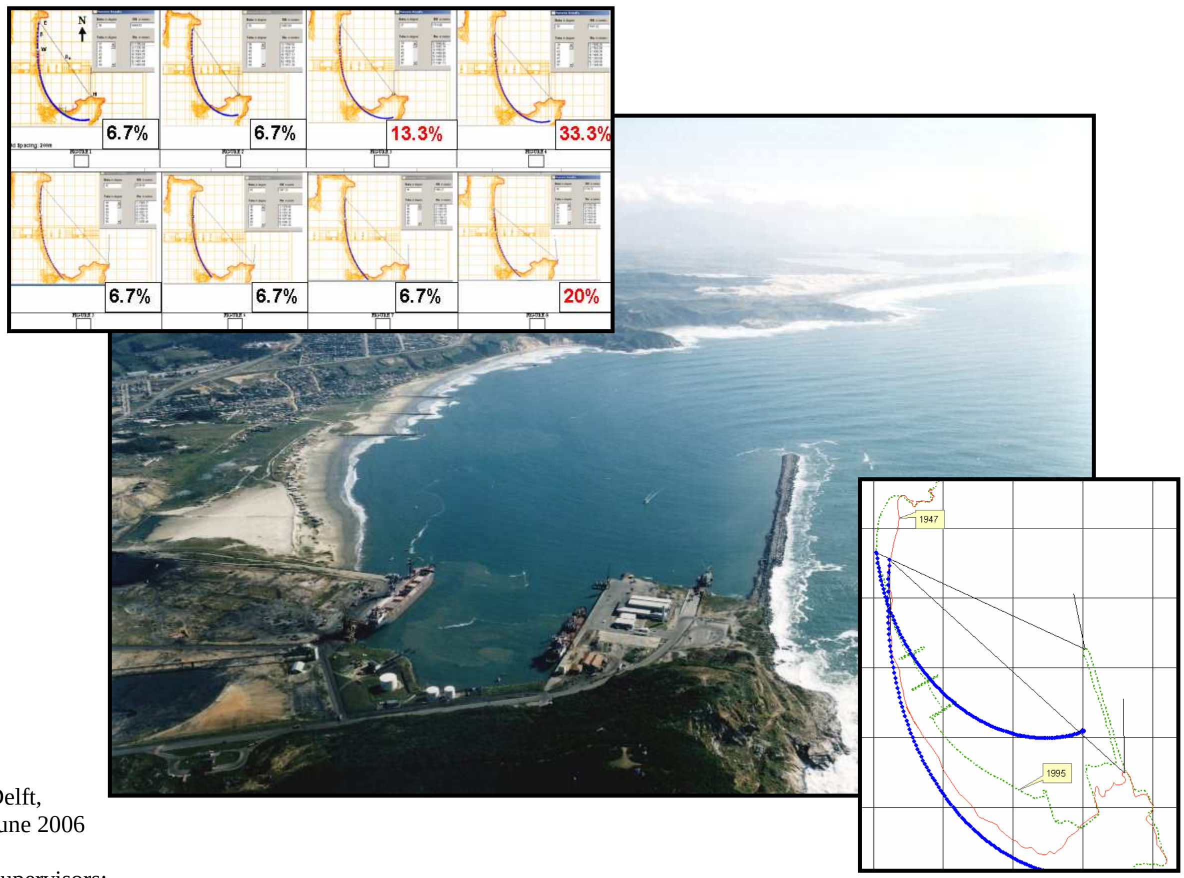
M.Sc. Thesis

Uncertainty in the application of Bay Shape Equations

A study on the quantification of the uncertainty in the application of the Parabolic Bay Shape Equation using existing bays

R.F. Lausman



Delft,
June 2006

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June 9, 2006
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This M.Sc. thesis can be downloaded at: www.hydraulicengineering.tudelft.nl

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Preface

This master dissertation comprises the results of research into probabilistic coastal morphology conducted at the Delft University of Technology and the Universidade do Vale do Itajaí (UNIVALI), carried out in order to complete the study of Civil Engineering at the Delft University of Technology.

During the last phase of the graduation project an unconventional approach was chosen. It was agreed with the graduation committee to present the results of the graduation work in the form of a scientific paper to be published in a special edition of 'Coastal Engineering'. This special edition of the journal will be edited by guest editors John Hsu and Antonio H.F. Klein. It was also agreed that the graduation report would consist of the before mentioned paper together with explanatory appendices. This document is the result of this agreement. An important advantage of this approach is that the graduation committee will automatically review the paper and unnecessary extra rewriting work is avoided.

The paper: 'Uncertainty in the application of Parabolic Bay Shape Equation: A case study' contained in this dissertation may be considered as the heart of this document, to be read and understood on its own.

The requirements for graduation work at the faculty of Civil Engineering at the Delft University of Technology are different from the requirements of a scientific paper subjected to a journal. Whereas the graduation work has an important educational goal, the objective of a paper is generally to present advances in science. During the writing of the paper, the layout and requirements by the journal 'Coastal Engineering' have been maintained.

This project could not have been performed without the help of a few but very important people. Gratitude is owed to the following persons:
The graduation commission consisting of: Prof. Dr. ir. M.J.F. Stive, Dr. A.H.F. Klein, Ir. H.J. Verhagen, Dr.ir. P.H.A.J.M. van Gelder and Dr. J.E.A. Storms.

For all their help during and after my stay at the Universidade do Vale do Itajaí (UNIVALI) in Brazil,
Prof. Dr. Rafael Medeiros Sperb, Msc. João Thadeu de Menezes and Rodrigo Sperb. Engineer Candido P. Jorge and Baga from Companhia de Docas de Imbituba (CDI) for supplying the valuable data.

Ir. Martijn Henriquez from the section Hydraulic Engineering at the TU Delft for his advice regarding wave calculations.

For their important input, the volunteers that participated in the opinion polls.

And finally, many thanks are also owed to the institutions that made this project financially possible, the Section Hydraulic Engineering DUT, het KIVI fonds, Stimuleringsfonds Internationale Universitaire Samenwerkingsrelaties DUT and dredging contractor Royal Boskalis Westminster nv.

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Abstract

From the several existing empirical equations that describe the planform of a bay, the Parabolic Bay Shape Equation (PBSE) is the only one that explicitly assesses an equilibrium bay shape. Research has been performed on the uncertainties regarding the static equilibrium planform (SEP) plotted by this equation but results have been more of a qualitative nature. This paper is an attempt to quantify the uncertainty in the application of the PBSE using existing bays. By means of an expert elicitation, a database consisting of the position of the control points needed to plot the SEP was generated. The elicitation was held under experts in the field of coastal/hydraulic engineering and consisted of two parts. In the Part 1 of the elicitation, twenty-two expert volunteers where asked to place the three control points needed to draw the SEP on a vertical aerial photograph of Taquaras/Taquarinhas Bay, an stable bay, approximately 1800m wide and 750m indent, in the south of Brazil.

The software program MEPBAY, which facilitates the use of the PBSE was used to translate the position of the control points into the SEP's corresponding to the bay. The distribution of the location of the SEP along four evenly spaced (200m) profiles in the southern part of the bay was determined. The overall bias of the location of the SEP calculated over the four profiles is in the order of 40m (landward) and the average bandwidth is 116 m. The bandwidth and standard deviation of the SEP increase when moving alongshore toward the curved section of the bay. This means that the uncertainty in the application of the PBSE is dependent on the particular point of interest along the bay. In Part 2 of the elicitation thirty volunteers participated. This time the consequence of the placement of the control points (the corresponding SEP) was visible. Comparing the results from Part 1 and 2, it was observed that when volunteers are directly confronted with the result of the placement of the control points (a plotted SEP) a much smaller variation in the position of the SEP occurs. This in turn means that the PBSE is a robust method provided the user sees the result of his/her choices in placement of the control points.

After quantifying the uncertainty when applying the PBSE to a stable bay an unstable situation was analyzed. For this case the bay of Imbituba in southern Brazil was chosen. The construction of a breakwater to shelter the port of Imbituba in the south of the bay was accompanied by an increase in sedimentation of the port. Superimposed plots of the coastline of the bay of Imbituba from different years confirm a general trend of accretion of the southern part of the bay accompanied with a retreat of the coastline in the northern part. After the application of the PBSE it was clear that the breakwater caused a change in the equilibrium state of the bay. Between 1947 and 2001 the Bay of Imbituba has changed from a dynamic equilibrium to a close to static equilibrium in the northern part of the bay and an unstable equilibrium status in the southern part. The tendency of the sedimentation of the southern part of the bay can be explained by looking at the SEP belonging to the new up coast diffraction point (tip of the breakwater): The seaward position of the SEP predicts a need for sediment in order to achieve a stable planform.

List of symbols

Roman symbols

Symbol	Description	Unit
a, b and m	Empirically-determined coefficients (Hyperbolic Tangent Shape equation)	-
C_0, C1. C_2	Constants generated by regression analysis to fit the peripheries of the 27 prototypes and model bays (Parabolic bay shape equation)	-
R_n	Radius from the point of diffraction to the coastline	m
$R_{0,\beta}$	Length of control line	m
r_1, r_2	Radii from the origin (logarithmic spiral equation)	radians
y	Distance across shore (Hyperbolic Tangent Shape equation)	m
x	Distance along shore (Hyperbolic Tangent Shape equation)	m

Greek Symbols

Symbol	Description	Unit
α	Constant angle of the tangent to the curve with radii r_1 and r_2 (logarithmic spiral equation)	^{o}
β	Angle between the wave crest and the control line	^{o}
θ	Angle between the wave crest and the radius	^{o}

Abbreviations

PBSE: Parabolic Bay Shape Equation

SEP: Static Equilibrium Profile

Point H: Upcoast control point (used in the Parabolic Bay Shape Equation)

Point E: Downcoast control point (used in Parabolic Bay Shape Equation)

Point W: Down coast tangent line (used in Parabolic Bay Shape Equation)

1. Introduction

Headland-bay beaches are the most recognizable feature on exposed and sheltered sedimentary coasts, which represent about 51% of the world coastline. The most widely used formulation for representing this kind of beaches is the Parabolic Bay Shape Equation proposed by Hsu and Evans (1989), who suggested a methodology to test and predict the stability of static equilibrium shapes in natural and man-made bays.

1.1. History of this graduation Project

The faculty of Civil Engineering and Geosciences at the Delft University of Technology has for years collaborated with the University of Vale do Itajaí (UNIVALI) in Brazil.
Prof. A.H. Klein of the Centro de Ciências Tecnológicas da Terra e do Mar, the Department of Oceanology at UNIVALI has performed extensive research on bayed beaches along the coast of the state of Santa Catarina, Brazil.
Part of this research consisted in the assessment of the stability of the planform these beaches.
The UNIVALI has developed a software program, MEPBAY, which facilitates the analysis of the behavior of headland bay beaches through application of the Parabolic Bay Shape Equation. With the help of this program the stability of various beaches along the Santa Catarina coast has been assessed. One of the bays studied was the Bay of Imbituba.
This bay was particularly interesting because of the large morphological changes that took place after human intervention in the form of coastal structures. Initial simulations with the software program MEPBAY where performed by Prof. A.H.F. Klein. More definite results regarding the harbor of Imbituba would be published in a paper to be submitted for the Fourth International Conference on Maritime Engineering, Ports and Waterways 'PORTS 2005' to take place between the 20th and 22nd of April 2005 in Barcelona, Spain. However, this paper was not published or completed, meaning that more definitive simulations using all available data were not executed.
In the search for a suitable graduation project, Prof. Klein indicated that the execution of simulations with all possible data and further research on the Bay of Imbituba would be a useful project.
When looking more closely at the Parabolic Bay Shape Equation and the software program MEPBAY, Prof. Dr. ir. M.J.F. Stive noted that because the Parabolic Bay Shape Equation is a not a very complex morphological model, it is very suitable to be analyzed with the help of probabilistics. It was agreed that the graduation project would encompass more then only application of the Parabolic Bay Shape Equation on the Bay of Imbituba. The uncertainty of the Parabolic Bay Shape Equation itself would have to be investigated.
Five months of the project were spent in Brazil, on the campus of UNIVALI in Itajaí and on location in the Bay of Imbituba. Under the supervision of Brazilian tutors, Dr. A.H.F. Klein, Dr. Rafael Medeiros Sperb and Msc. João Thadeu de Menezes, different data was collected, the evolution of the morphology of the bay of Imbituba was determined and more extensive simulations with MEPBAY were performed.
After the period in Brazil, work continued at the faculty of Civil Engineering and Geosciences at the Delft University of Technology. Here together with the help of the tutors at the TU Delft, the emphasis was put on quantifying the uncertainty of the parabolic bay shape method. An expert elicitation was developed and several experts where asked to collaborate in the application of the parabolic bay shape method on existing bays. The outcome of this elicitation was analyzed and additional wave diffraction/refraction calculations where performed to better understand certain aspects concerning bay stability. The result of these efforts has been comprised in a paper to be published in a special issue of 'Coastal Engineering'. It is also this paper which forms part of the M.sc. Thesis needed to concluded the study of civil engineering at the Delft University of Technology.

1.2. Why this topic?

Literature study showed that no in-depth investigation yielding quantitative results has been performed regarding the uncertainty of the application of the Parabolic Bay Shape model. Research in the uncertainty in the application of the parabolic bay shape equation using existing bays seemed thus to be a valuable contribution to the area of coastal engineering.

1.3. What is the extra value of my work compared to the work already performed by Prof. Klein?

The executed simulations of the harbor of Imbituba presented in the thesis of Prof. Klein were not based on all available data and research regarding the harbor of Imbituba was not completed.
The additional value of this graduation work would be the completion of the work on the harbor of Imbituba started by Prof. Klein and the quantification of the uncertainty in the application of the Parabolic Bay Shape Equation on existing bays.

1.4. What is the contribution to society?

Research on this topic could lead to better insight into of the interference of harbor breakwaters on the original planform of a bay. The opportunity to elaborate further on the work of Prof. Klein can contribute to better understanding of the processes that play a role in optimizing harbor design.
The design of the breakwater to provide calm water for ships at a harbor could then be optimized without adversely affecting the equilibrium plan form. And with research on the uncertainty of the Parabolic Bay Shape Method, a better insight in the accuracy of the predicted static equilibrium planform could be obtained. Ultimately contributing to more understanding of morphological changes such as erosion and deposition patterns.

