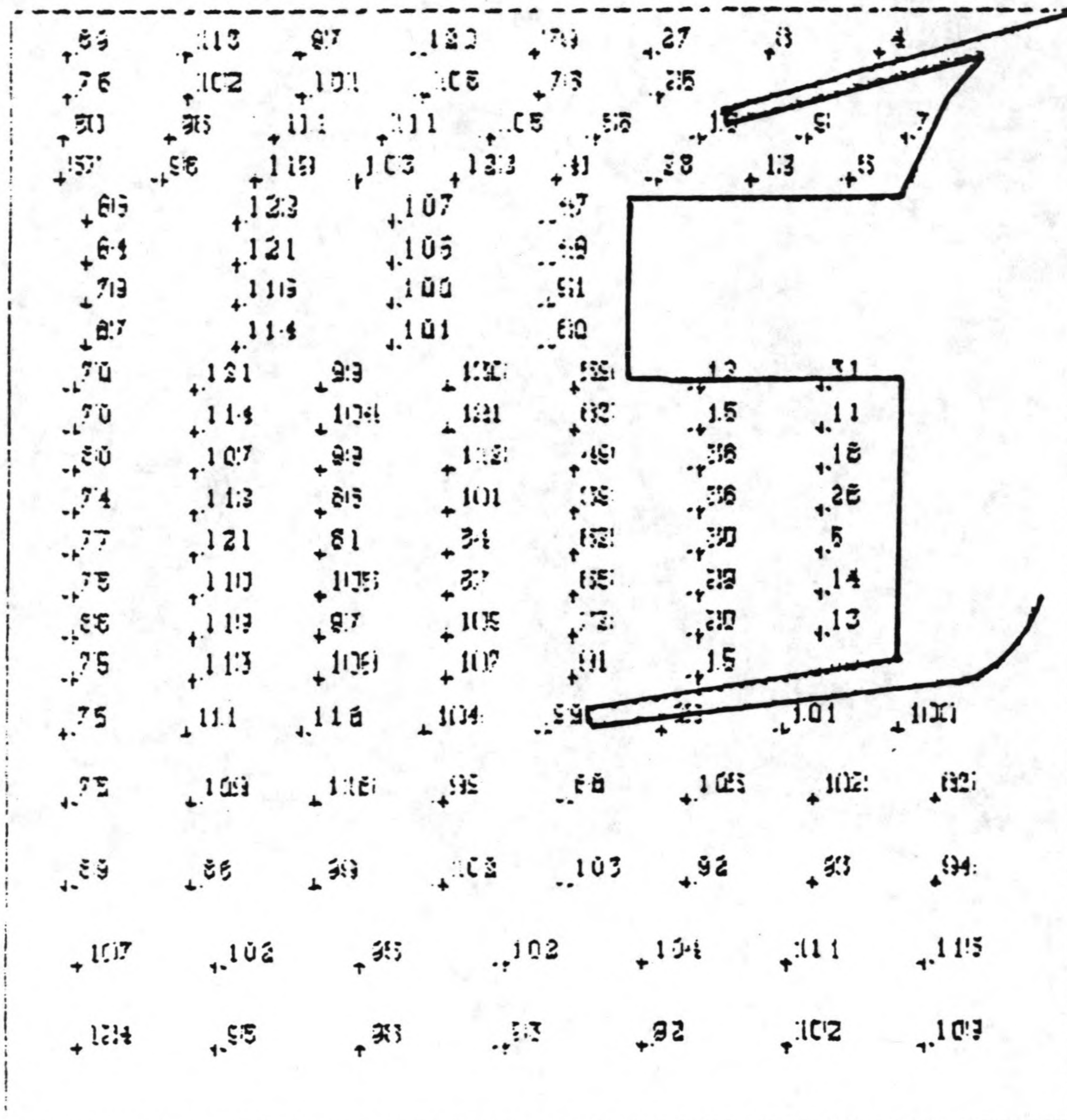
ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE G

T = 8	D = 135
SCALE: DISTORTED	
7810.2	FIG. 34

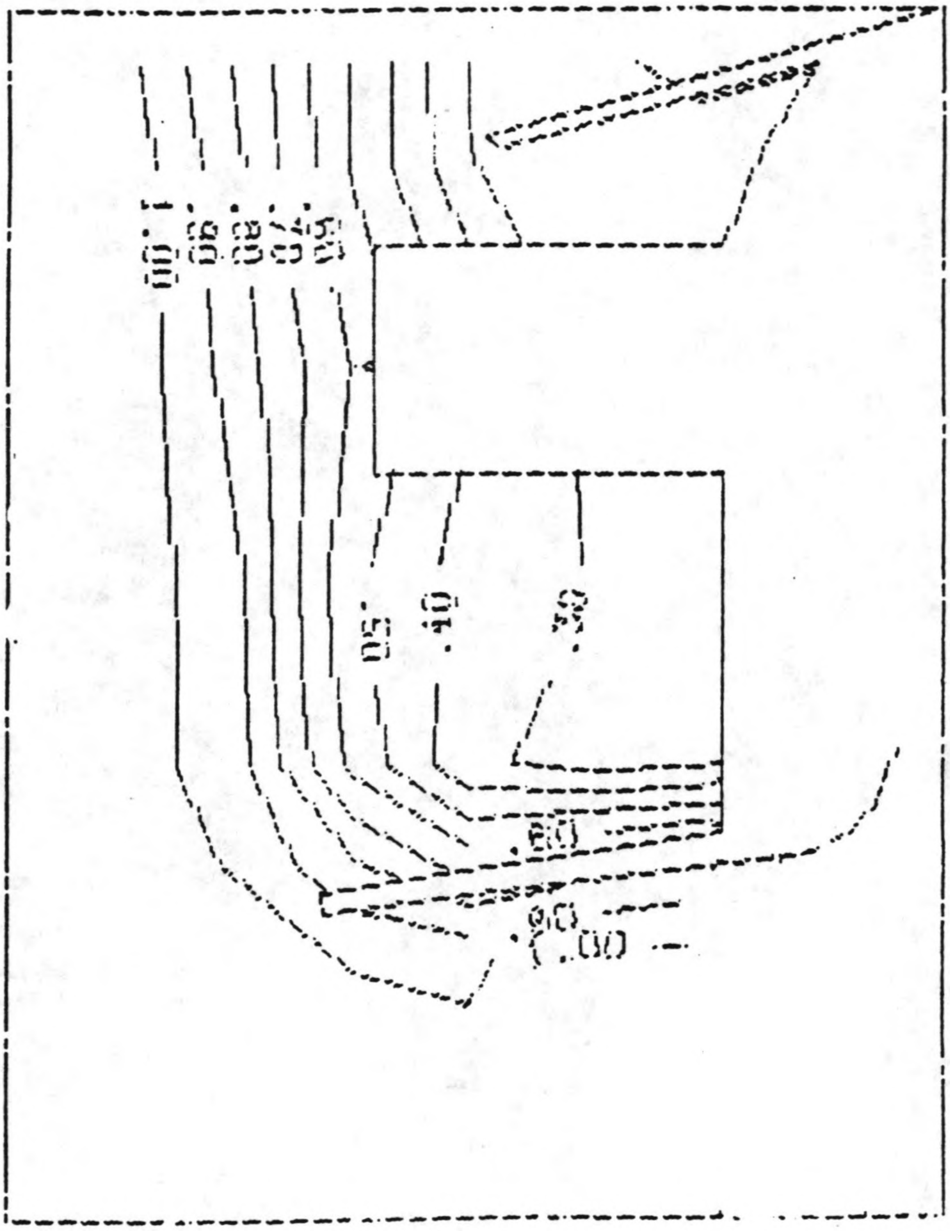
Grabowsky&Poort BV, Consulting Engineers



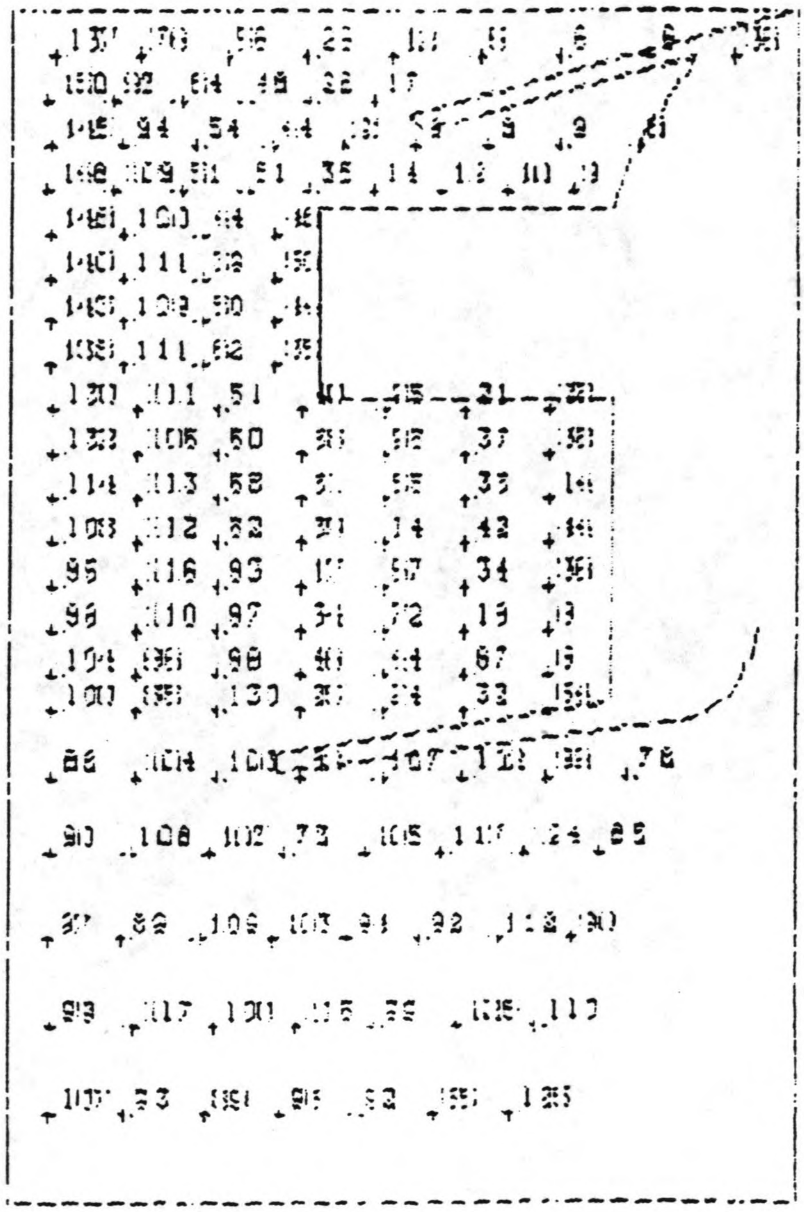
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 5	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 35