2. Paper

3. Conclusions

Conclusions of the research are included at the paper, but are repeated here to maintain logical order.

With the help of an expert elicitation an attempt was made to quantify the sensitivity of the Parabolic Bay Shape Equation applying it to the existing stable bay of Taquaras/Taquarinhas. The following can be concluded from the analysis of the results from this expert elicitation:

- When strictly adhering to the definition of the control points and not seeing the result of the control point configuration, twenty-two expert volunteers provided the that, in the particular case of a stable bay, 1800m wide and 750m indentation, the overall bias of the location of the SEP calculated over 4 evenly spaced (200m) profiles in the southern part of the bay is in the order of 41m (landward) with an average bandwidth of 116 m.
- The bandwidth and standard deviation of the SEP increase when moving alongshore from profile 1 to 4. Indicating the following behaviour:
- The uncertainty in the application of the PBSE is dependent on the particular point of interest along the bay.
- When moving along the SEP from the downcoast control point to the more strongly curved area of the bay the uncertainty of the PBSE increases. This behaviour is opposite of the relationship found earlier by martino et al. (2005), where the uncertainty decreases when moving along the SEP from the downcoast control point to the more strongly curved area of the bay.
- Provided the volunteer sees the consequences of the placement of the control points (the corresponding SEP) the variation of the position of the SEP along the four profiles is much smaller. This in turn means that the PBSE is a robust method provided the user sees the result of his/her choices in placement of the control points (SEP plot)

Applying the PBSE on the Bay of Imbituba lead to the following conclusions:

- As a consequence of the construction of the breakwater and groins the equilibrium status of the Bay of Imbituba has changed from dynamic to close to static in the north and unstable in the south
- The tendency of the sedimentation of the port can be explained by looking at the SEP belonging to the new upcoast diffraction point (the tip of the breakwater): To reach this new SEP the southern part of the bay requires massive accretion.

The statement given by one expert during the expert elicitation that point E cannot exist in the Bay of Imbituba was the motive to conduct more research on the relationship between the positioning of control point E and the wave diffraction pattern in the bay. The conclusions of this research are:

- The Cornu Spiral is not a suitable tool to investigate the limits of the diffraction effects. Finding the point where there is no more diffraction, requires high ($W>4$) values of the Cornu parameter W, which are not accurately represented in the spiral.
- In the case of the Bay of Imbituba:

  It is difficult to derive a relationship between the position of the control point E and the diffraction pattern. The REFDIF simulation with only the breakwater as diffraction point placed the area where no diffraction effect occurred, outside of the bay of Imbituba. A section where the envelope of the wave height variation is constant occurs between points B and C*. REFDIF calculations including the diffraction from the Ponta da Ribanceira, which represents reality more accurately, give a more complicated representation of the wave height behaviour. The bay experiences diffraction from two headlands, which causes overlapping diffraction patterns.

- In the case of Taquaras/Taquarinhas Beach:

  In this particular case the separation point along the bay between the area under influence of diffraction (wave height variation) and the area free from influence of diffraction coincides with control point E. Control point E being the downcoast control point in the most frequently chosen figure in the Expert Elicitation Part 2. This supports the supposition by (Martino et al. 2005), that the control point E is a boundary for the curved section of the beach controlled by diffraction and the straight section of beach perpendicular to the assumed predominant wave direction.

After having numerously applied the software program MEPBAY to the several bays the following general conclusions on the application of MEPBAY version 1.0 can be made:

- In using MEPBAY as an engineering tool there are several sources of uncertainty that are more related to image processing than coastal engineering. One of these uncertainties is the distortion of data introduced by conversion by different software programs. It is of utmost importance that the images are not distorted. An alteration of the coastline by a software operation could lead to erroneous conclusions about the state of equilibrium when comparing the plotted static equilibrium with the (distorted) coastline. Although there was no ‘visible’ distortion of the images, no quantitative method was applied to prove that the image was not distorted.
- Another source of uncertainty is the aspect of image size (in KB). It is possible to place the control points more precisely when using large (>12.000KB) images. But there is a limit to the amount of KB that you can load and the coastline is poorly visible when zoomed out to the extend of the whole bay. Also here quantification of the difference in accuracy is needed when working with different size images.
- It is evident that like in all software programs the quality of the results obtained from MEPBAY are as good as the quality of the input. When using charts the vertical datum must be known and with aerial photographs the exact time and local conditions of taking of the photograph have to be recorded so that the shoreline indicator can be related to other data using tidal charts.

  So even though the MEPBAY program can be accurate in its functioning, complete and exact data is of crucial importance especially when considering a flat beach slope and high tidal difference, as is the case in the Bay of Imbituba.

4. Recommendations

A subject can rarely be investigated in its fullest extent; especially a graduation work cannot cover all facets of an intricate subject as equilibrium bays. That is why recommendations for further research are listed here.

- **Regarding the uncertainty of the Parabolic Bay Shape Equation.**
  In this thesis the uncertainty regarding the application of one specific bay has been quantified.
  This is just a start. It would be useful to derive a general relationship for the uncertainty, a relationship, which would present the user, the uncertainty of the application of the PBSE on any bay. This relationship would have to be incorporated into bay shape programs such as MEPBAY. This general relationship would have to take into account the dependency of the uncertainty on the location along the bay. The user should be informed what the uncertainty is along any specific point along the predicted bay shape.

- **Regarding the conditions of application of the Parabolic Bay Shape Equation**.
  To this day the PBSE can *only* be used to predict the *static equilibrium planform*. This means that only the shape of the bay given no (more) sediment bypass can be predicted. Bays in dynamic equilibrium cannot be predicted, mainly because the littoral drift that is still occurring is difficult to asses. A recommendation could be to investigate the possibilities to include the effects of sediment bypass on the bay planform into the PBSE. In fact, extend the application of the PBSE to also predict the shape of the *dynamic equilibrium planform* given the sediment bypass in the bay. This would greatly increase the number of bays on which the PBSE could be applied.

- **Regarding the morphological behavior of the Bay of Imbituba.**
  The morphological evolution of the coastline in Imbituba shows a large difference in area size between the erosion and accretion area. As possible reason for this difference was stated, that the erosion area consists of a (high) sedimentary sea-cliff and the accretion area of a flat beach. However, no quantitative analysis was performed to verify this. A recommendation would be to try to compose a sand budget and compare the eroded material from the northern part of the bay with the accreted material in the south. If this would prove to be approximately the same the bay could be considered as a closed system. If not, then bypass of sediment around Ponta de Imbituba could be proven and quantified.

- **Regarding the dependency of the uncertainty on the location along the bay.**
  In the particular case of the Bay of Taquaras/Taquarinhas it was found that the uncertainty of the SEP increases when moving along the bay toward the curved section of the bay. This is opposite to the behaviour established in earlier research by MARTINO ET AL. (2005). The uncertainty of more stable bays should be investigated to discover the reason for this opposite behavior.

- **Regarding the relationship between the control point E and the diffraction pattern in the bay.**
  Initial simulations with simplified topography where conducted to investigate the relationship between the positioning of the control point E in the bay and the diffraction pattern. In the case of the Bay of Taquaras/Taquarinhas the control point E coincides with the separation point along the bay between the area under influence of diffraction (wave height variation) and the area free from influence of diffraction. Due to the fact that the positioning of the control point E has always been a difficult issue, more research would be useful in deriving a general relationship between the shape of the bay (the boundary between the curved and straight

section of the beach, also the location of point E) and the diffraction pattern. In bays under influence of multiple diffraction points (protruding headlands at both sides of the bay), where there is no clear 'straight' section of coastline, it would be particularly useful to investigate what the relationship is between the wave diffraction pattern and the position of control point E along the Bay.

- **Regarding the next version of MEPBAY.**
  - Improve the capability to load, simulate and save results using large images (>12.000KB). Simultaneously, better zooming and moving properties have to be introduced because otherwise the images become too cumbersome to work with.
  - Amplify the formats that are allowed to be loaded (not only .JPEG and .BMP) but also. TIFF and other file extensions commonly used in engineering
  - Improve the way the numeric output is saved (e.g .TXT or .XL format)
  - Allow the user to choose the color, style and line width of the plotted static equilibrium planform.

Appendix 1: Expert Elicitations

Appendix 2: Theoretical background on the PBSE

Introduction

Rocky coasts with headland-bay beaches represent about 51% of the world coastline. Several empirical models have been derived to verify the planforms of these beaches. Among them, only the parabolic bay shape model (Hsu and Evans, 1989) has the mechanism for the evaluation of beach stability, in static or dynamic equilibrium (see figure 1). It also has the capacity to predict possible shoreline changes due to construction/extension of coastal structures on the beach. Originally, the application of the parabolic model was largely in manual form, by way of hand calculation and tracing the calculated bay shape on a copy of map or aerial photograph. To overcome this drawback, a software package called MEPBAY has been developed by the Universidade do Vale do Itajaí (UNIVALI) in Brazil. Starting from a copy of the plan of a bay beach and a set of basic information supplied by the user, MEPBAY calculates the idealized shoreline planform of a headland-bay beach in static equilibrium based on the parabolic model. It then presents the results in graphic form on a screen display (See Figure 2). It allows the stability of a headland-bay beach, in static or dynamic, to be assessed by comparing the existing periphery with the idealized planform.

$$\frac{R}{R_0} = C_0 + C_1\left(\frac{\beta}{\theta}\right) + C_2\left(\frac{\beta}{\theta}\right)^2$$

$R_{0,\beta}$	=	Control line length
β	=	Wave obliquity
C	=	Constants generated by regression analysis to fit the peripheries of the 27 prototypes and model bays
θ	=	Angle between wave crest and radius to any point on the bay periphery in static equilibrium

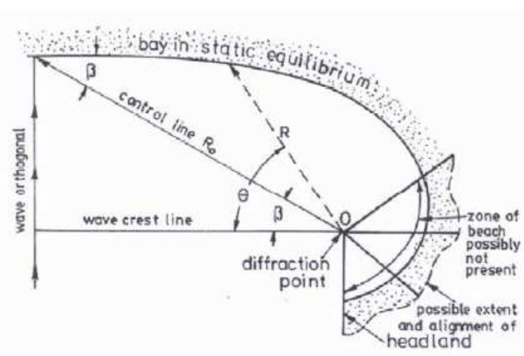


Figure A1-1: The parabolic bay shape equation and definition sketch (Hsu and Evans, 1989)

After loading the image of the planform of a bay beach into MEPBAY the user has to place control points on the image. These control points are the input for the calculation with the parabolic bay shape equation. The MEPBAY input parameters are:

1. Up coast diffraction point (Point **'H'**)
2. Down coast control point (Point **'E'**)
   Point 'E' is to be chosen in a stretch of beach assumed to be perpendicular to the wave orthogonal.
3. Down coast tangent-line (Point **'W'**)

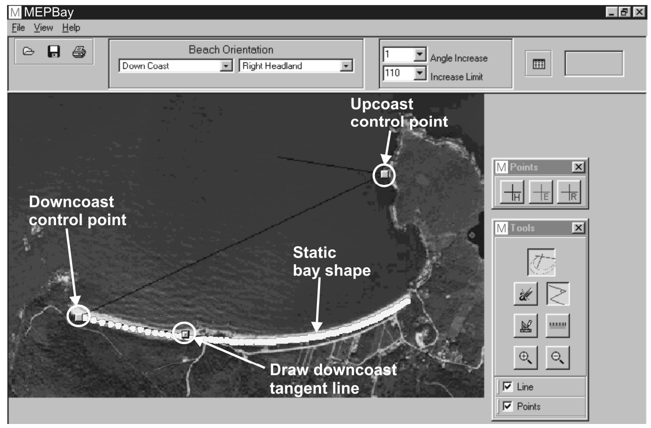


Figure A1-2: Input parameters and the plotted static bay shape

Objective of the Poll

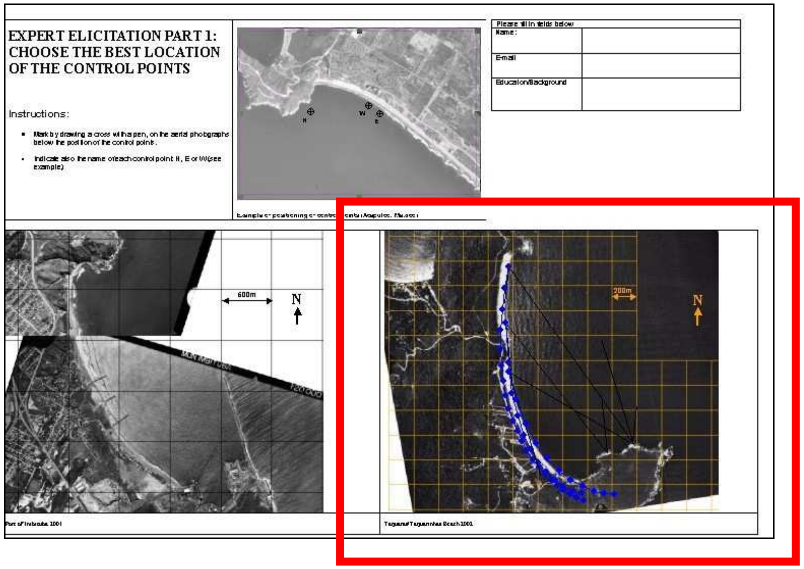
When looking at Figure 2 it becomes clear that the placing of the control points on the figure is a **subjective** operation.
An example of this subjectivity is the placing of the down coast control point followed by the placing of the down coast tangent-line. To place these points the user must identify on the image a straight down coast segment of the beach.
Since the placing of the points depends on visual interpretation a different input can be expected when several users assess the stability of the same bay.