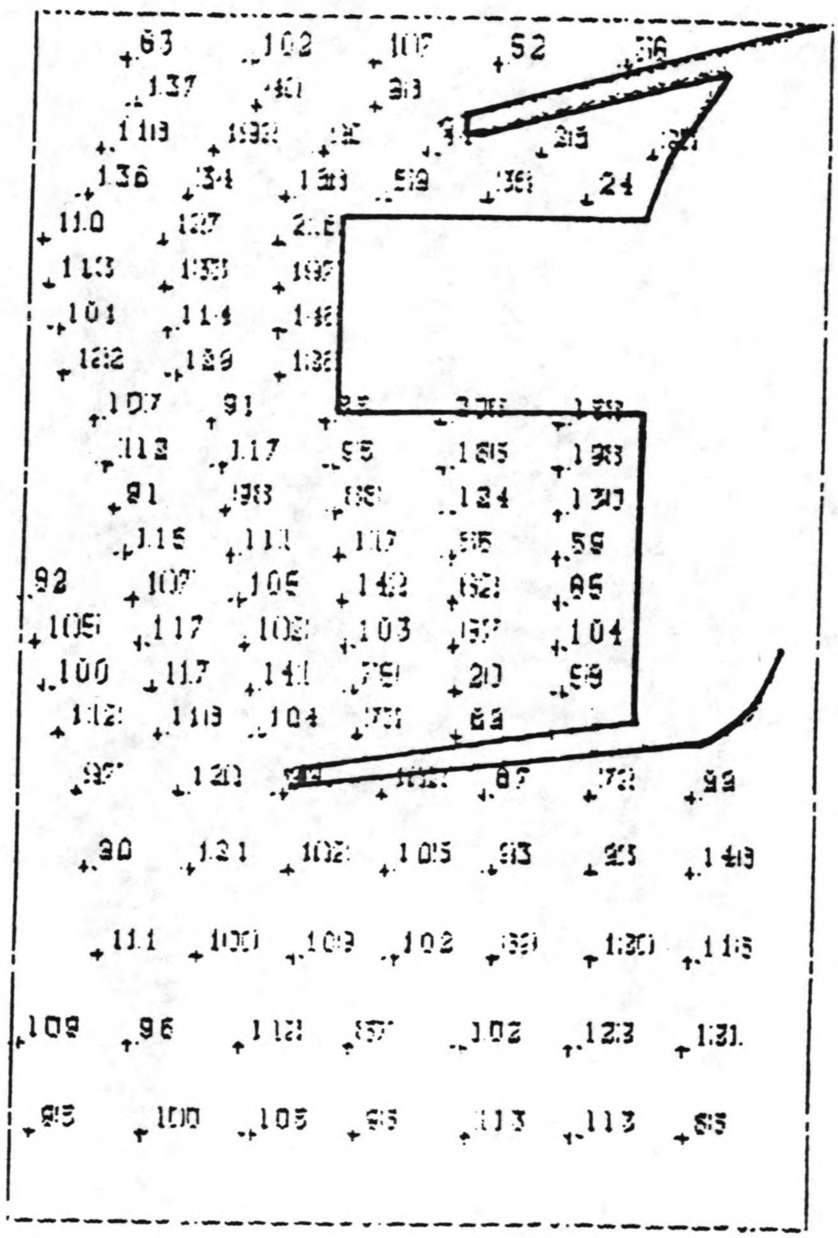
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 8	D = 180
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 36



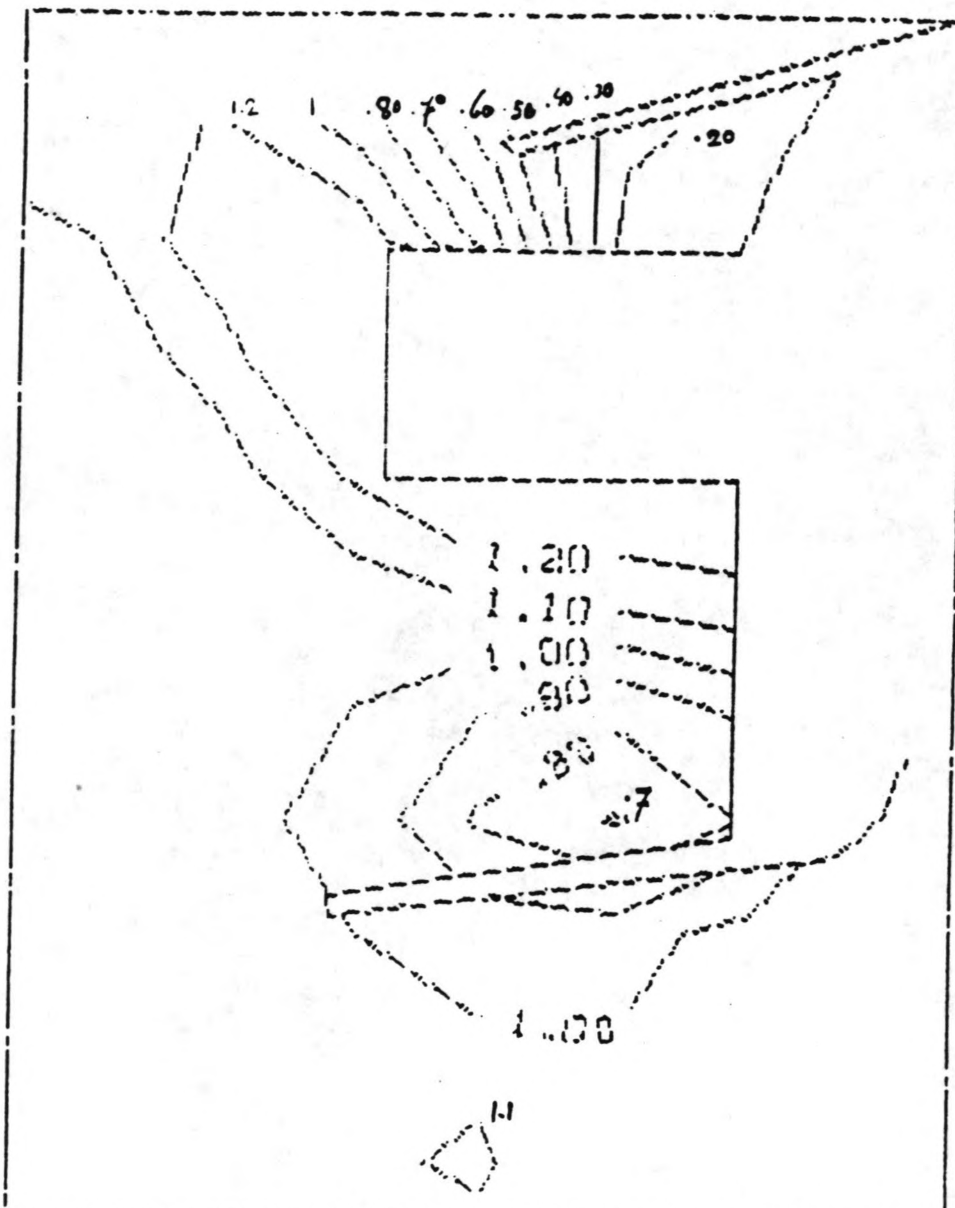
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 8	D = 180
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 37



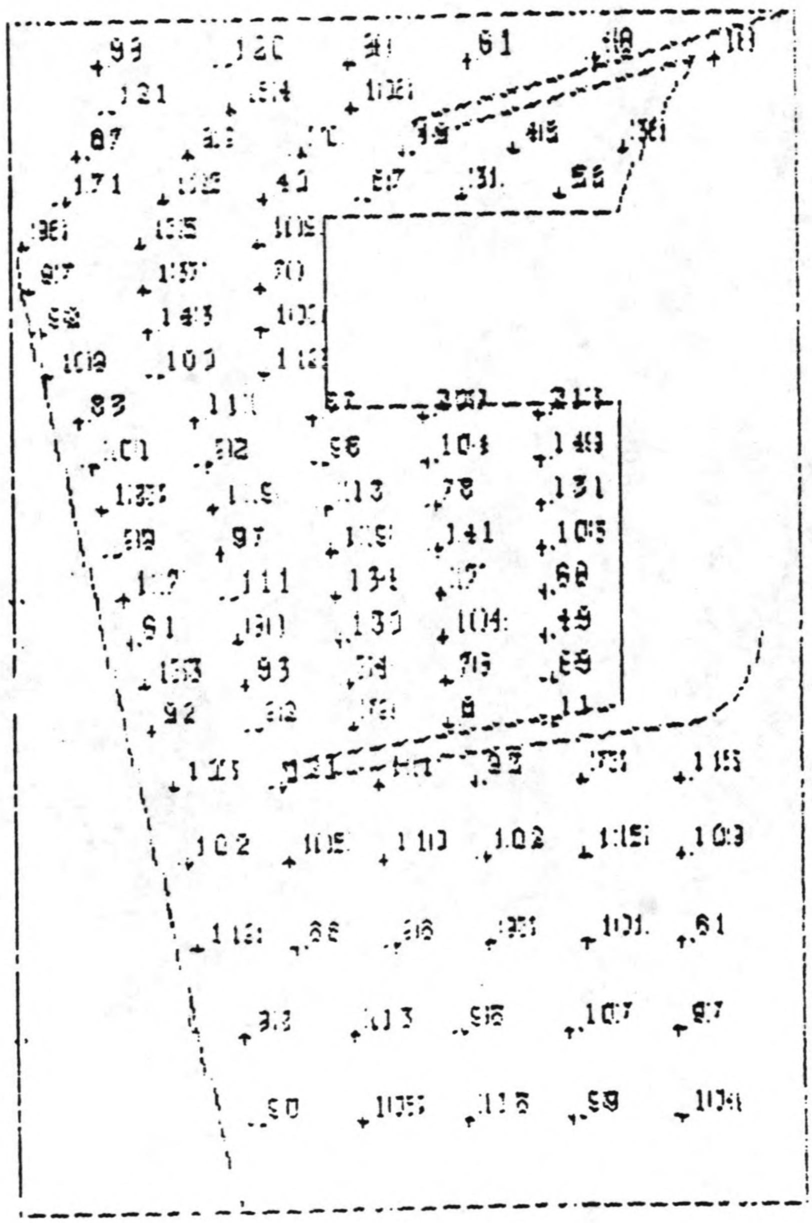
ST. MAARTEN HARBOUR	T = 12	D = 180
DIFFRACTION STUDY ALTERNATIVE G	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 38



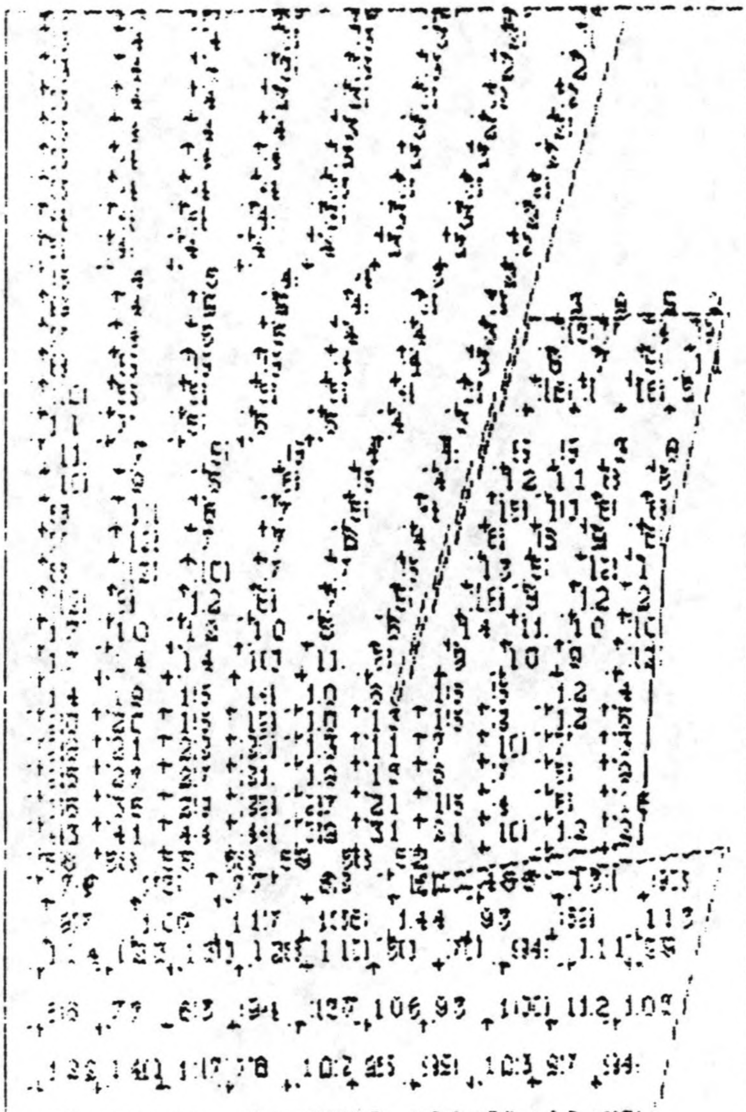
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 9	D = 225
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 39



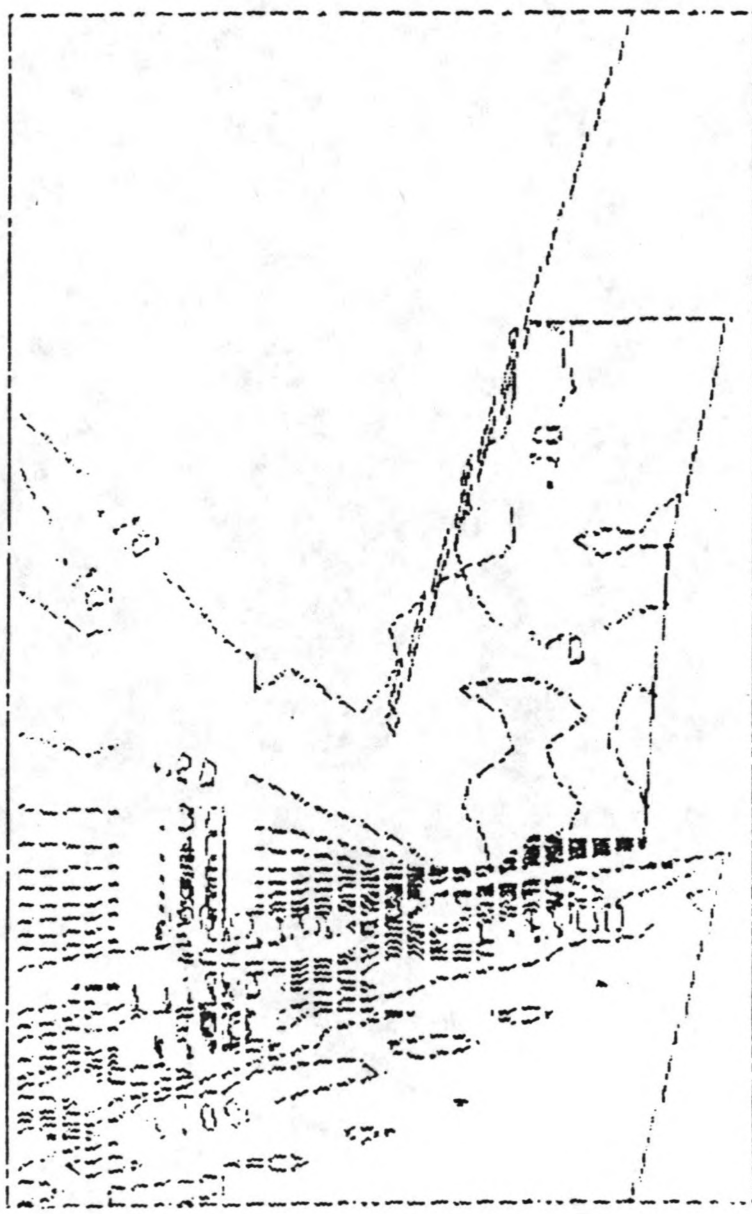
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 9 | D = 225 SCALE: DISTORTED
Grabowsky&Poort BV, Consulting Engineers	7810.2 | FIG. 40



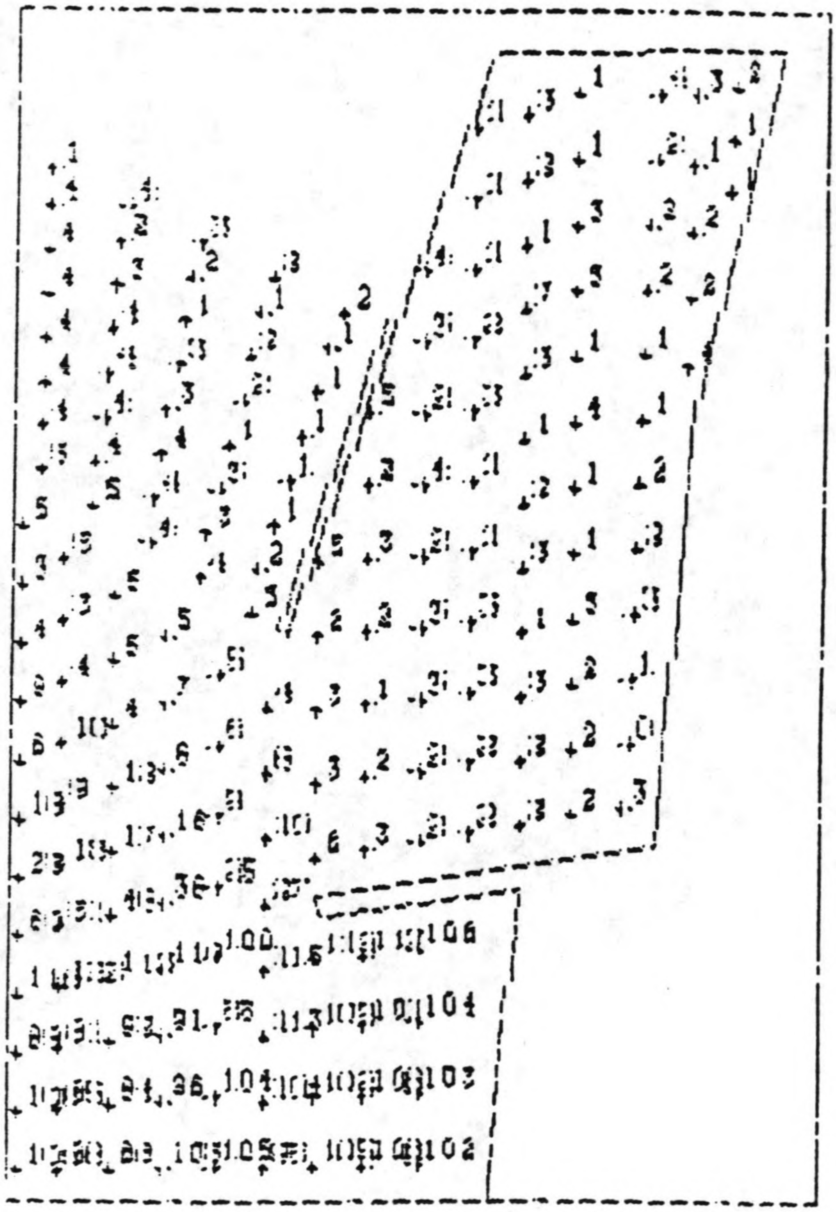
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE G	T = 12	D = 225
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 41