This poll has been developed to quantify the subjectivity in the placement of the control points, by analyzing the choices made by potential MEPBAY users. It has as objective to generate a distribution function of the placement of the control points so that the spread of the input parameters can be determined

Appendix 3: Participants Expert Elicitation

Name	Institution/ Function	Part 1	Part 2
TU DELFT staff			
P. Van Gelder	TUDELFT Hydr. Eng. (tutor)	x	x
J. Van de Graaff	TUDELFT Hydr. Eng.	x	x
H.J. Verhagen	TUDELFT Hydr. Eng. (tutor)	x	x
J. Storms	TUDELFT Geologist (tutor)	x	x
M. Henriques	TUDELFT Hydr. Eng.	x	x
M.J.F. Stive	TUDELFT Hydr. Eng. (tutor)	x	x
L.H. Holthuijsen	TUDELFT Fluid Mechanics	x	x
A. Reniers	TUDELFT Hydr. Eng.	x	x
R.J. Labeur	TUDELFT Fluid Mechanics	x	x
Experts Abroad			
Andre Raabe	UNIVALI Computer Aplication	x	
Antonio Klein	UNIVALI Oceanographist (tutor)	x	
John Hsu	University of Taiwan	x	
Rodrigo Sperb	UNIVALI student geography	x	
Lindino Benedet	Coastal Planning & Eng, USA	x	
Tadheu Menenzes	UNIVALI Geography	x	
WBK Students			
Evert Euleman	TUDELFT student WBK	x	x
Ben de Sonneville	TUDELFT student WBK	x	
Evan Heeringa	TUDELFT student WBK	x	x
Mark Groeneveld	TUDELFT student WBK	x	x
Robert Smits	TUDELFT student WBK	x	x
Ronald Brouwer	TUDELFT student WBK	x	x
Hans jorritsma	TUDELFT student verkeerskunde	x	x
Auke Algera	TUDELFT student WBK	x	x
Rutger Over	TUDELFT student WBK	x	x
Tom Segboer	TUDELFT student WBK	x	x
Menno Fousert	TUDELFT student WBK	x	x
Le Hai Tsung	TUDELFT student WBK	x	x
Maaike Poort	TUDELFT student WBK	x	x
Other			
Jiri Lausman	Civil Engineer	x	
Tom Lausman	Student Industrial Design	x	x
	count	30	22

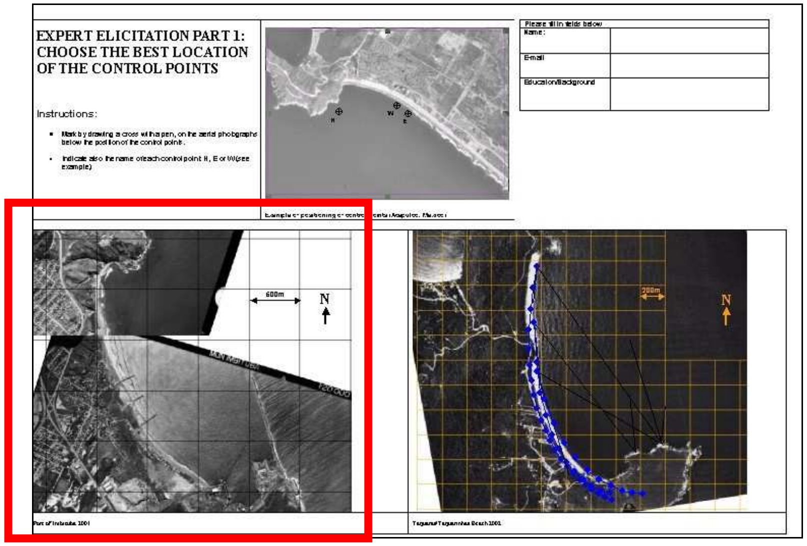
Results Expert Elicitation Part 1: Stable Bay



		UTM coordinatesControl points (m)					
		H		E		W	
	Participants	Easting	Northing	Easting	Northing	Easting	Northing
1	Dr.Ir. P. Van Gelder	740970.73	7010346.93	739927.60	7011767.96	739919.73	7011248.36
2	Dr.ir. J. Van de Graaff	741199.04	7010343.00	739974.83	7011086.97	739978.77	7011795.51
3	Ir.H.J. Verhagen	741258.09	7010366.61	739907.92	7011512.09	739852.81	7010476.83
4	Ir.Joep Storms	740962.86	7010354.81	739903.98	7011366.45	739915.79	7011563.27
5	Ir.Martijn Henriques	740982.54	7010331.19	739931.53	7011653.80	739911.85	7011425.49
6	Prof.dr.ir. M.J.F. Stive	740966.80	7010346.93	739939.41	7011456.99	739939.41	7011303.47
7	L.H. Holthuijsen	741238.41	7010287.89	739955.15	7011047.60	739959.09	7010799.61
8	Ad reniers	740966.80	7010346.93	739955.15	7011831.77	739911.85	7011540.48
9	R.J. Labeur	741240.71	7010278.02	739954.38	7011838.19	739893.12	7011384.19

10	Evert Uelman	741265.96	7010311.51	739931.53	7011401.88	739915.79	7011201.12
11	Evan Heeringa	740977.68	7010336.46	739972.39	7010912.97	740004.82	7010224.76
12	Mark Groeneveld	741258.09	7010311.51	739955.15	7011000.37	739943.34	7011413.69
13	Robert Smits	741289.58	7010295.76	739935.47	7011401.88	739943.34	7011240.49
14	Ronald Brouwer	741292.22	7010327.30	739970.90	7011024.82	739974.83	7011288.55
15	Hans jorritsma	741305.32	7010374.49	739978.77	7010968.88	739947.28	7011271.98
16	Auke Algera	740966.80	7010350.87	739927.60	7010913.77	739923.66	7010224.91
17	Rutger Over	741199.04	7010335.12	739927.60	7011394.00	739907.92	7011712.85
18	Tom Segboer	741258.09	7010260.33	739974.83	7010941.32	739994.52	7010228.84
19	Menno Fousert	741183.30	7010327.25	739919.73	7011606.57	739896.11	7011240.49
20	Le Hai Trung	741262.02	7010311.51	739990.58	7011000.37	739951.22	7010669.71
21	Maaike Poort	740958.92	7010323.31	739955.15	7010992.49	739955.15	7010795.68
22	Tom Lausman	741208.28	7010245.59	739983.20	7011067.11	739943.57	7010670.76
		22	22	22	22	22	22
	STD DEV	140.06	33.24	25.03	320.49	35.50	485.61
	AVERAGE	741145.97	7010323.33	739948.77	7011281.28	739935.64	7011078.23
	MIN	740958.92	7010245.59	739903.98	7010912.97	739852.81	7010224.76
	MAX	741305.32	7010374.49	739990.58	7011838.19	740004.82	7011795.51
	Interval	346.40	128.90	86.60	925.22	152.01	1570.75
	Recommended # bins (m)	5	5	5	5	5	5
	Binwidth	69	26	17	185	30	314

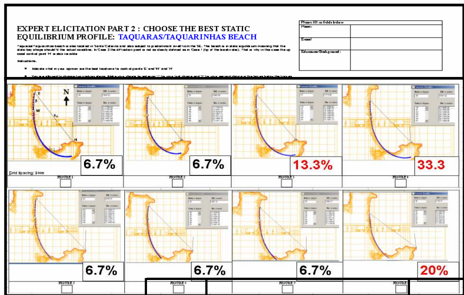
Results Expert Elicitation Part 1: Unstable Bay



		UTM coordinatesControl points (m)					
	Control point	H		E		W	
	UTM coordinates in meters ->	Easting	Northing	Easting	Northing	Easting	Northing
1	Dr.Ir. P. Van Gelder	730516.09	6876138.98	729000.1	6877000	729089.92	6876403.6
2	Dr.ir. J. Van de Graaff	NA	NA	NA	NA	NA	NA
3	Ir.H.J. Verhagen	730516.09	6876138.98	728952.1	6877348.73	728947.33	6876179.25
4	Ir.Joep Storms	730516.09	6876138.98	729067.99	6876605.34	729004.25	6876848.02
5	Ir.Martijn Henriques	730516.09	6876138.98	729002.23	6876839.91	729084.35	6876471.21
6	Prof.dr.ir. M.J.F. Stive	730516.09	6876138.98	728992.87	6876947.7	729007.08	6876695.65
7	L.H. Holthuijsen	730516.09	6876138.98	729094.45	6876500.81	729254.31	6876091.24
8	Ad reniers	730516.09	6876138.98	729035.72	6877114.98	729010.68	6876904.62
9	R.J. Labeur	730516.09	6876138.98	729007.56	6876793.3	729124.4	6876379.5
10	Evert Uelman	730516.09	6876138.98	729040.43	6877066.08	728970.37	6876772.12
11	Evan Heeringa	730515.06	6876130.47	729069.62	6876474.62	729188.93	6876185.53

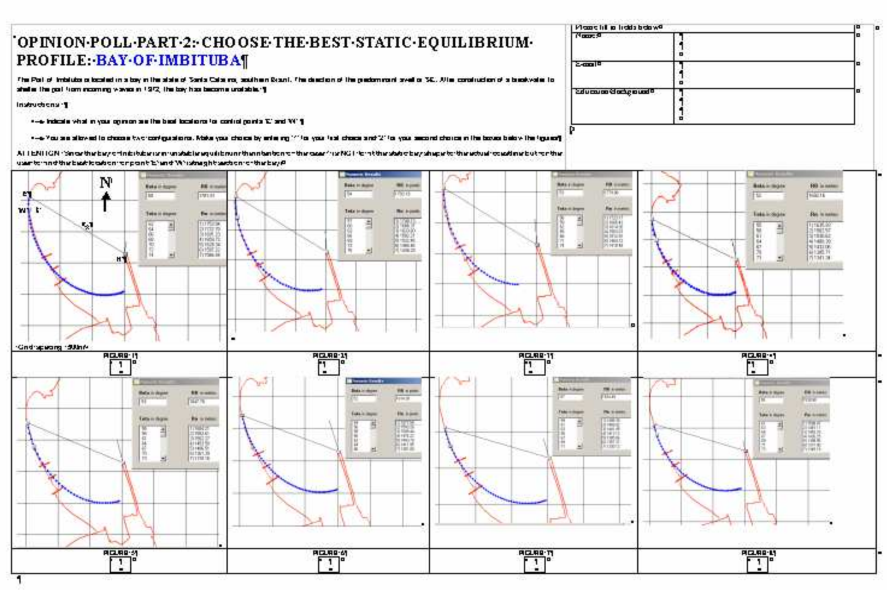
12	Mark Groeneveld	730516.09	6876138.98	729220.15	6876122.38	729389.21	6875849.75
13	Robert Smits	730516.09	6876138.98	729039.86	6876609.68	729105.34	6876395.76
14	Ronald Brouwer	730516.09	6876138.98	729013.49	6876852.99	728998.17	6877225.71
15	Hans jorritsma	730516.09	6876138.98	729079.86	6876521.12	729151.34	6876153.51
16	Auke Algera	730516.09	6876138.98	729059.44	6876541.54	729151.34	6875658.25
17	Rutger Over	730516.09	6876138.98	729054.33	6876587.5	729156.45	6876173.93
18	Tom Segboer	730516.09	6876138.98	729079.15	6876500.53	729157.73	6876046.5
19	Menno Fousert	730516.09	6876138.98	729035.49	6876705.72	729127.17	6876125.08
20	Le Hai Tsung	730516.09	6876138.98	729175.19	6876242.96	729310.53	6875994.11
21	Maaike Poort	729293.07	6877199.05	729135.9	6876321.54	729253.78	6876098.89
22	Tom Lausman	730516.09	6876138.98	729080.58	6876501.2	729177.95	6876038.73
	STD DEV	260.73838	226.101313	62.119985	305.008545	114.93568	385.411817
	AVERAGE	730460.45	6876186.78	729058.88	6876676.13	729126.7	6876318.62
	MIN	729293.07	6876130.47	728952.1	6876122.38	728947.33	6875658.25
	MAX	730516.09	6877199.05	729220.15	6877348.73	729389.21	6877225.71
	Interval	1223.02	1068.58	268.05	1226.35	441.88	1567.46
	Recommended # bins (m)	5	5	5	5	5	5
	Bin width	244.604	213.716	53.61	245.27	88.376	313.492

Results Expert Elicitation Part 2: Stable Bay



			Profile 1		Profile 2		Profile 3		Profile 4
			Position real CL:	739986.18	Position real CL:	740035.92	Position real CL:	740116.28	Position real CL:
		choice 1	Position CL	Distance to real CL	Position CL	Distance to real CL	Position CL	Distance to real CL	Position CL
1	Dr.Ir. P. Van Gelder	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
2	Dr.ir. J. Van de Graaff	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
3	Ir.H.J. Verhagen	5	739991.24	5.06	740040.69	4.77	740122.05	5.77	740241.69
4	Ir.Joep Storms	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
5	Ir.Martijn Henriques	3	739978.48	-7.70	740029.52	-6.4	740110.88	-5.4	740238.5
6	Prof.dr.ir. M.J.F. Stive	3	739978.48	-7.70	740029.52	-6.4	740110.88	-5.4	740238.5
7	L.H. Holthuijsen	8	739989.64	3.46	740048.67	12.75	740130.03	13.75	740252.86
8	Ad reniers	2	739989.64	3.46	740040.69	4.77	740120.45	4.17	740241.69
9	R.J. Labeur	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
10	Andre Raabe	6	739978.48	-7.70	740024.74	-11.18	740106.1	-10.18	740203.41
11	Antonio Klein	3	739978.48	-7.70	740029.52	-6.4	740110.88	-5.4	740238.5
12	John Hsu	3	739978.48	-7.70	740029.52	-6.4	740110.88	-5.4	740238.5
13	Lindino Benedet	1	739982.12	-4.06	740031.39	-4.53	740109.26	-7.02	740234.82
14	Rodrigo Sperb	5	739991.24	5.06	740040.69	4.77	740122.05	5.77	740241.69
15	Tadheu Menenzes	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
16	Evert Uelman	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
17	Ben de Sonneville	7	739991.24	5.06	740043.88	7.96	740125.24	8.96	740241.69
18	Evan Heeringa	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
19	Mark Groeneveld	8	739989.64	3.46	740048.67	12.75	740130.03	13.75	740252.86
20	Robert Smits	7	739991.24	5.06	740043.88	7.96	740125.24	8.96	740241.69
21	Ronald Brouwer	8	739989.64	3.46	740048.67	12.75	740130.03	13.75	740252.86
22	Hans jorritsma	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
23	Auke Algera	2	739989.64	3.46	740040.69	4.77	740120.45	4.17	740241.69
24	Rutger Over	6	739978.48	-7.70	740024.74	-11.18	740106.1	-10.18	740203.41
25	Tom Segboer	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
26	Menno Fousert	8	739989.64	3.46	740048.67	12.75	740130.03	13.75	740252.86
27	Le Hai Tsung	8	739989.64	3.46	740048.67	12.75	740130.03	13.75	740252.86
28	Maaike	4	739980.07	-6.11	740034.31	-1.61	740115.67	-0.61	740247.66
29	Jiri Lausman	1	739982.12	-4.06	740031.39	-4.53	740109.26	-7.02	740234.82
30	Tom Lausman	8	739989.64	3.46	740048.67	12.75	740130.03	13.75	740252.86
	STD DEV		5.3	5.28	7.5	7.5	7.7	7.7	12.0
	AVERAGE		739983.93	-2.25	740037.1993	1.279333333	740118.22	1.94	740242.4787
	MIN		739978.48	-7.70	740024.74	-11.18	740106.1	-10.18	740203.41
	MAX		739991.24	5.06	740048.67	12.75	740130.03	13.75	740252.86
	Interval		13	12.76	24	24	24	24	49