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2	T = 8	D = 90
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 48



ST. MAARTEN HARBOUR	T = 8	D = 90
DIFFRACTION STUDY ALTERNATIVE D 2	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 49

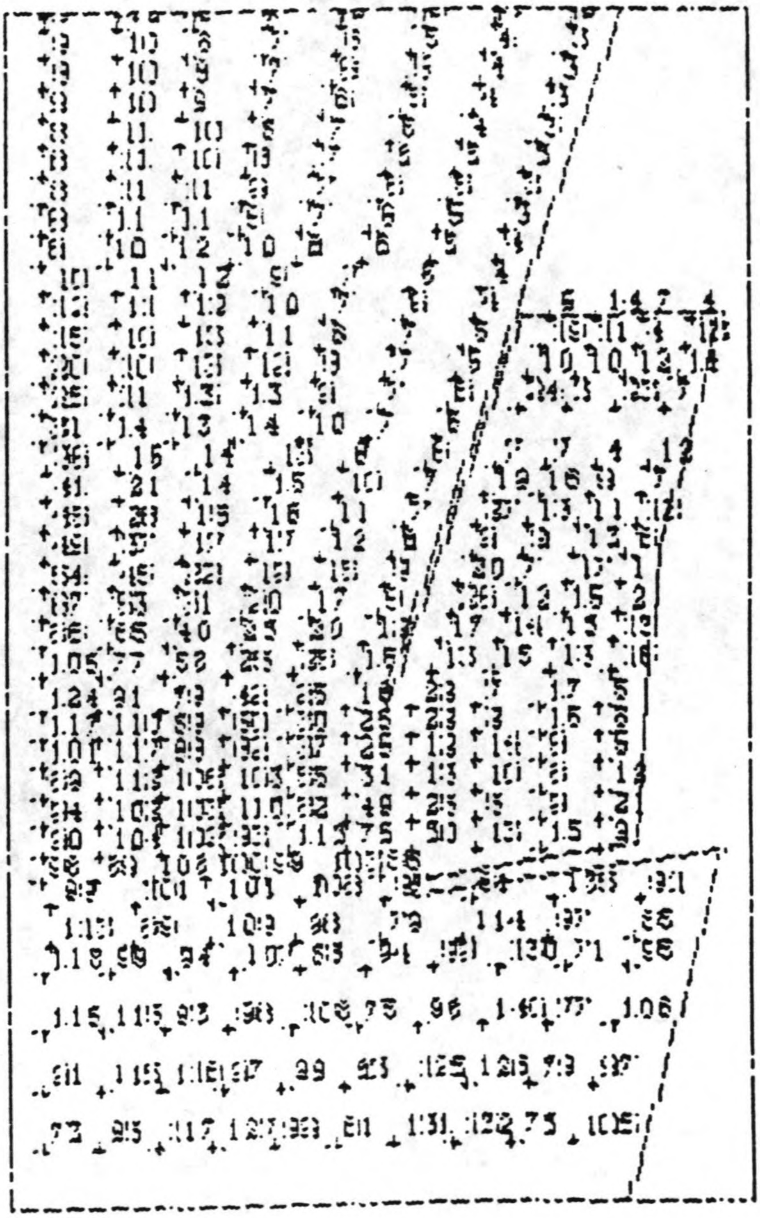


ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE D2

T = 5 | D = 90

SCALE: DISTORTED

Grabowsky&Poort BV, Consulting Engineers | 7810.2 | FIG. 50

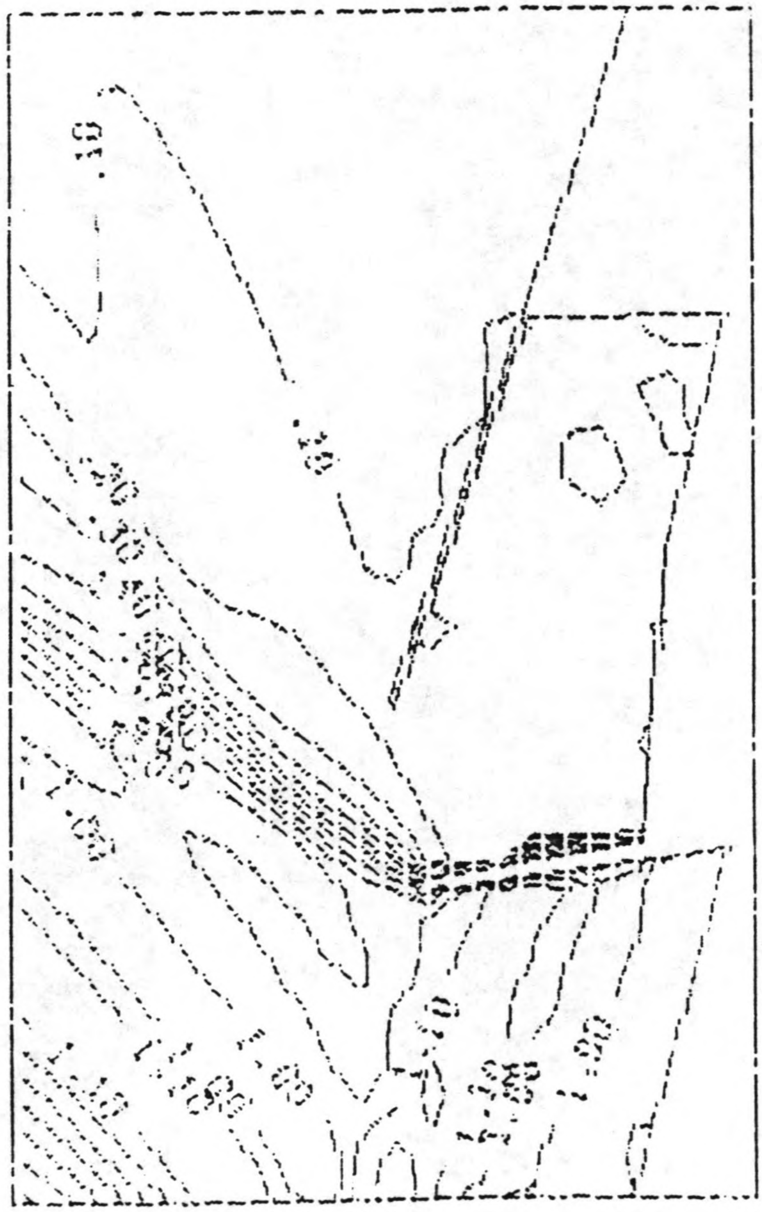


ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE D2

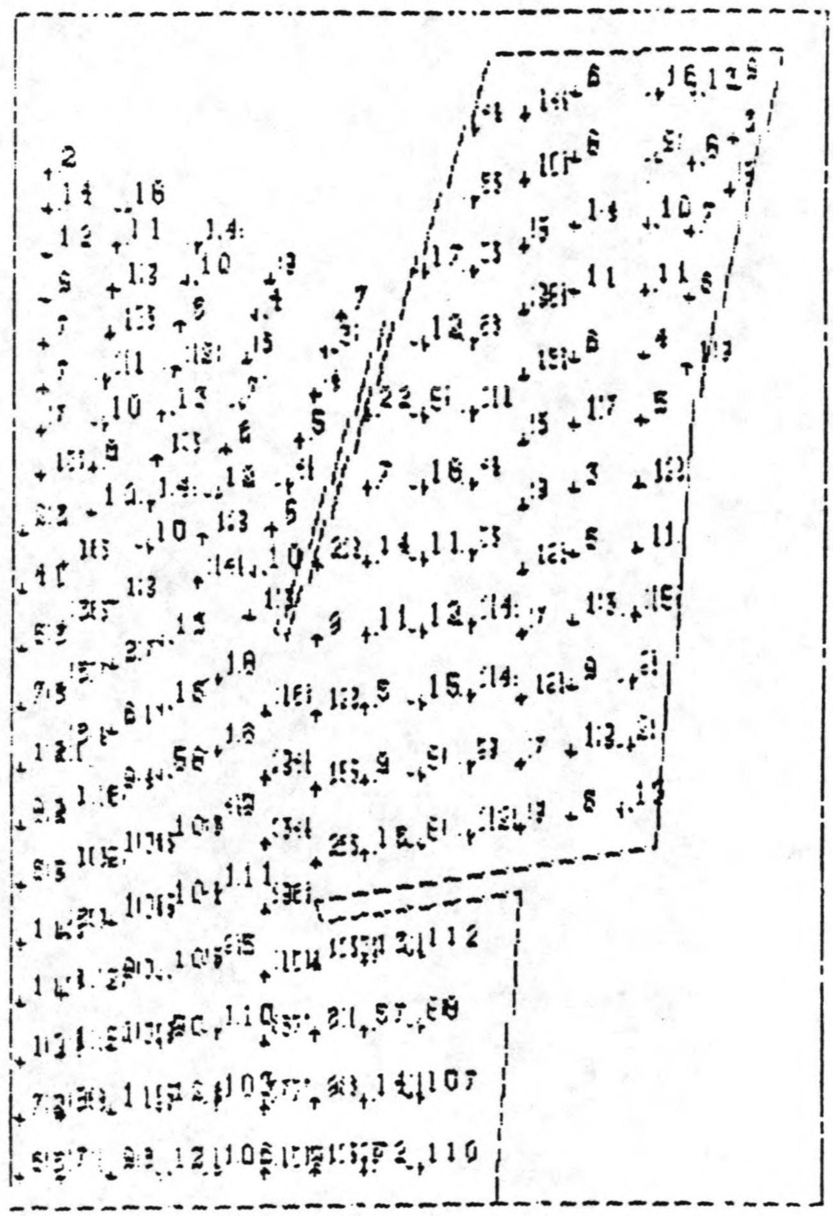
T = 8 | D = 135

SCALE: DISTORTED

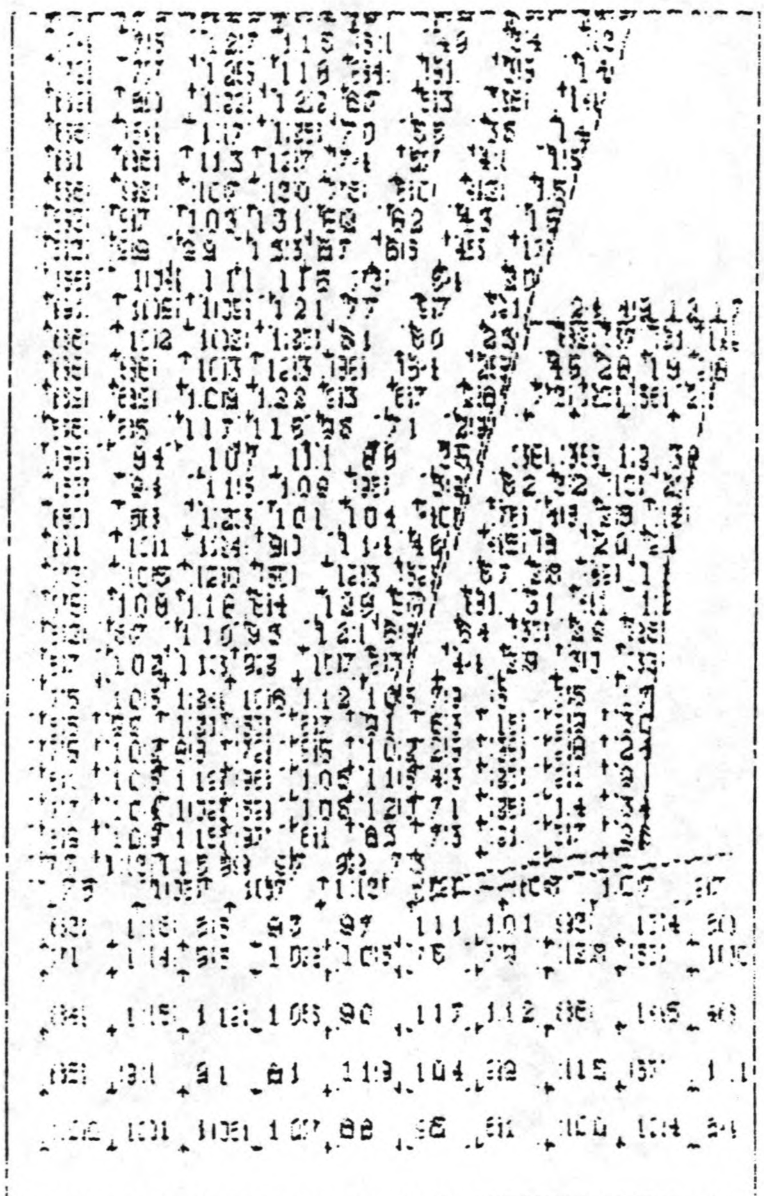
Grabowsky&Poort BV, Consulting Engineers | 7810.2 | FIG. 51



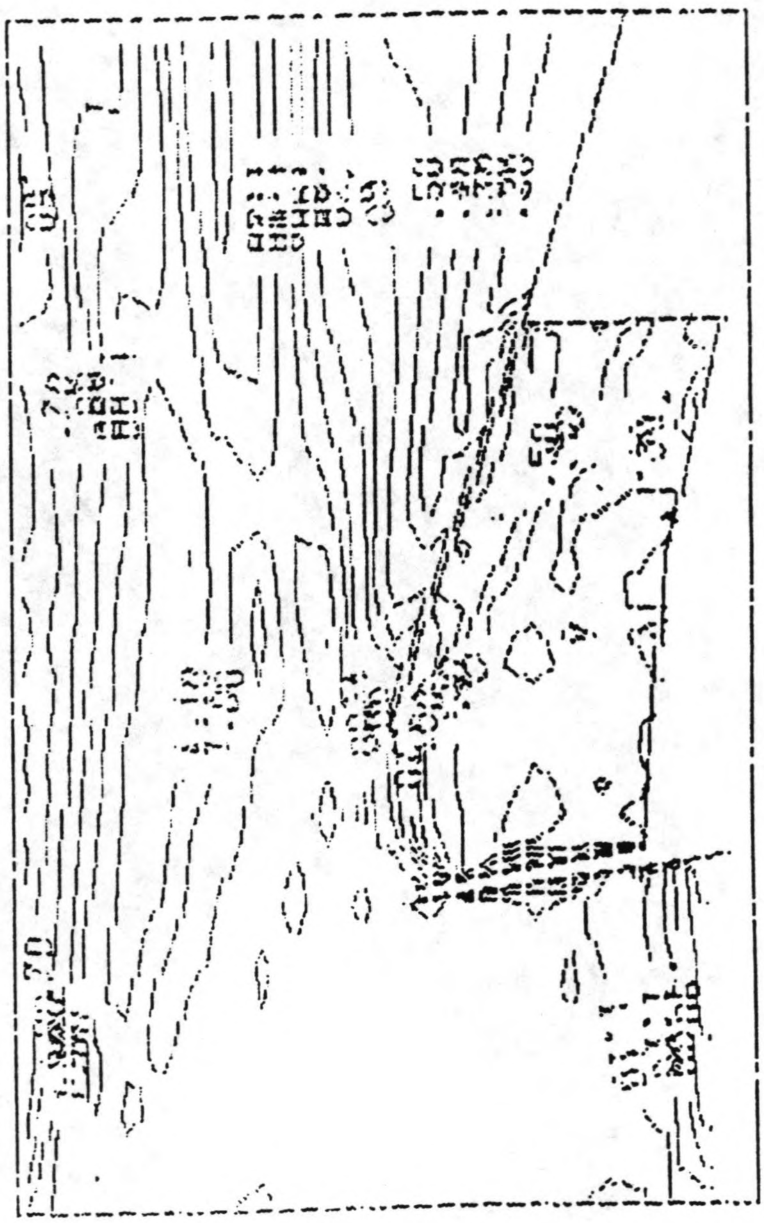
ST. MAARTEN HARBOUR	T = 8	D = 135
DIFFRACTION STUDY ALTERNATIVE D2	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 52



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2	T = 5	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 53



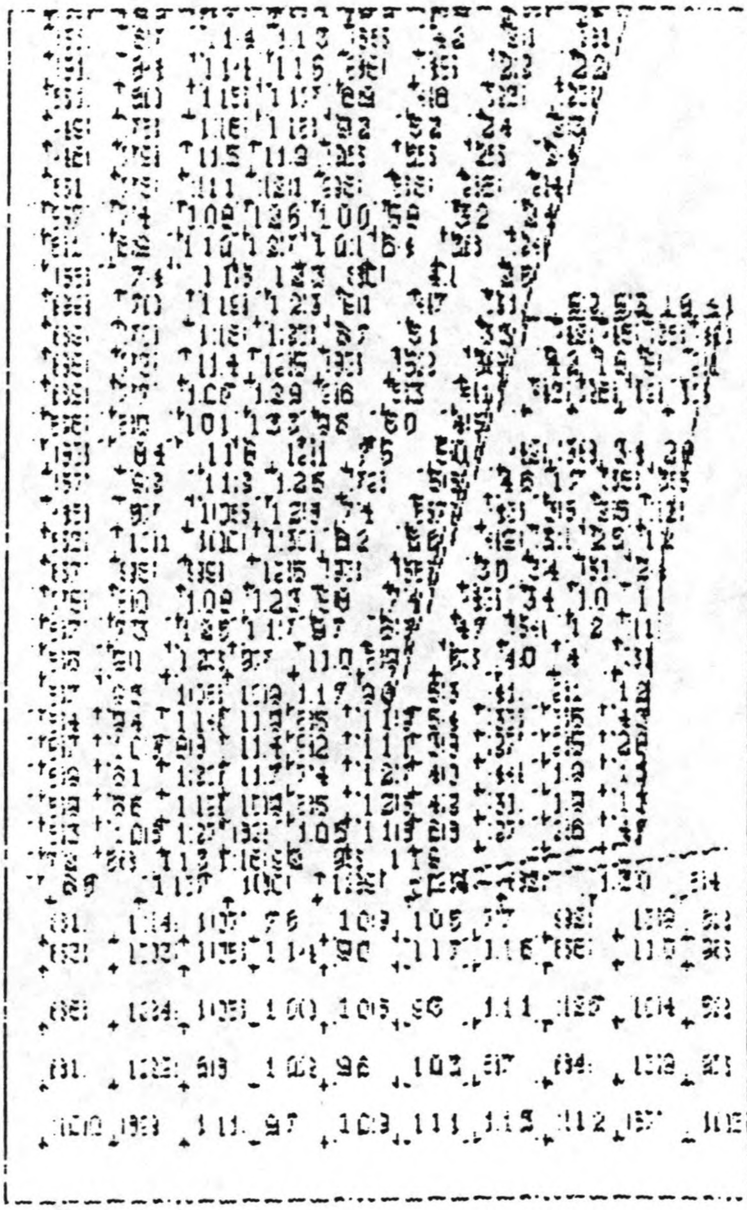
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2	T = 8	D = 180
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 54