Results Expert Elicitation Part 2: Unstable Bay



	1st Choice
TU DELFT staff	
Dr.Ir. P. Van Gelder	6
Dr.ir. J. Van de Graaff	NA
Ir.H.J. Verhagen	NA
Ir.Joep Storms	5
Ir.Martijn Henriques	4
Prof.dr.ir. M.J.F. Stive	2
L.H. Holthuijsen	1
Ad reniers	1
R.J. Labeur	5
Experts Abroad	
Andre Raabe	5
Antonio Klein	1
John Hsu	1
Lindino Benedet	4
Rodrigo Sperb	2
Tadheu Menenzes	2
WBK Students	
Evert Uelman	1
Ben de Sonneville	2
Evan Heeringa	7
Mark Groeneveld	8
Robert Smits	8
Ronald Brouwer	1
Hans jorritsma	6
Auke Algera	7
Rutger Over	7
Tom Segboer	6
Menno Fousert	2
Le Hai Tsung	7
Maaike	8
Non-experts	
Jiri Lausman	1
Tom Lausman	8

Appendix 4: Data from Imbituba

For the Bay of Imbituba there are data available from 1947 to 2001. This covers a time span of 54 years. In this period large morphological changes took place between 1972 and 1982, the most important being the construction of the 850m breakwater in the south of the bay and three groins on the Do Porto beach

The majority of the data used was acquired through the Companhia de Docas de Imbituba CDI (Port authority of Imbituba). Several charts produced in time by different governmental organs where studied. Unfortunately, during the processing of the data an error was discovered in the plotting of the nautical charts from 1979, 1980, 1981, 1982, 1983 and also 1992. The Port of Imbituba confirmed this error. An overview of the used data is given below.

Charts

Imbituba 1947

Name	Departamento nacional de portos rios e canais 17º distrito s.c. Porto e enseada de Imbituba Desenho: No 4776
Datum	**Vertical:** Sondagens expressadas em metros referidas ao plano do zero hidrográfico **Horizontal:** Not indicated on chart
Scale	1:2500
Date	1947

Imbituba 1979

Name	Companhia Brasileira de Dragagem Sondagem Batimetrica da enseada de Imbituba Desenho: CBD-DT No 1665
Datum	**Vertical:** Profundidades em metros reduzidas ao zero hidrográfico da Portobrás Nota: O nível de redução da D.H.N esta a 7 cm acima do zero hidrográfico da Portobrás **Horizontal:** U.T.M. / Origem Itajubá
Scale	1:5000
Date	Período de sondagem 17/01/79 a 22/01/1979

Imbituba 1980

Name	Companhia Brasileira de Dragagem Levantamento topohidrografico da enseada de Imbituba CBD-DT No 1724
Datum	**Vertical:** Profundidades em metros reduzidas ao zero hidrográfico da Portobrás Nota: O nível de redução da D.H.N esta a 7 cm acima do zero hidrográfico da Portobrás **Horizontal:** U.T.M. / Origem Itajubá

Scale	1:5000
Date	Período da sondagem 05 a 13-02-1980

Imbituba 1981

Name	Companhia Brasileira de Dragagem Levantamento topohidrografico da enseada de Imbituba Desenho: CBD-DT No. 1842
Datum	**Vertical:** Profundidades em metros reduzidas ao zero hidrográfico da Portobrás Nota: O nível de redução da D.H.N esta a 7 cm acima do zero hidrográfico da Portobrás **Horizontal:** U.T.M. / Origem Itajubá
Scale	1:5000
Date	Período de sondagem 09/02/81 a 14/02/81

Imbituba 1982

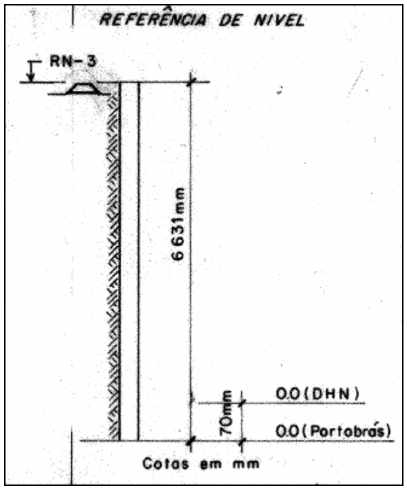
Name	Companhia Brasileira de Dragagem Batimetria da enseada de Imbituba S.C. Desenho: CBD-DT No.1935
Datum	**Vertical:** Profundidades em metros reduzidas ao zero hidrográfico da Portobrás Nota: O nível de redução da DHN esta 7cm acima do zero Hidrográfico do PortoBras **Horizontal:** U.T.M. / Origem Itajubá
Scale	1:5000
Date	Período de sondagem 23/11, 30/11,01/12 e 04/12/82

Imbituba 1983

Name	Companhia Brasileira de Dragagem Levantamento topohidrografico da enseada de Imbituba Desenho CBD-DT No. 2018
Datum	**Vertical:** Profundidades em metros reduzidas ao zero hidrografico da Portobras Notas: O nível de redução da D.H.N esta a 7 cm acima do zero hidrográfico da Portobrás As cotas com sinal negativo, estão acima do zero hidrográfico da Portobrás Linhas de contorno de topografia aproximadas **Horizontal:** U.T.M. / Origem Itajubá
Scale	1:5000
Date	Período da sondagem 09/a 17/12/83

Imbituba 1992

Name	Projeto Provida –SC Companhia Docas de Imbituba – SC Levenatamento Topo-Hidrografico na Enseada de Imbituba – SC Desenho no.: CDRJ-INPH 143-59

Datum	**Vertical:** Profundidade em metros Reduzidos ao Nível de Redução DHN  **Horizontal:** U.T.M. / Origem Itajubá
Scale	1:2000
Date	Período da sondagem 14-10-92 a 6-11-92

Aerial photographs

PHOTO #	NAME	Scale	Date
1	Imbituba 1966	1:30.000	1966
2	Imbituba 1995	1:12.500	11/1995
3	Centro.jpg and Divinea-Aguada.jpg	1:20.000	08/2001

Autocad drawings

DRAW. #	NAME	scale	YEAR
1	Imbituba 2001	1:4000	2001
2	Carta Nautica 1908 SAD 69.dwg	1:4000	Based on charts from 1988 and 1956
3	SPU	-	Based on nautical charts from 1995

GPS measurements

DRAW. #	NAME	scale	YEAR
1	Imbituba 2005	1:15000	2001

Appendix 5: Georeferencing of the data

Before applying the parabolic bay shape equation, preparation of the raw data was needed. This included using the GIS software program ArcMAP 9 to designate the correct UTM coordinates to the images (georeferencing) and to digitalize the coastline. In the following paragraphs a description of the data preparation. is given.

1.1. ALINING THE RASTER DATA

The nautical charts and aerial photographs were digitalized by means of a scanner. (Generation of *raster data*)

To use these *raster datasets* in conjunction with other spatial data, the aligning, or *georeferencing* to a map *coordinate system* is required. A map coordinate system is defined using a map projection (a method by which the curved surface of the earth is portrayed on a flat surface). The coordinate system used in this project was:

Projected coordinate system:
UTM South American 1969 UTM Zone 22S
SAD_1969_UTM_Zone_22S
Projection: Transverse_Mercator
False_Easting: 500000.000000
False_Northing: 10000000.000000
Central_Meridian: -51.000000
Scale_Factor: 0.999600
Latitude_Of_Origin: 0.000000
Angular Unit: Degree (0.017453292519943295)
Prime Meridian: Greenwich (0.000000000000000000)

Datum: D_South_American_1969
Spheroid: GRS_1967_Truncated
Semimajor Axis: 6378160.000000000000000000
Semiminor Axis: 6356774.719195305400000000
Inverse Flattening: 298.250000000000000000

The georeferencing of the raster dataset was done using existing spatial data (*target data*)

This assumes that there are features in the *target data* that are also visible in the raster—for example, street intersections or building corners. The process involves identifying a series of ground control points—known x,y coordinates—that link locations on the raster dataset with locations in the spatially referenced target data. The control points are used to build a polynomial transformation that will convert the raster dataset from its existing location to the spatially correct location. The connection between one control point on the raster dataset (the "from point") and the corresponding control point on the aligned target data (the "to point") is called a link. The number of links needed to create depends on the complexity of the polynomial equation chosen to transform the raster dataset to map coordinates. However, adding more links will not necessarily yield a better registration. If possible, the links should be spread out over the entire raster dataset rather than concentrating them in one area. Typically, having at least one link near each corner of the raster dataset and a few throughout the interior produces the best results.

The spatially referenced *target data* used, as the basis for georeferencing was an image obtained from the Secretaria Do Patrimônio Da União (SPU) it is a digital chart composed from nautical charts of 1995 of the south coast of Santa Catarina.

1.2. TRANSFORMATION OF THE RASTER

After creating enough links the raster dataset is transformed (or *warped*) to permanently match the map coordinates of the target data. The transformation uses a polynomial equation to determine the correct map coordinate location for each cell in the raster.

ArcMAP 9 allows transformation of the raster up to the fourth order. A first-order—or affine—transformation is used to shift, scale, and rotate the raster dataset. This generally results in straight lines on the raster dataset mapped as straight lines in the warped raster dataset. Thus squares and rectangles on the raster dataset are commonly changed into parallelograms of arbitrary scaling and angle orientation.

With a minimum of three links, the mathematical equation used with a first-order transformation can exactly map each raster point to the target location. Any more than three links introduces errors, or residuals, that are distributed throughout all the links.

However, during the georeferencing more than three links where added because if one link is positionally wrong, it has a much greater impact on the transformation.

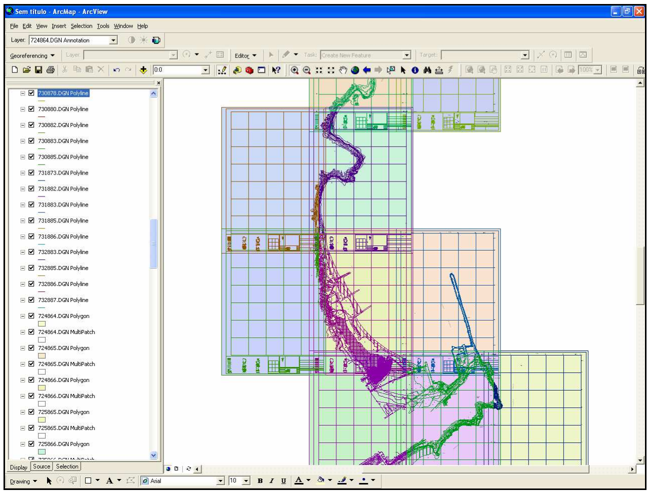
Thus, even though the mathematical transformation error may increase as more links are created, the overall accuracy of the transformation will increase as well.

The higher the transformation order, the more complex the distortion that can be corrected. However, transformations higher than third order are rarely needed. Higher-order transformations require more links and thus will involve progressively more processing time.

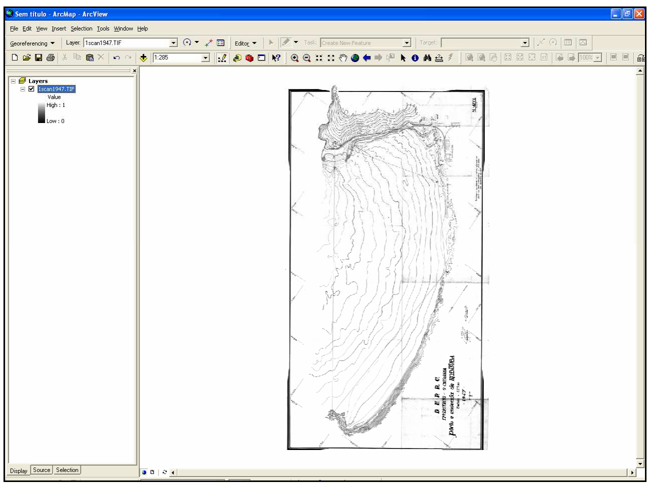
If the raster dataset needs to be stretched, scaled, and rotated, the ArcMAP 9 help file advises to use a first-order transformation. If, however, the raster dataset must be bent or curved, a second- or third-order transformation is required.

This was not the case during this project that is why only the first-order—or affine—transformation was applied on the data from Imbituba The georeferencing process is illustrated in steps 1-3.

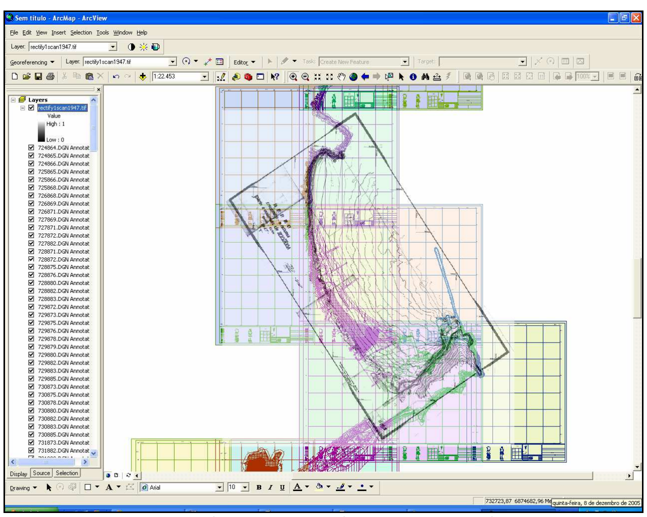
GEOREFERENCING OF THE RASTER DATA



Step 1: The reference chart (SPU) is loaded into ArcMAP 9



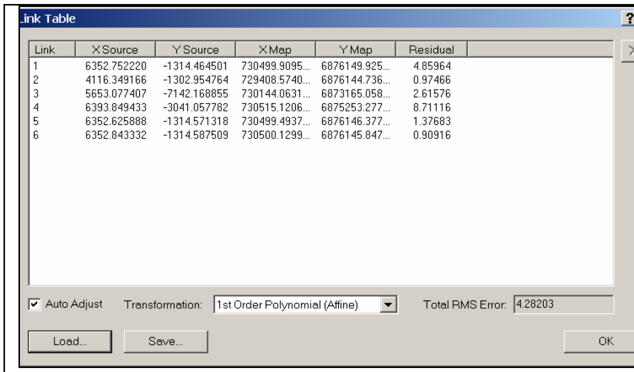
Step 2: Scan of the original chart (e.g. 1947) is loaded into ArcMAP 9 in. TIFF format



Step 3: Using the chart from SPU as reference the chart from 1947 is georeferenced and then rectified, permanently transforming and saving the raster dataset after georeferencing.

1.3. ACCURACY OF THE TRANSFORMATION OF THE RASTER

The degree to which the transformation can accurately map all control points can be measured mathematically by comparing the actual location of the map coordinate with the transformed position in the raster. This information is given in the link table
(Figure A5-1) of ArcMAP 9
The distance between these two points is known as the residual error. The total error is computed by taking the root mean square (RMS) sum of all the residuals to compute the RMS error. This value describes how consistent the transformation is between the different control points (links). Links can be removed if the error is particularly large, and more points can be added. (Figure A5-2)



Link Table

Link	X Source	Y Source	X Map	Y Map	Residual
1	6352.752220	-1314.464501	730499.9095...	6876149.925...	4.85964
2	4116.349166	-1302.954764	729408.5740...	6876144.736...	0.97466
3	5653.077407	-7142.168855	730144.0631...	6873165.058...	2.61576
4	6393.849433	-3041.057782	730515.1206...	6875253.277...	8.71116
5	6352.625888	-1314.571318	730499.4937...	6876146.377...	1.37683
6	6352.843332	-1314.587509	730500.1299...	6876145.847...	0.90916

Auto Adjust   Transformation: 1st Order Polynomial (Affine)   Total RMS Error: 4.28203

Load...   Save...   OK

Figure A5-1: Example of the *link table* in ArcMAP 9, which displays the residual error of the links, the order of transformation and the error of the transformation (Root Mean Square)

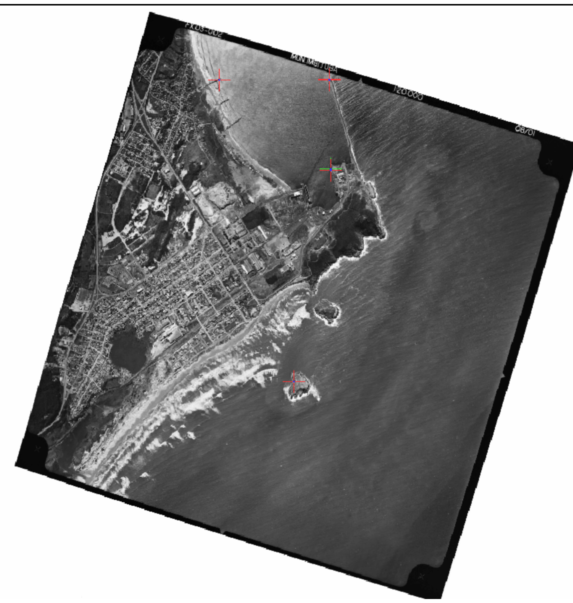


Figure A5-2: Position of the links needed for georeferencing of the aerial photograph

While the RMS error is a good assessment of the accuracy of the transformation, a low RMS error does not necessarily mean an accurate registration. For example, the transformation may still contain significant errors due to a poorly entered control point.
During the georeferencing of the images it was therefore the goal to minimize as much as possible the RMS and at the same time position the links as accurately as possible.

The RMS error of the transformed images used in this project is displayed in Table A5-1. It can be seen that the error of the aligning was in average of 1,5722 meters. The high value of the RMS error of the chart of 1983 is probably due to inaccurate plotting. It was difficult to fit the reference image SPU to this chart without getting a high RMS error.

Table A5-1 RMS of the georeferencing of the images from Imbituba

Image	Scale	RMS error (meters)
1947	1:2500	1.21276
1966	1:30.000	0.93426
1979	1:5000	0.92152
1983	1:5000	3.26118
1988	1:50.000	Already referenced
1995	1:12.500	Already referenced (SPU)
2001 south (centro)	1:20.000	1.82332
2001 north (Divinea- aguada)	1:20.000	1.28051
Average RMS error:		1,5722

1.4. DIGITALIZING THE COASTLINE

After georeferencing the images, the next step is to digitalize the coastline. This is done by creating a *shape file, which* will overlap the image as a layer that can be edited independently from the image. The *shape file* is projected on the same coordinate system as the image: UTM *South American 1969 UTM Zone 22S*

Working in the shape file the coastline can be traced using the *editor tools* in ArcMAP 9.The result can be seen in Figure A5-3

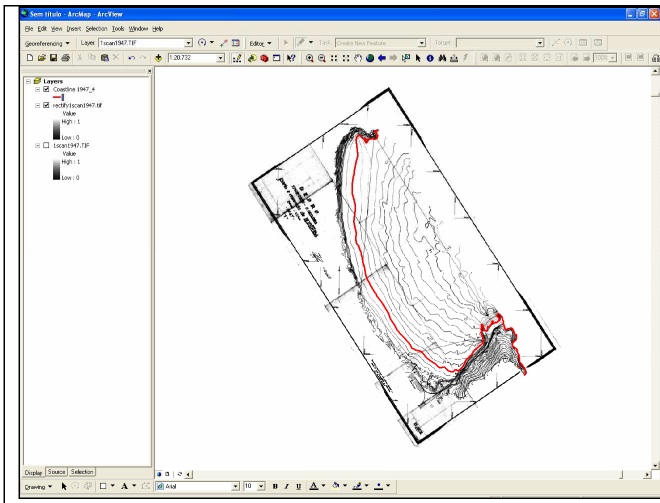


Figure A5-3: Digitalized coastline of the georeferenced chart Imbituba 1947

1.5. VERTICAL REFERENCE: SHORELINE DEFINITION

When digitalizing the shoreline different sources where used in this project to achieve the desired temporal coverage. These sources can be divided in two groups: *Nautical charts* and *Aerial photographs.* According to Boak et.al. (2005), the identification of a 'shoreline' involves two stages: the first requires the selection and definition of a *shoreline indicator* feature, and the second is the detection of the chosen shoreline feature within the available data source.

1.5.1. NAUTICAL CHARTS

When digitalizing the coastline from nautical charts it is of crucial importance that the vertical reference is known.

In Table A5-2 it can be seen that the vertical reference of the charts from 1947 and 1995 was not indicated on the chart.

The vertical reference of the charts from 1979 and 1983 is the

- *Zero hidrográfico da Portobrás*

On these charts the *shoreline indicator* used was the contour line marked as *batente preamar*. (Figure A5-4)

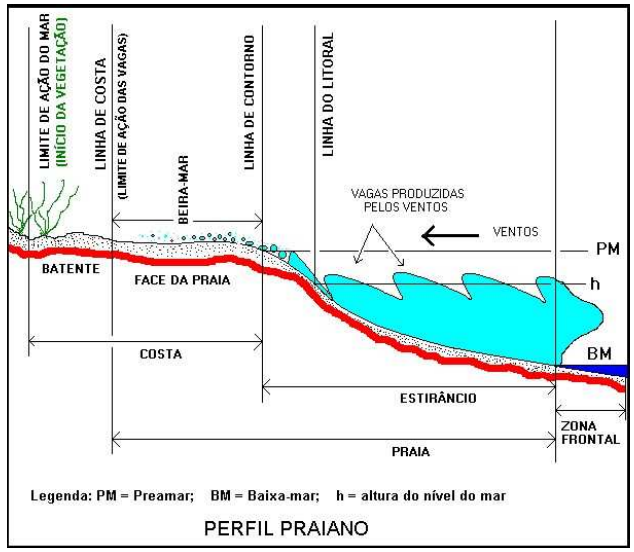


Figure A5-4: Definition of the beach profile and the shoreline indicators

Table A5-2: Vertical reference of used images

Chart	Vertical reference as indicated on chart
1947	Not indicated on chart
1966	Not available: waterline as seen on aerial photograph
1979	Zero hidrografico da PortoBras The contour line indicated as: *Batente Preamar* was digitalized as the coastline
1983	Zero hidrografico da PortoBras The contour line indicated as: *Batente Preamar* was digitalized as the coastline
1988	Diretoria de Hidrografia e Navegação (D.H.N.)
1995	Not indicated on chart
2001	Not available: waterline as seen on aerial photograph

1.5.2. AERIAL PHOTOGRAPHS

Where it is available, aerial photography is the most common data source for determining past shoreline positions.

The digitalization of the coastline was performed manually by visually detecting the waterline on each aerial photograph (Figure A5-5) By definition there can be no means of objective, quantitative control on the repeatability of this inherently subjective method. Recent photogrammetry, topographic data collection, and digital image-processing techniques which now make it possible for the coastal investigator to use objective shoreline detection methods where not (yet) available to the student.

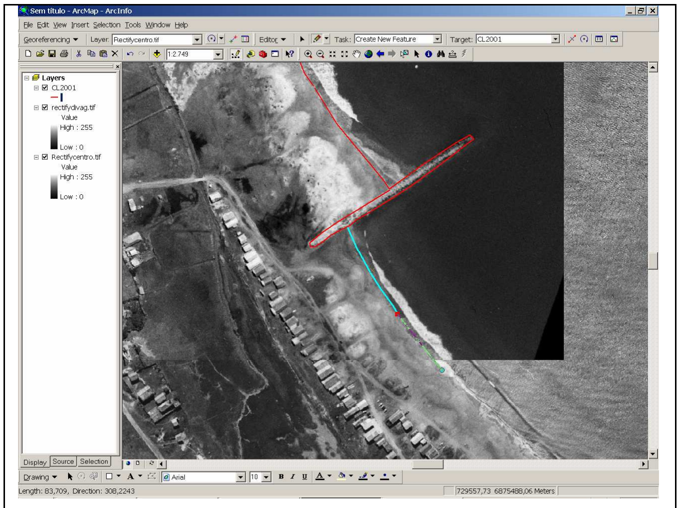


Figure A5-5: **Identification of the waterline can sometimes be difficult, in particular when using (low resolution) aerial photographs with unknown dating.**

Another uncertainty is caused due to the lack of data on the exact time that the photographs were taken.

Therefore only a crude estimate of the error of the digitalization of the coastline can be given by looking at the tidal difference and the slope of the beach. The average slope of Do Porto Beach as determined from Report INPH-65/87[3] in 1987 is:

- Average beach slope: 1:47

The tidal range was obtained from the engineering department from the Port of Imbituba:

- Tidal range 1.50m (max.)

Theoretically the maximum error could be 70.5m (Figure A5-6)

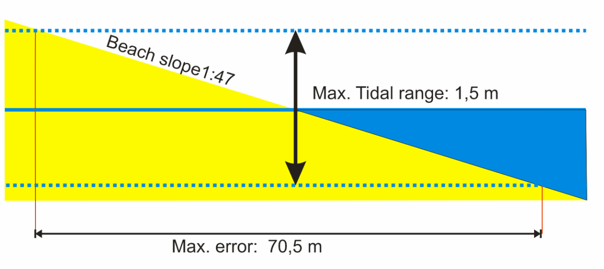


Figure A5-6: Schematical representation of the theoretical error of the digitalization of the coastline of the Bay of Imbituba

1.6. OBSERVED ERRORS IN THE PLOTTING OF NAUTICAL CHARTS

During the georeferencing of the different nautical charts obtained at Imbituba an error in their plotting was observed. As seen in Figure A5-7. On the nautical charts the objects seems to be dislocated + 100m to the east of their correct position. This error in plotting was confirmed by the port of Imbituba. Unfortunately this error was observed in the charts of 1979, 1980, 1981, 1982, 1983 and also 1992. It is for this reason that the mentioned plots were georeferenced according to the characteristic objects on the map (breakwater, groins, Ponta da Ribanceira etc.) and not on the UTM grid.

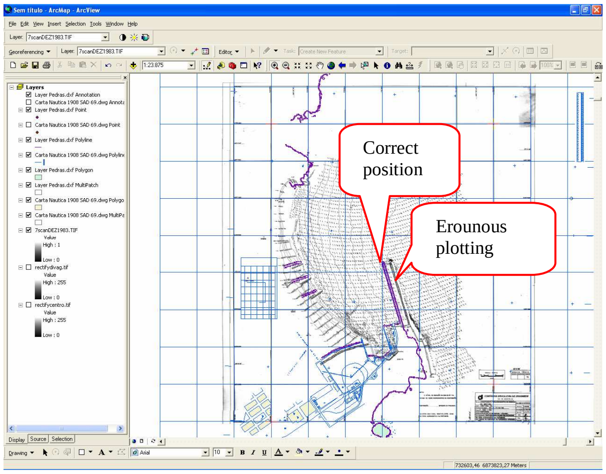


Figure A5-7: Comparing different nautical charts a plotting error was encountered.