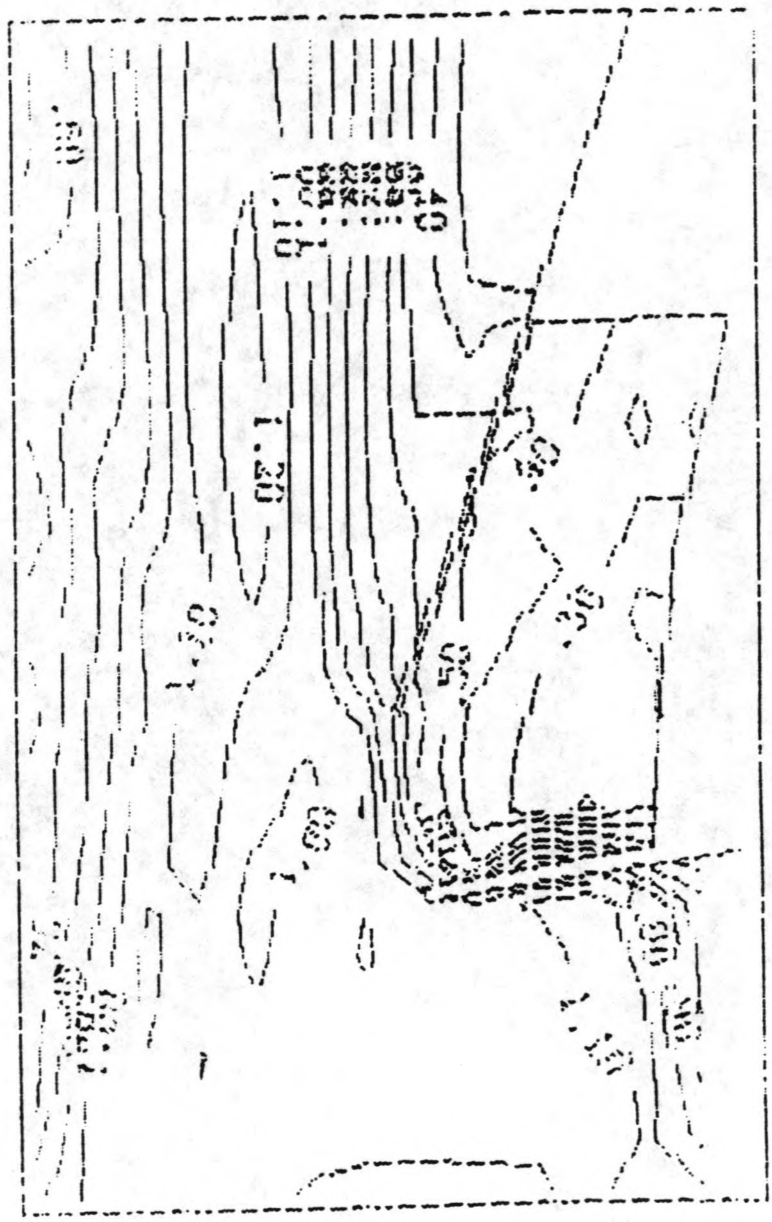
ST. MAARTEN HARBOUR
DIFFRACTION STUDY
ALTERNATIVE D2

T = 8	D = 180
SCALE: DISTORTED	
7810.2	FIG. 55

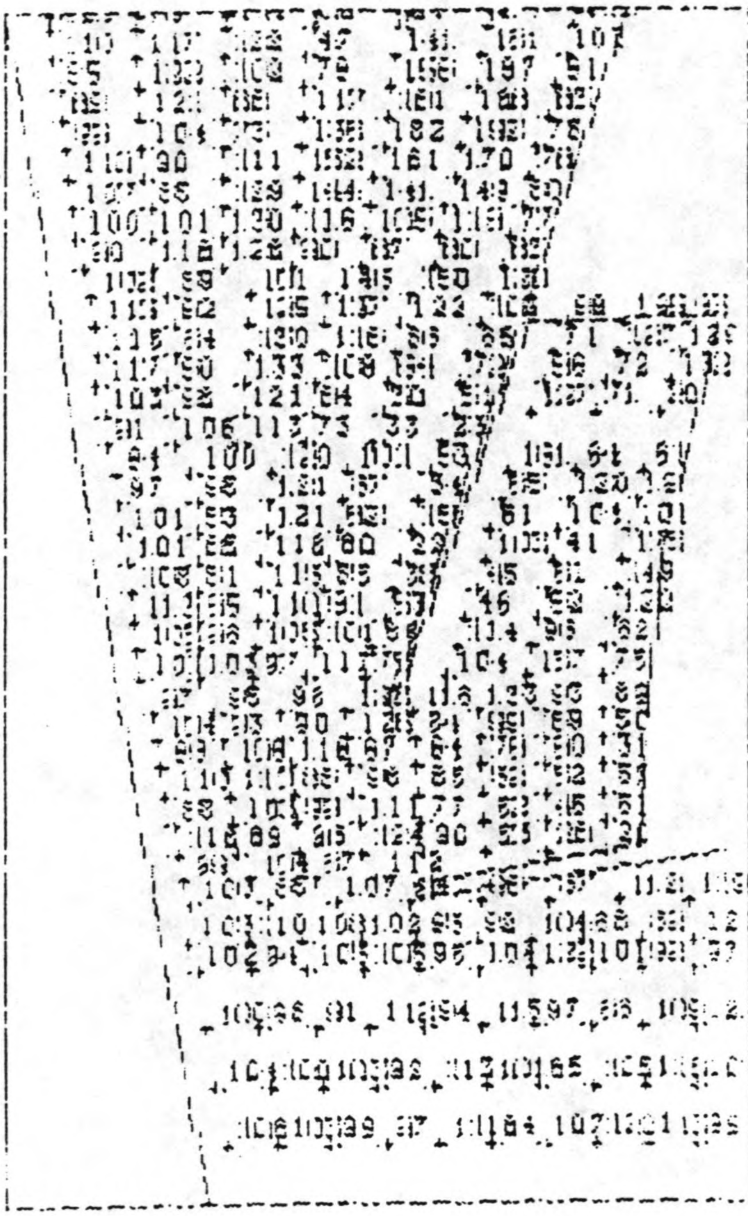
Grabowsky&Poort BV, Consulting Engineers



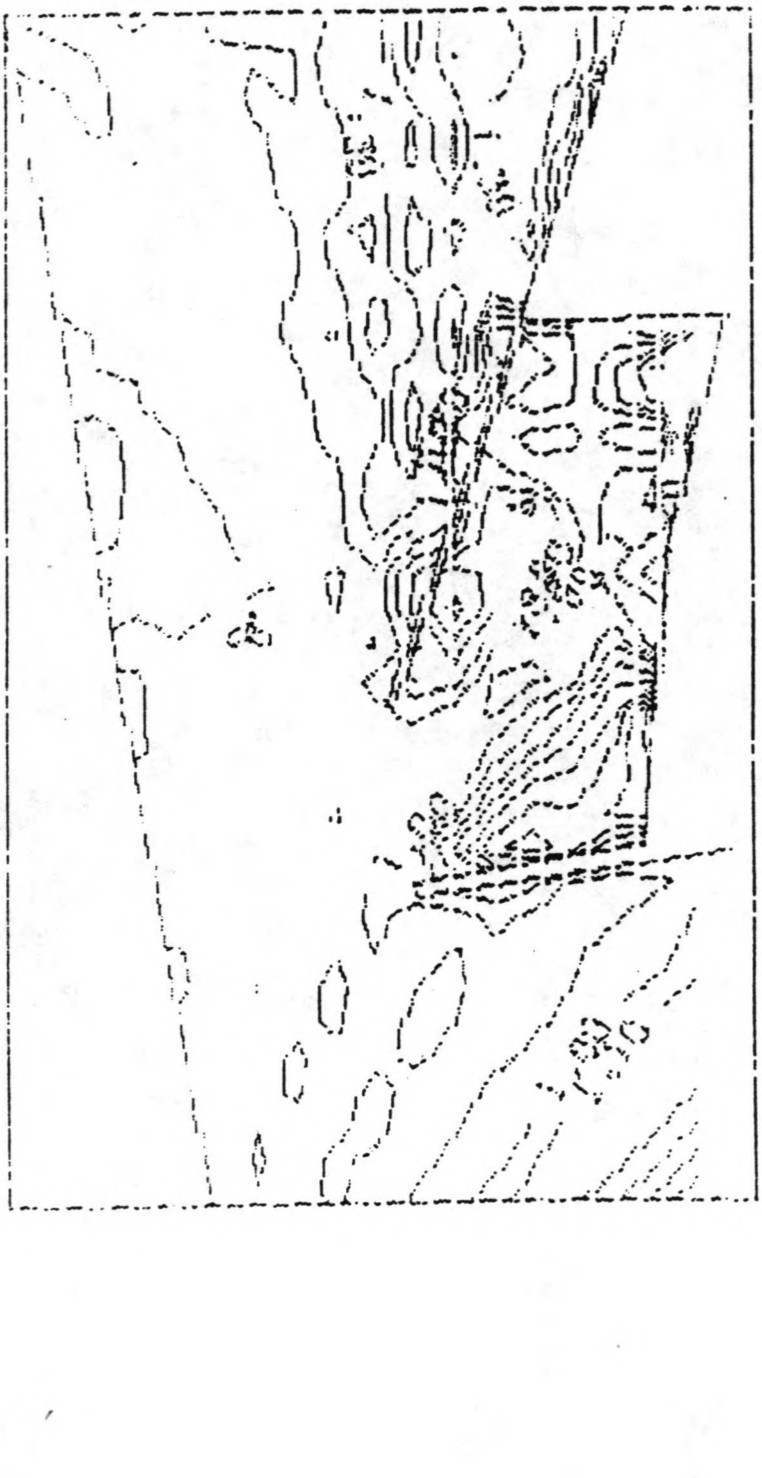
ST. MAARTEN HARBOUR	T = 12	D = 180
DIFFRACTION STUDY ALTERNATIVE D2	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 56