Appendix 6: Evolution Of The Coastline Of Do Porto Beach

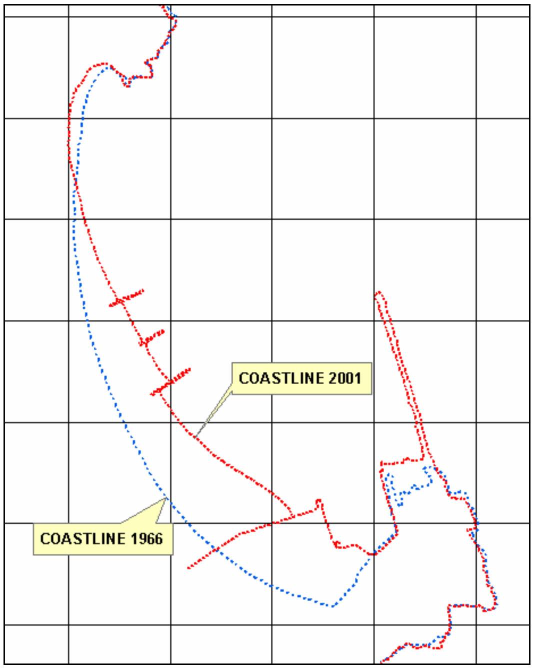


Figure A6 - 1: Plots of the coastlines of Imbituba as taken from the aerial photographs from 1966 and 200. Erosion in the north and accretion in the south can be distinguished.

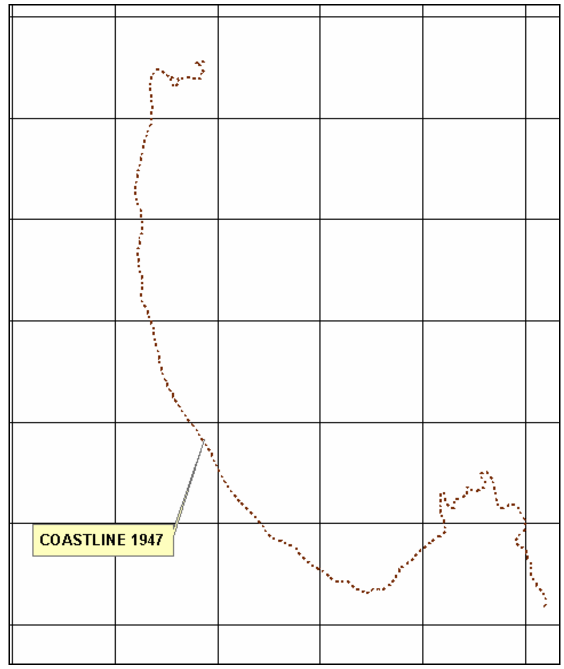


Figure A6 - 2: **Coastline 1947.**

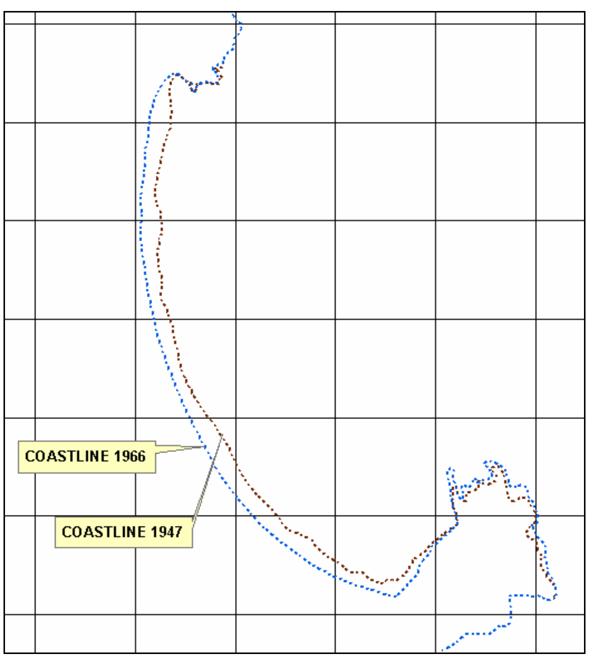


Figure A6 - 3 : Plots coastline 1947 and 1966.Since there are no structures in the bay the difference in position of the coastlines is peculiar. This difference can be attributed to use of different vertical reference levels.

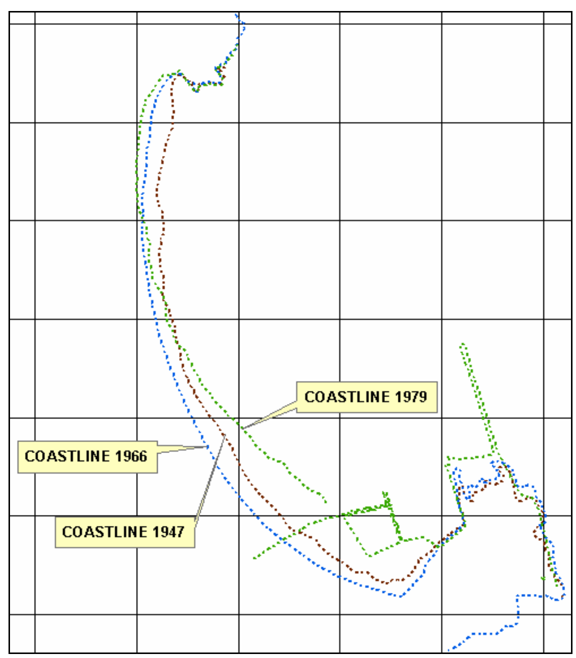


Figure A6 - 4: Plots of the coastlines of Imbituba 1947, 1966 and 1979. The coastline of 1979 shows erosion in the north and accretion in the south of the bay. Construction in the bay is in full progress.

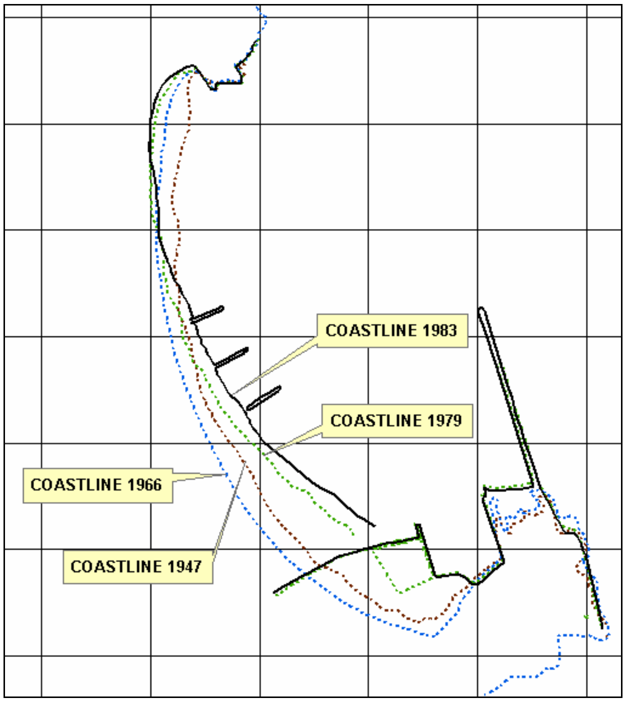


Figure A6 - 5:Plots of the coastlines of Imbituba 1947,1966,1979 and 1983.The addition of coastline of 1983 to the plots reveals: The breakwater is extended to 850 m. Presence of 3 groins. Further sedimentation of the south of the bay and (little) erosion in the north.

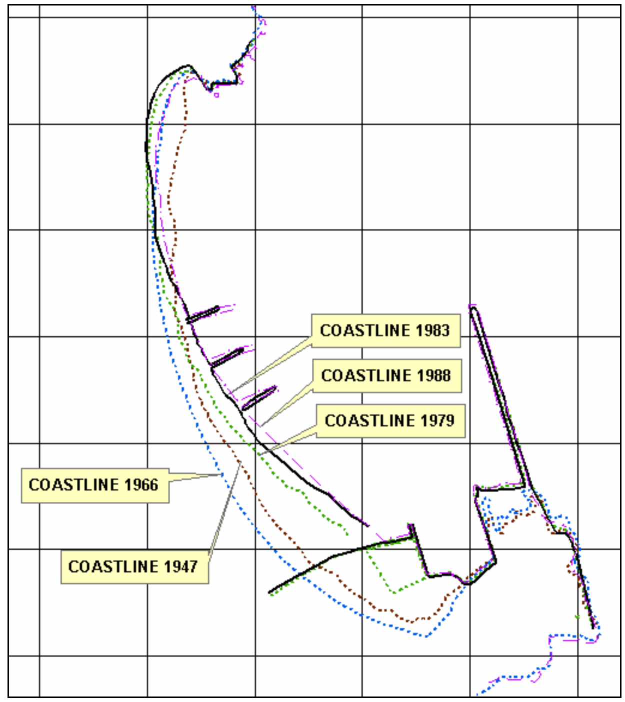


Figure A6 - 6: **Plots of the coastlines of Imbituba 1947,1966,1979,1983 and 1988. The addition of coastline of 1988 to the plots reveals: Accretion in the south and north (!) of the bay.**

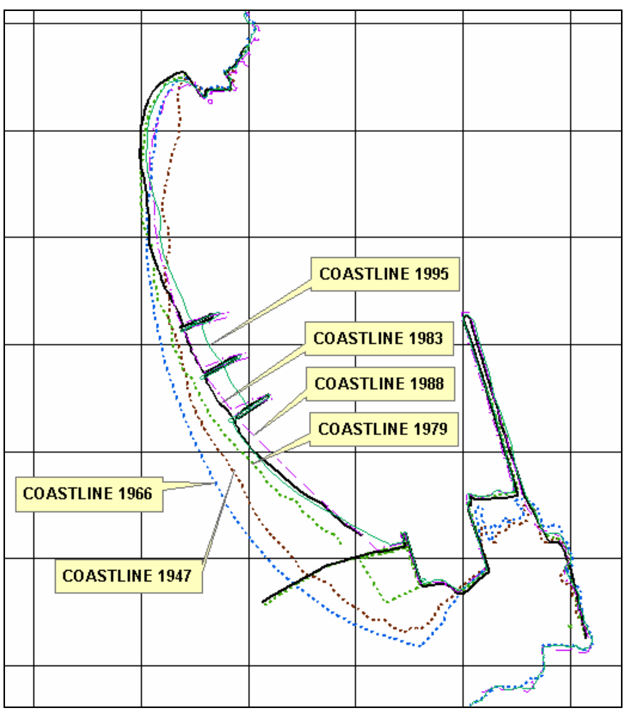


Figure A6 - 7: **Plots of the coastlines of Imbituba 1947,1966,1979,1983,1988 and 1995. The addition of coastline of 1995 to the plots reveals: Erosion in the north of the bay. Sedimentation of the area between the groins.**

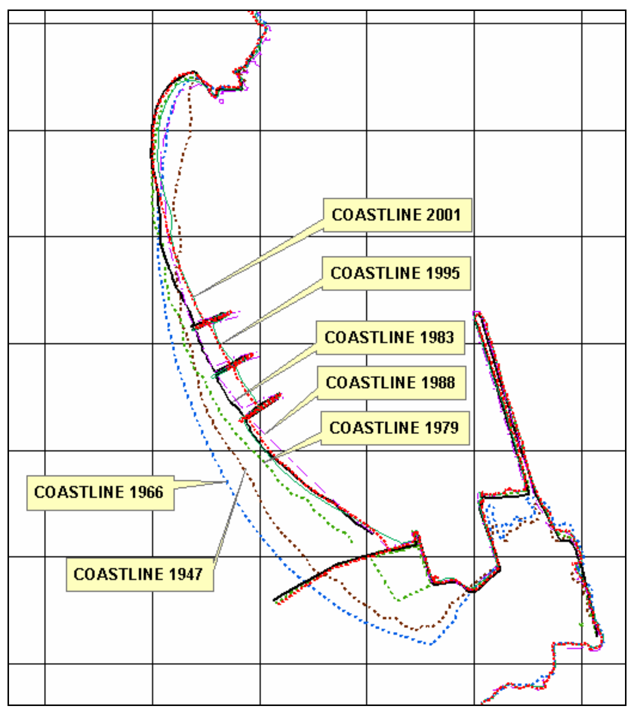
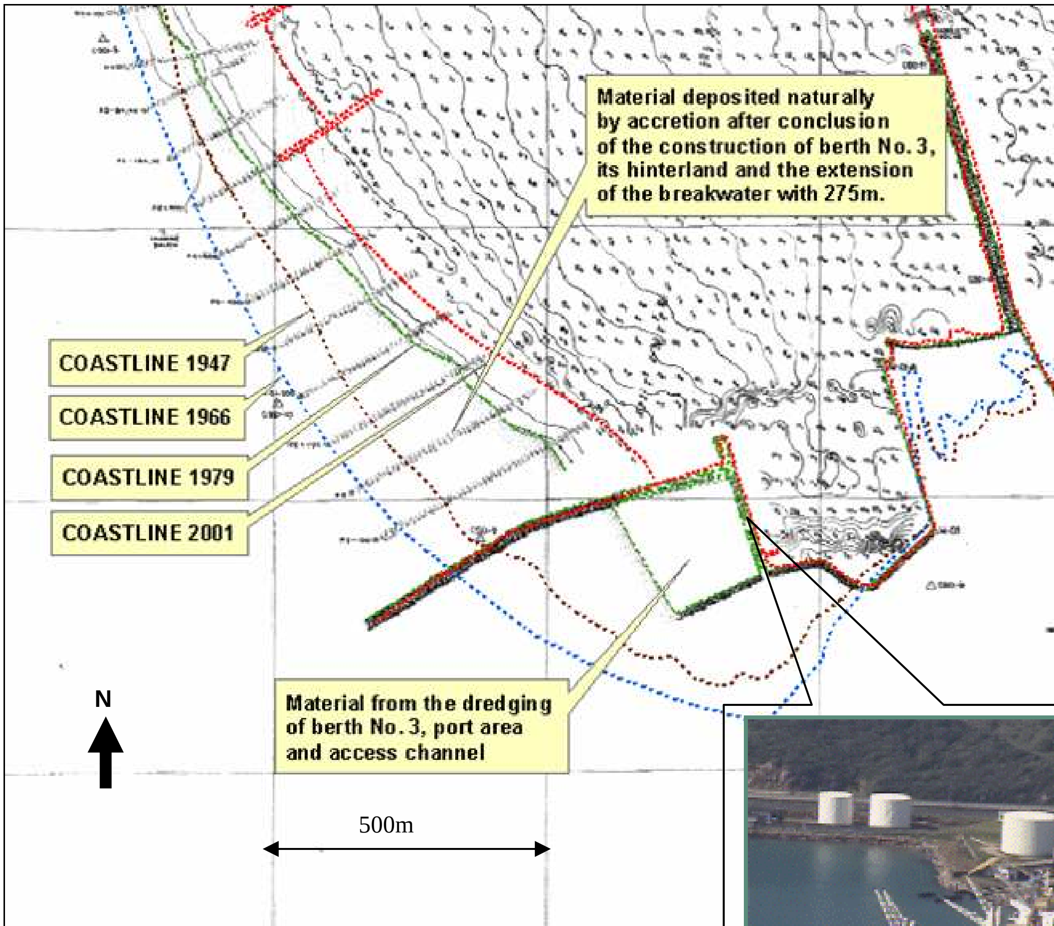


Figure A6 - 8: **Plots of the coastlines of Imbituba 1947,1966,1979,1983,1988,1995 and 2001. The addition of coastline of 2001 to the plots reveals: Slight erosion in the north (compared to the coastline of 1995).**



Berth No. 3

Figure A6 - 9: Accretion of the south of the bay

Appendix 7: Application of the PBSE to Imbituba

In this section the results of the application of the software program MEPBAY to the bay of Imbituba are presented. Data in different formats and of different dates were used. Before interpretation of the results a few comments have to be made regarding the application of the program MEPBAY

System configuration

MEPBAY version 1.0 (November 2002) has been used operating on a Microsoft Windows XP Professional 2002 system, using an Intel Pentium III 930 MHz processor, with 284 MB RAM memory. It is worthy to mention that at the moment a new version of MEPBAY is being elaborated by UNIVALI. Functions are being added to increase user-friendliness and many of the shortcomings of version 1 mentioned here are being eliminated.

mepbay: program description

A good description of the program MEPBAY (Model for Equilibrium Planform of Bay Beaches) is already given by Klein et al 2003[1]. The help file in MEPBAY also contains an elaborate description of the program. Therefore only an abstract of the program description is included in this progress report:

Rocky coasts with headland-bay beaches represent about 51% of the world coastline. Several empirical models have been derived to verify the planforms of these beaches. Among them, only the parabolic model has the mechanism for the evaluation of beach stability, in static or dynamic equilibrium. It has also the capacity to predict possible shoreline changes due to construction/extension of coastal structures on the beach. At the present, the application of the parabolic model is largely in manual form, by way of hand calculation and tracing the calculated bay shape on a copy of map or aerial photograph. To overcome this drawback, a software package called MEPBAY is proposed to facilitate the model application. The MEPBAY is written in Object Pascal language, with computer graphics to display the result of the programming. Starting from a copy of the plan of a bay beach and a set of basic information supplied by the user, MEPBAY calculates the idealized shoreline planform of a headland-bay beach in static equilibrium based on the parabolic model. It then presents the results in graphic form on a screen display. It allows the stability of a headland-bay beach, in static or dynamic, to be assessed by comparing the existing periphery with the idealized planform. The use of MEPBAY not only enhances the understanding of the theme, but also provides a link between the theoretical concepts taught in the classroom and its practical applications for coastal stabilization and coastal management. The software offers an experimental environment where direct manipulation of the information and instant visualization of the results contribute to a better learning of this subject.

Size (in bytes) and format of the data

When importing an image, MEPBAY version 1.0 only accepts .jpeg and .bmp formats. Throughout the application, it has been the goal to import the largest possible file into the program. The image size directly influences the accuracy of the positioning of the control points. The larger the file the more it is possible to zoom-in on the image without loss of image quality. However MEPBAY presents the following problems when working with larger (above 12.000 KB) images:

- The largest image (.bmp) loaded into MEPBAY was 23.932 KB, however it was not possible to save the results from the calculation. The following error message is generated even though sufficient disc space was available.

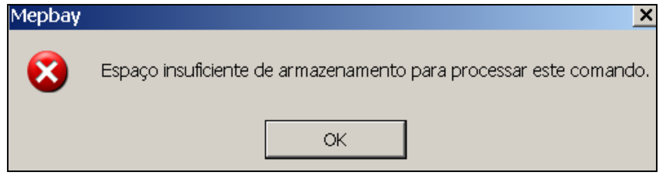


Figure A7 - 1: MEPBAY error message, even with sufficient disc space available.

- Large images (>12.000 KB) that are loaded into MEPBAY are displayed in a close zoomed position. Zooming in and out of the picture to find the right locations of the control points is a laborious and (depending on the processing power of the computer) slow process. A region specific zooming tool as in AutoCAD 2002 would be very useful here.

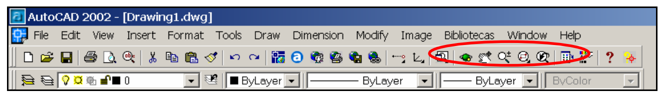


Figure A7 - 2: Region specific zooming tools as in AutoCAD 2002 would be very useful in MEPBAY

- For smaller images (< 12.000 KB .bmp) the static equilibrium planform is displayed in the color blue. In larger images (>12.000 KB) this is not so. The static equilibrium planform is plotted in black, making in sometimes difficult to distinguish from background (contour) lines in the image.

Table A7-3 Characteristics of small and large format images in MEPBAY.

Small format images: (< 12.000 KB)	• Quick to load • Static equilibrium planform is displayed in blue and can be seen clearly on the image when fully zoomed out (complete bay) • Results from application can be saved as .jpeg figure • Lower accuracy
Large format images: (> 12.000 KB)	• Slow to load and to work with • Static equilibrium planform is displayed as a thin black line making it difficult to distinguish. When image is fully zoomed out (complete bay) it is practically impossible to see the plotted planform. • Results from application cannot be saved, due to insufficient space error message. • Higher accuracy in positioning of the control points

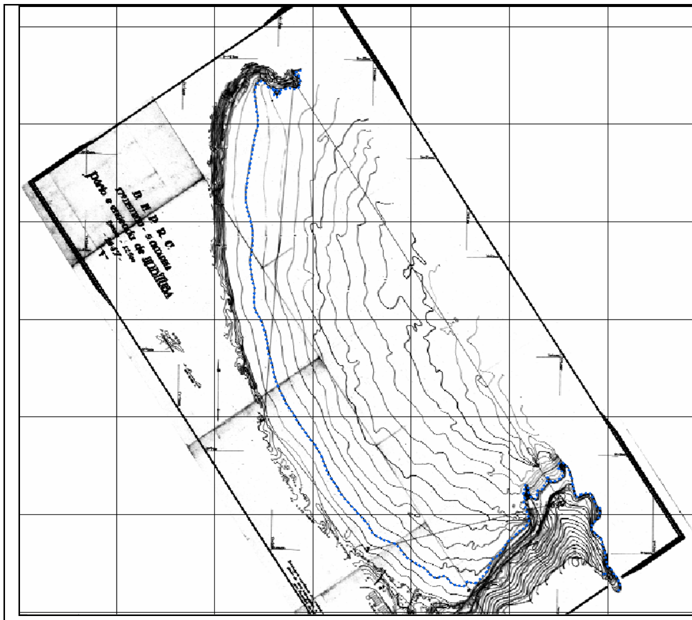
The procedure after georeferencing and digitalization of the coastline is as follows:

1. The georeferenced and digitalized coastline is loaded into MEPBAY in BMP. format
2. The beach orientation is chosen in this case: '***left coast***' and '***down headland***'
3. The scale of the image is introduced (spacing of the grid is 500m)

4. The ***up coast control point*** is introduced at the location where wave diffraction takes place. In the case of Imbituba, the direction of the predominant swell is SE therefore it has been chosen only to apply the Parabolic Bay Shape Equation on the southern headland (Ponta de Imbituba).
5. The ***downcoast control point*** is introduced where the beach starts to become straight and is therefore free from direct influence of the headland. (Benedet, 2004)
6. The last step is to introduce the ***wave direction***. This is done by drawing a tangent to the *downcoast controlpoint*. This tangent may be taken as the wave crest line. The angle formed between the wave crest line and the control line is denoted as β
7. After following these steps, MEPBAY draws the control line, wave direction and the static equilibrium profile. A numeric output is also generated where the value of β, Ro and Rn with the corresponding θ is given

From the above-mentioned, steps 5 and 6 are the most *subjective* of the procedure. They require the user to find a straight part of the Bay of Imbituba. Since straight sections of coastline cannot always be clearly defined on the images used, these steps require careful interpretation and understanding of coastal morphology as viewed from aerial photographs and maps.

Imbituba 1947



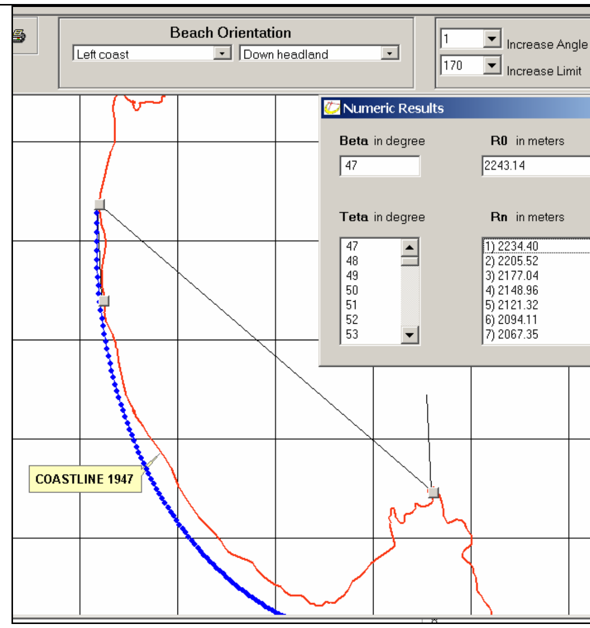
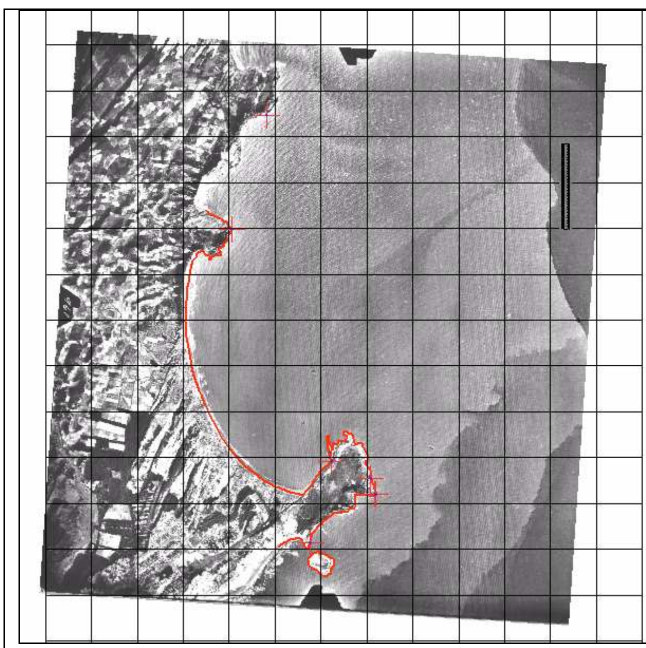


Figure A7 - 3: Georeferenced chart of Bay of Imbituba in 1947. This is the oldest of the nautical charts received from the Port of Imbituba.

Figure A7 - 4: From the georeferenced chart of 1947 the coastline was digitalized and MEPBAY was applied. It can be seen that the SEP is landward of the coastline, particularly in the south of the bay. This indicates *dynamic equilibrium*.

Imbituba 1966



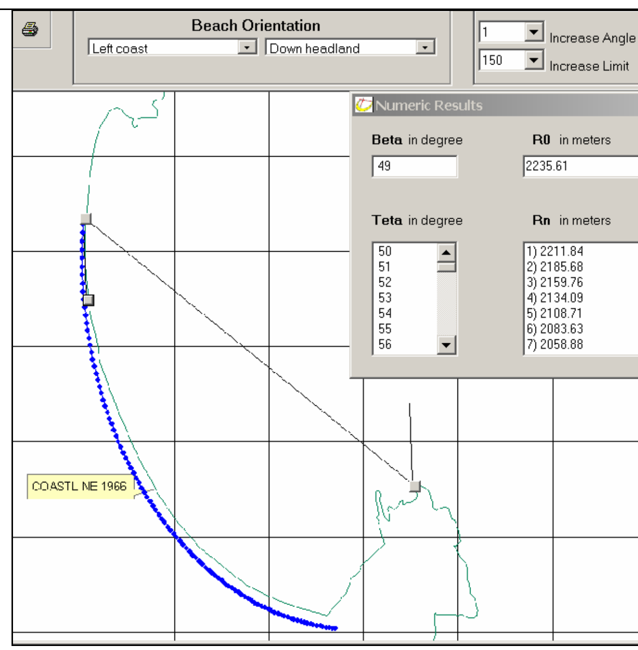


Figure A7 - 5: The next available image is an aerial photograph taken in 1966 (scale: 1:30.000). The coastline has been tracked and imposed on the image

Figure A7 - 6: SEP of the bay in 1966. The existing shoreline is in closer to the predicted static equilibrium.planform than in 1947 but still *dynamic equilibrium*. is maintained

Imbituba 1979

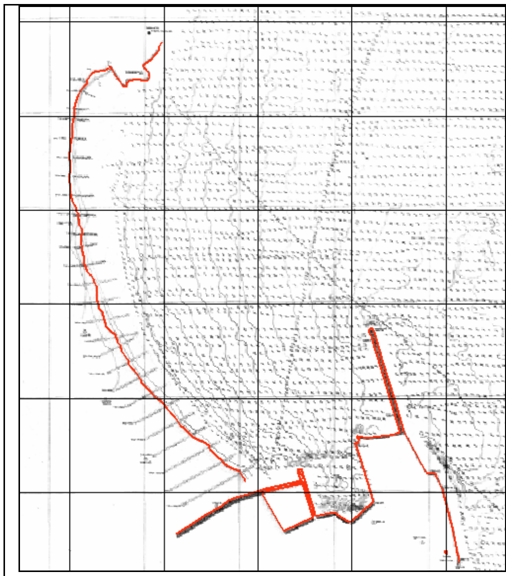


Figure A7 - 7: This nautical chart from 1979 was plotted erroneously as stated above. Therefore the georeferencement was done using the characteristic objects on the map (breakwater, groins, Ponta da Ribanceira etc.) and not on the UTM grid. The coastline has been tracked and imposed on the image.