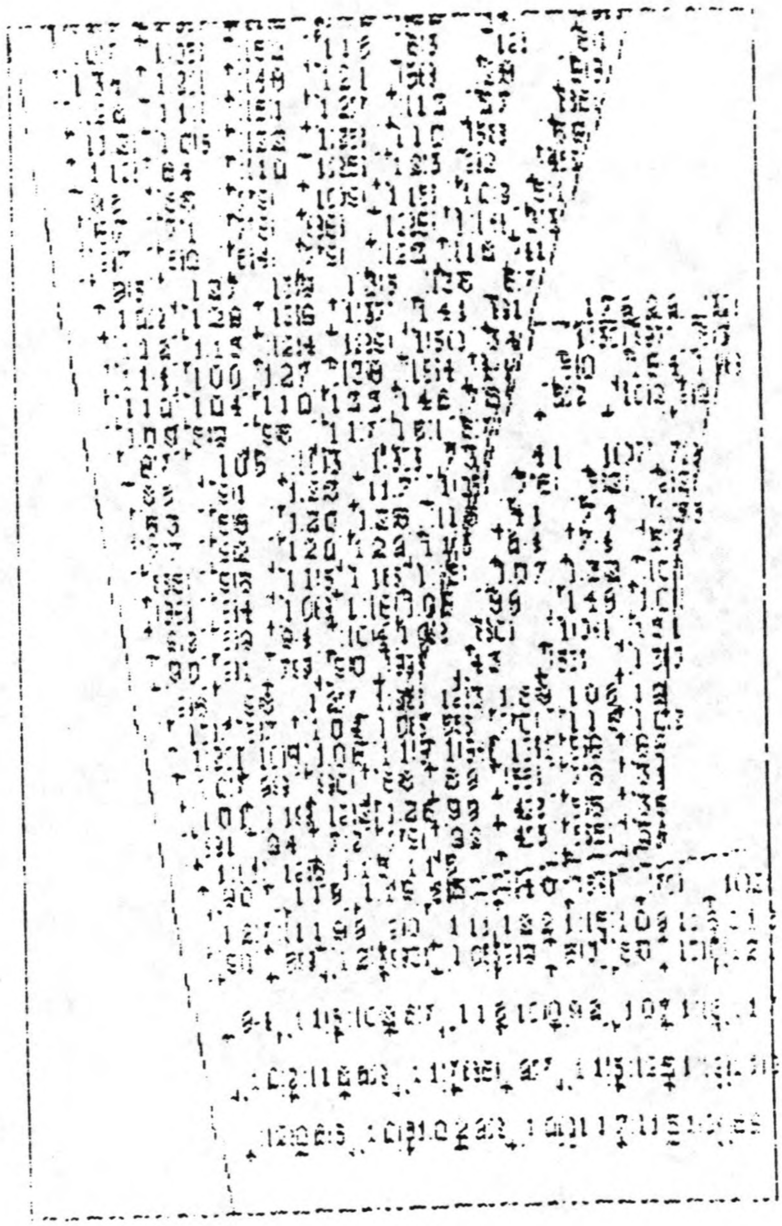
ST. MAARTEN HARBOUR	T = 12	D = 180
DIFFRACTION STUDY ALTERNATIVE D2	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 57



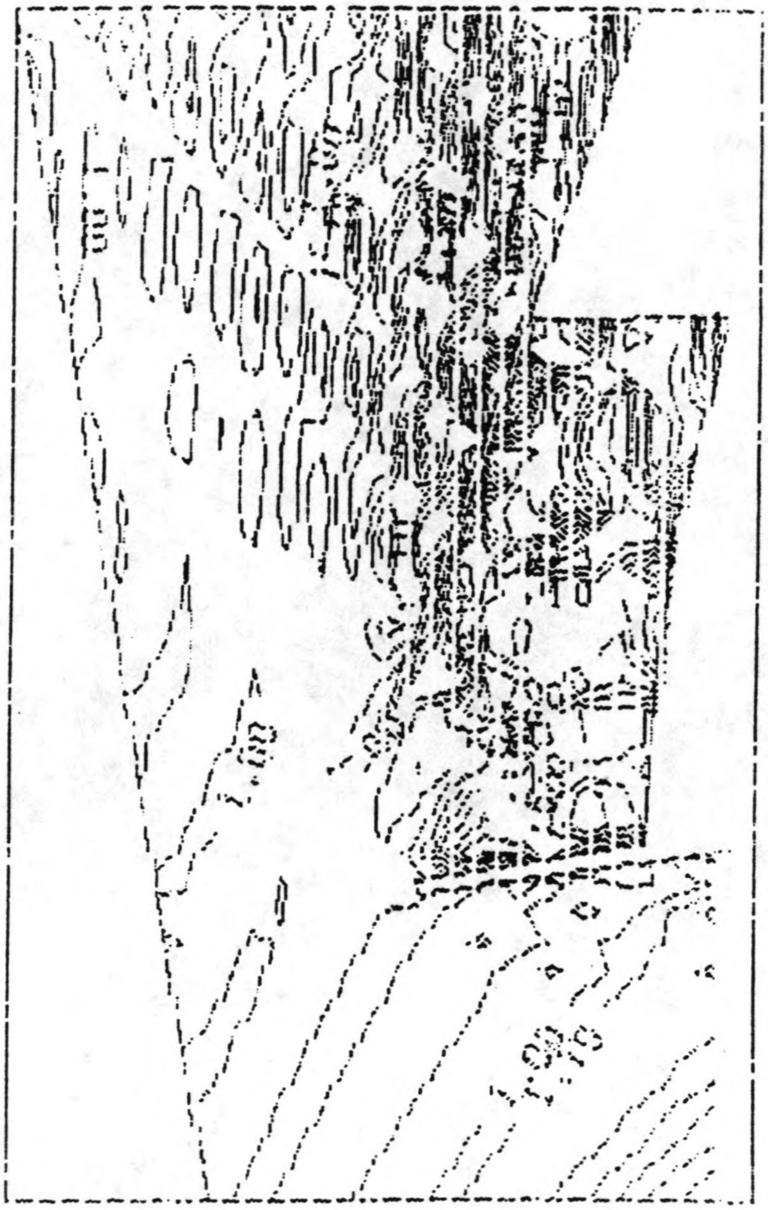
ST. MAARTEN HARBOUR	T = 9	D = 225
DIFFRACTION STUDY ALTERNATIVE D2	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 58



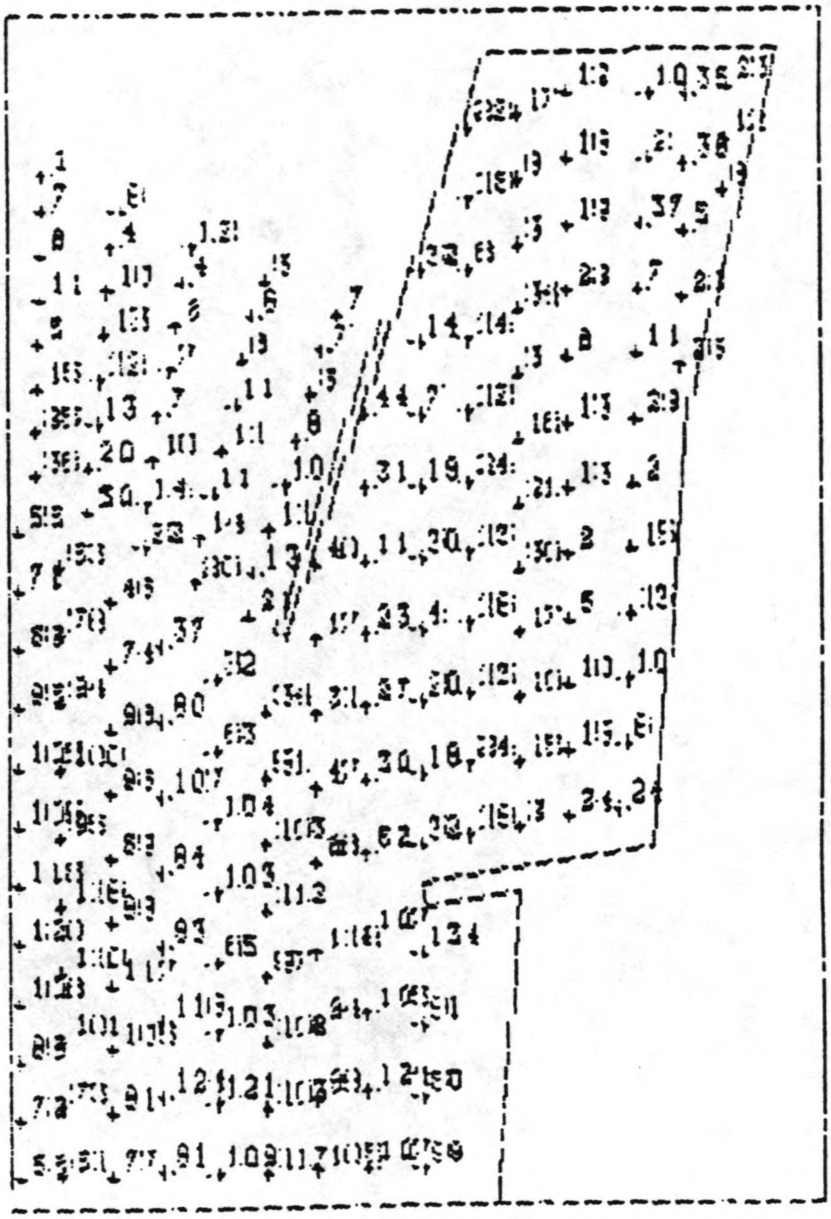
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2	T = 9	D = 225
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 59



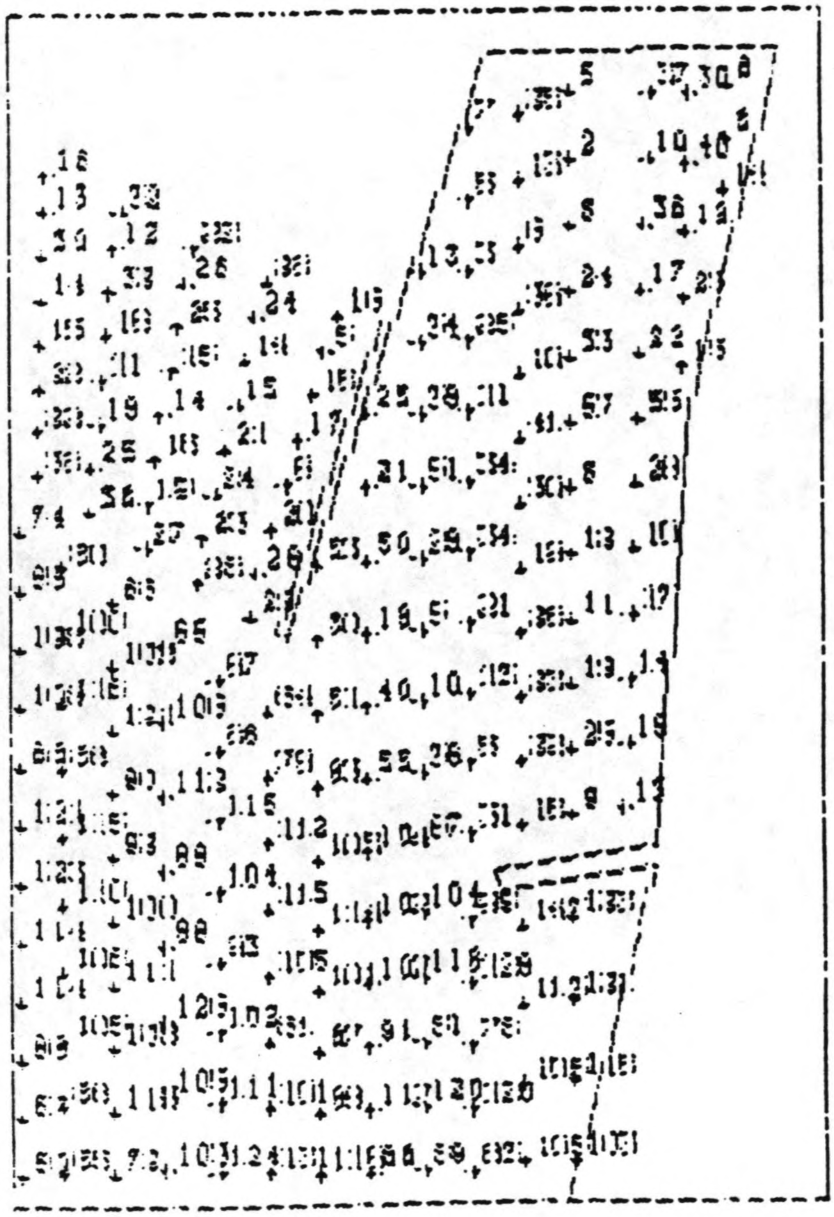
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2	T = 12	D = 225
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 60



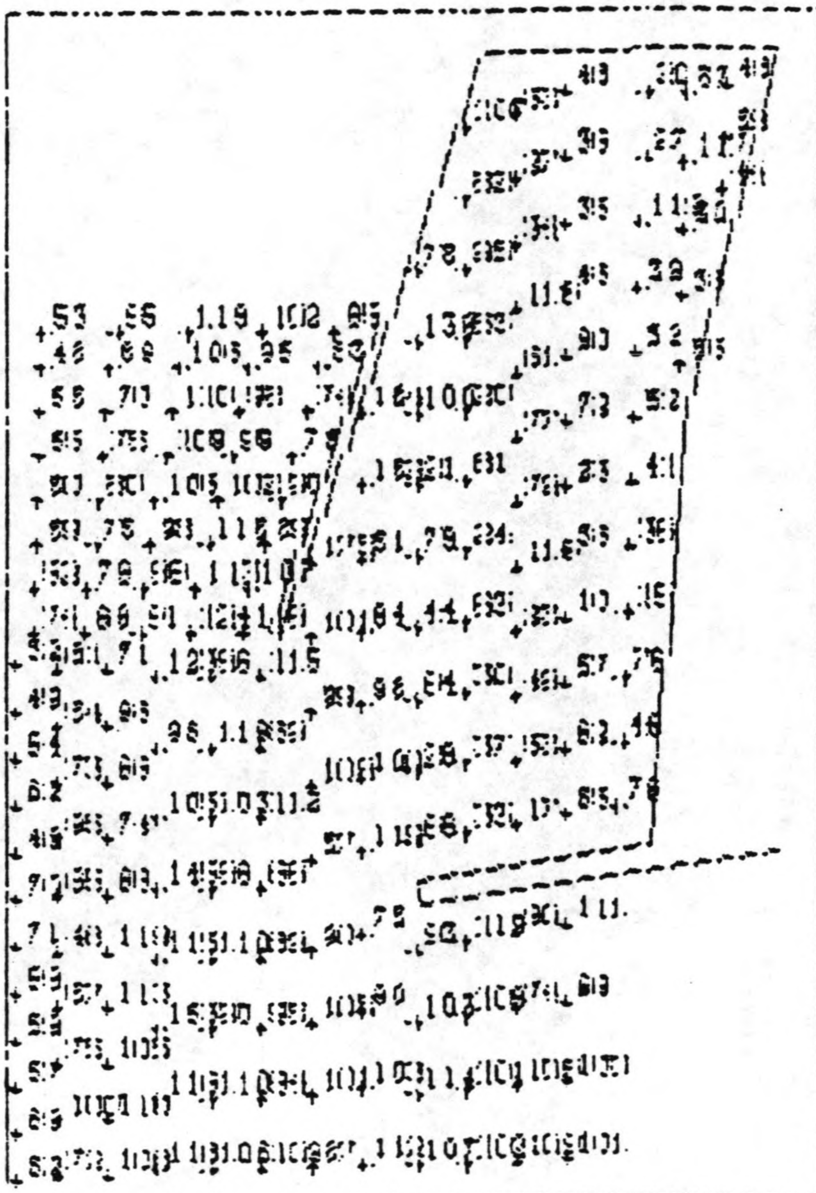
ST. MAARTEN HARBOUR	T = 12	D = 225
DIFFRACTION STUDY ALTERNATIVE D2	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 61



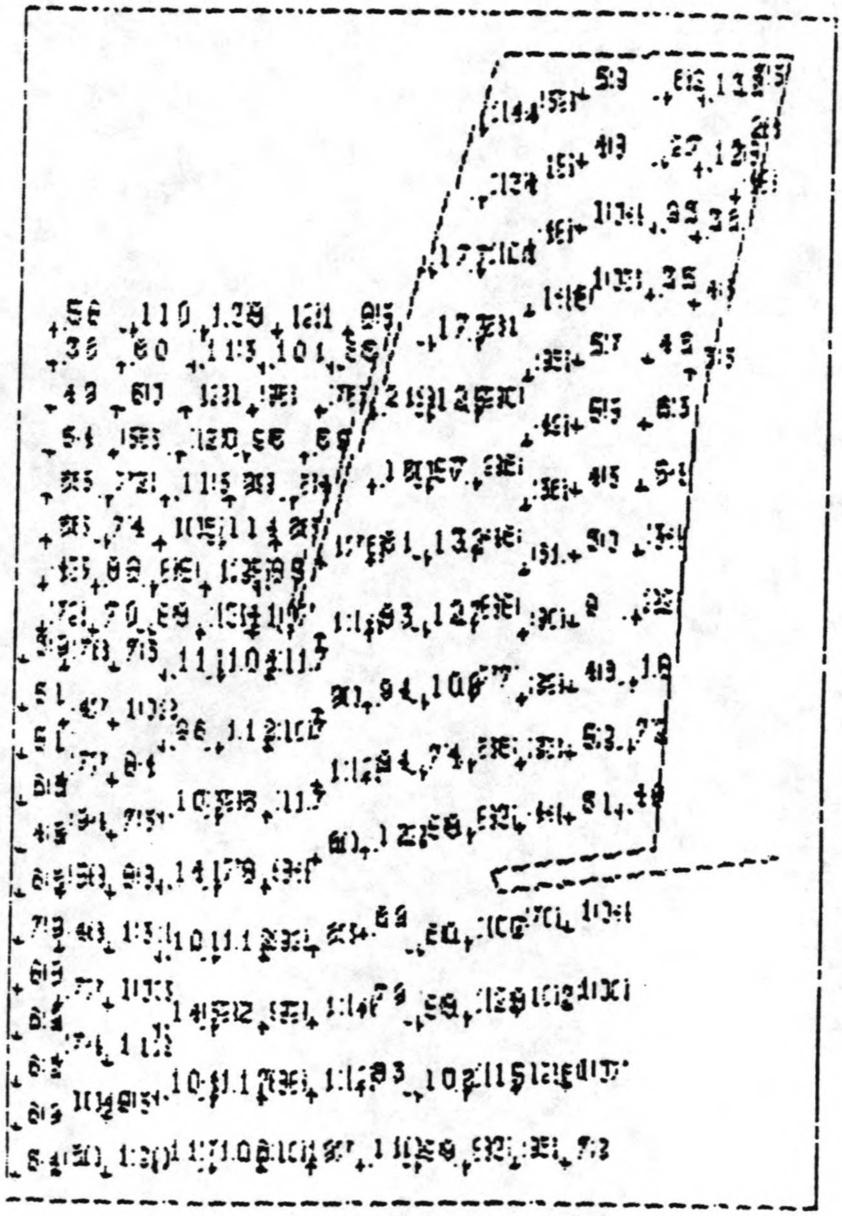
ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2 (Short breakwater)	T = 8	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 62



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2 (Short bra. w. II)	T = 8	D = 135
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 63



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2 Short breakwater I	T = 8	D = 180
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 64



ST. MAARTEN HARBOUR DIFFRACTION STUDY ALTERNATIVE D2 Short breakwater II	T = 8	D = 180
	SCALE: DISTORTED	
Grabowsky&Poort BV, Consulting Engineers	7810.2	FIG. 65

APPENDIX E. REFERENCES

1. **Evaluation of environmental criteria for proposed harbour facilities in Great Bay St. Maarten Netherlands Antilles.**
   Coastal Environmental Associates (COA)
2. **Preliminary environmental study, present situation**
   St. Maarten Ports Authority,
   Grabowsky&Poort International BV.
3. **Wave Climate Study,**
   St. Maarten Ports Authority,
   Grabowsky&Poort International BV.
4. **Hydrodynamics of coastal zones,**
   S.R. Masel
   Elsevier Oceanographic Series
5. **Shore Protection Manual,**
   Coastal Engineering research centre,
   Department of the Army,
   Volume I and II
6. **Lecture notes, Korte Golven b76,**
   J.A. Battjes,
   TU Delft, section Hydrodynamics
7. **User manual DIFFRAC-model**
   Delft Hydraulics de Voorst.