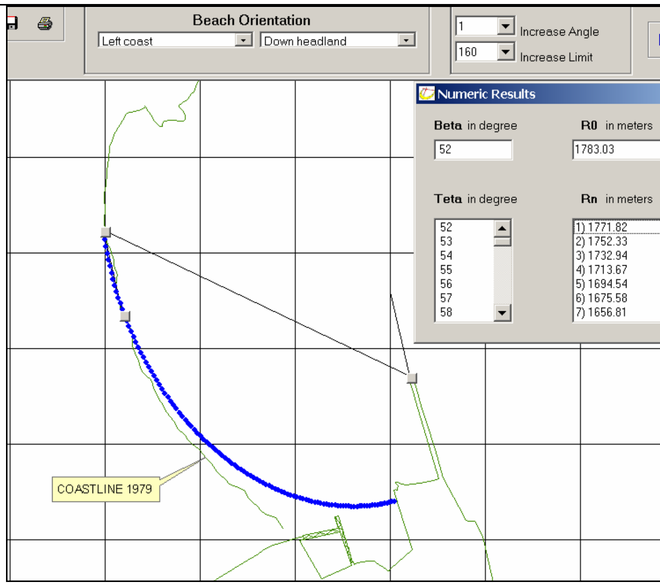


Figure A7 - 8: SEP of the bay in 1979. Construction of 4 berths in the south of the bay is in progress. The first 500 m of the breakwater have been completed and as can be seen in the image the equilibrium status has changed from *dynamic* to *close to static* in the north and *unstable* in the south of the bay.

Imbituba 1983

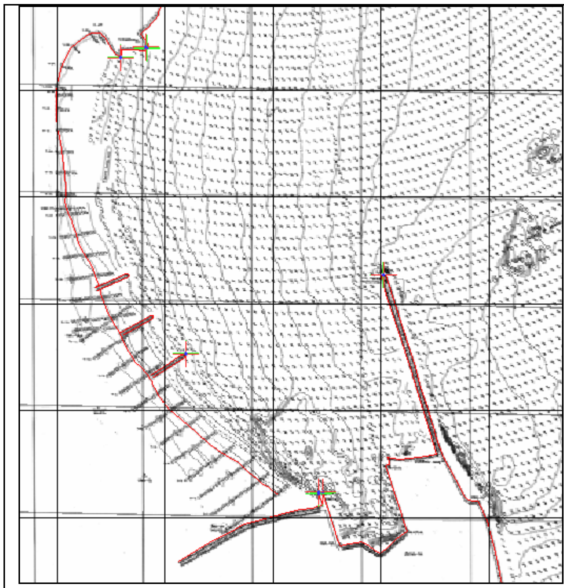


Figure A7 - 9: Nautical chart from 1983 also plotted erroneously as stated above. Therefore the georeferencement was done using the characteristic objects on the map (breakwater, groins, Ponta da Ribanceira etc.) and not on the UTM grid. The coastline has been tracked and imposed on the image.

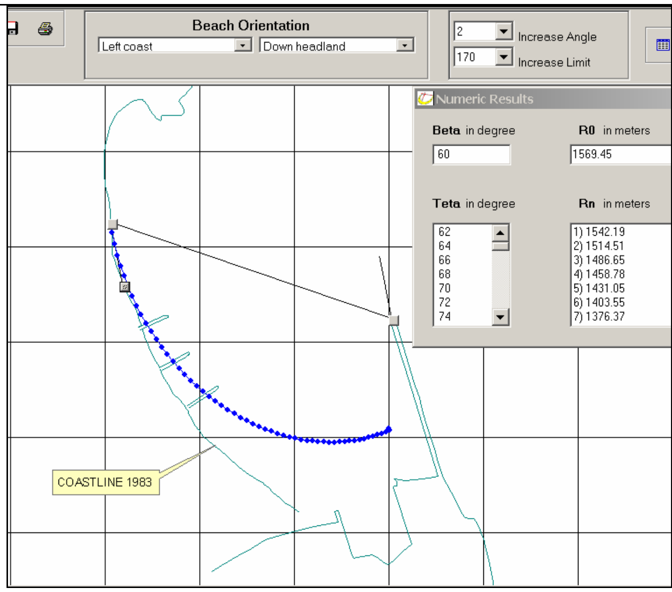
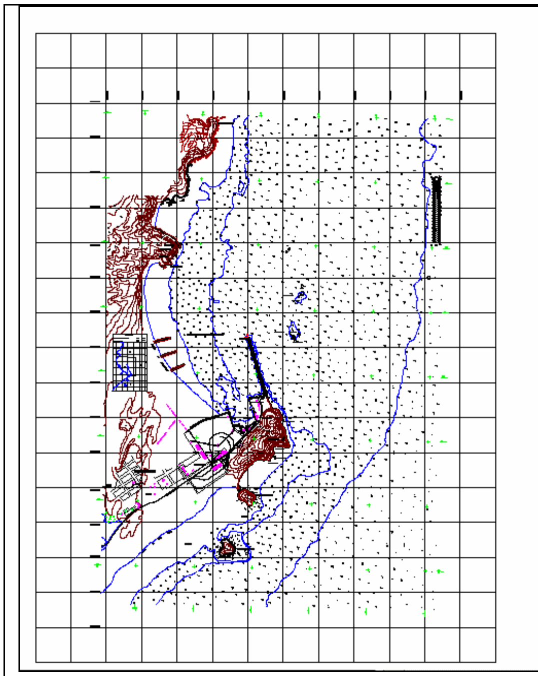


Figure A7 - 10: SEP of the bay in 1983. The breakwater has been extended to 850m and three groins have been constructed on Do Porto Beach and as can be seen in the image the SEP has moved further seawards. The equilibrium status is *close to static* in the north and *unstable* in the south of the bay.

Imbituba 1988



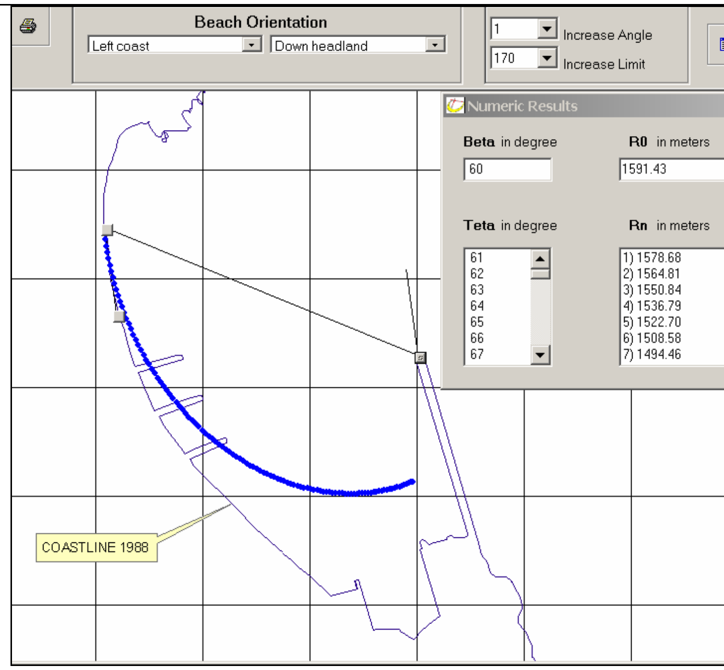
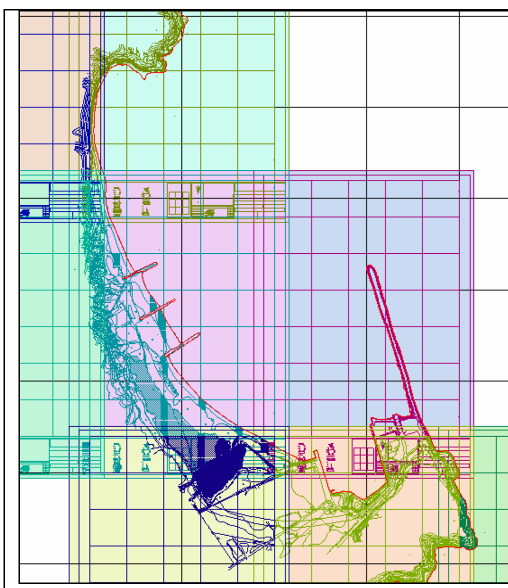


Figure A7 - 11: ***Carta Nautica 1908 SAD 69.dwg*** **obtained by the Port of Imbituba. In this chart the Bay of Imbituba was plotted from a nautical charts dating from 1988.**

Figure A7 - 12: Application of MEPBAY on the bay of Imbituba coastline in 1988. The Bay remains in *close to static equilibrium* in the north and *unstable* in the south of the bay.

Imbituba 1995



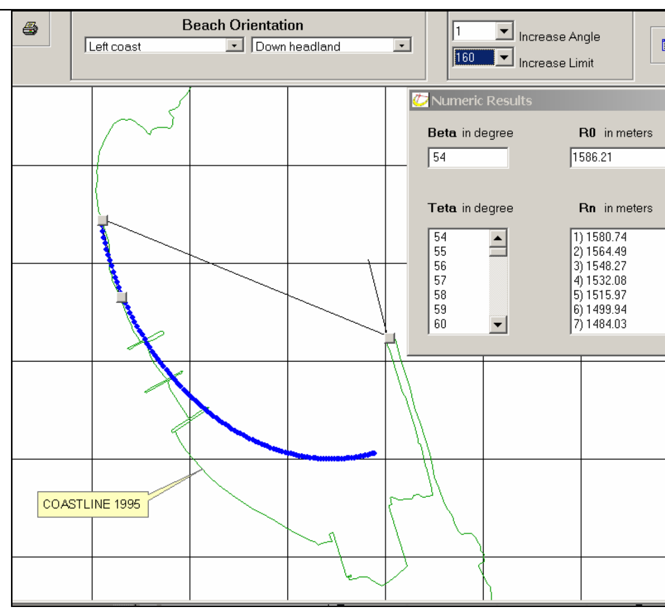


Figure A7 - 13: The drawings from the SPU where used to obtain the coastline in 1995.

Figure A7 - 14: The situation of the bay in 1995 remains *close to static* in the north and *unstable* in the south of the bay, β has slightly changed. The coastline is adapting itself the breakwater. Identification of a straight section of the coastline has been somewhat difficulted by the salient formed by a sunked ship.

Imbituba 2001

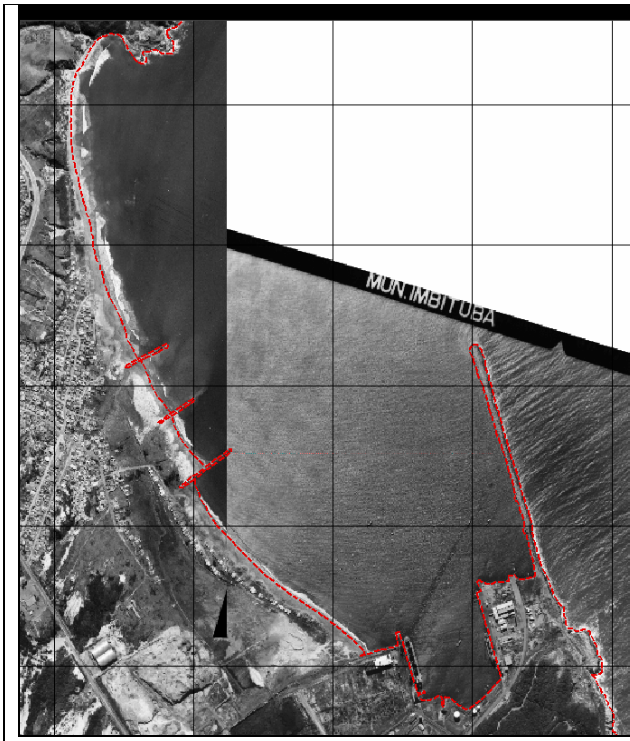


Figure A7 - 15: Georeferenced and joined aerial photographs (scale:1:20.000) of Imbituba in 2001. The digitalized coastline has been imposed on the image.

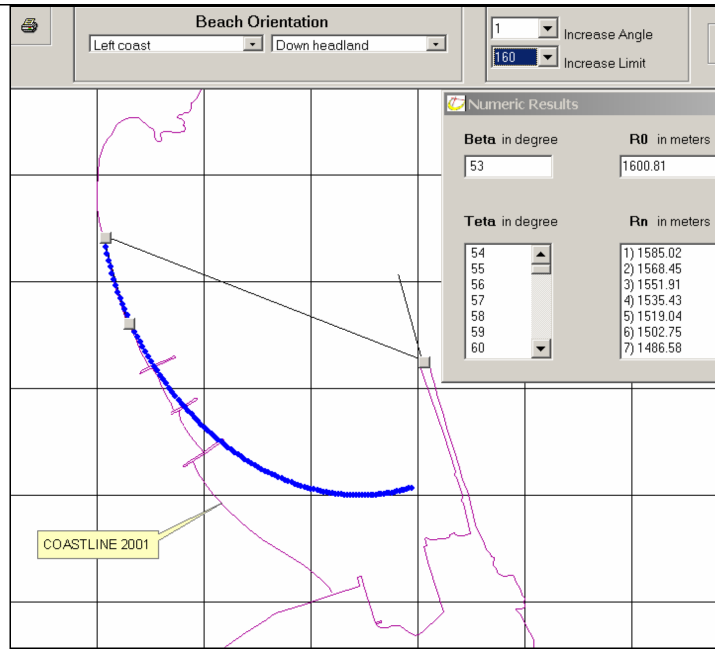


Figure A7 - 16: In 2001 the situation remains the same as in 1995 the bay is still *IN close to static equilibrium* in the north and *unstable* in the south of the bay. β has decreased slightly

Appendix 8: Pictures from Imbituba

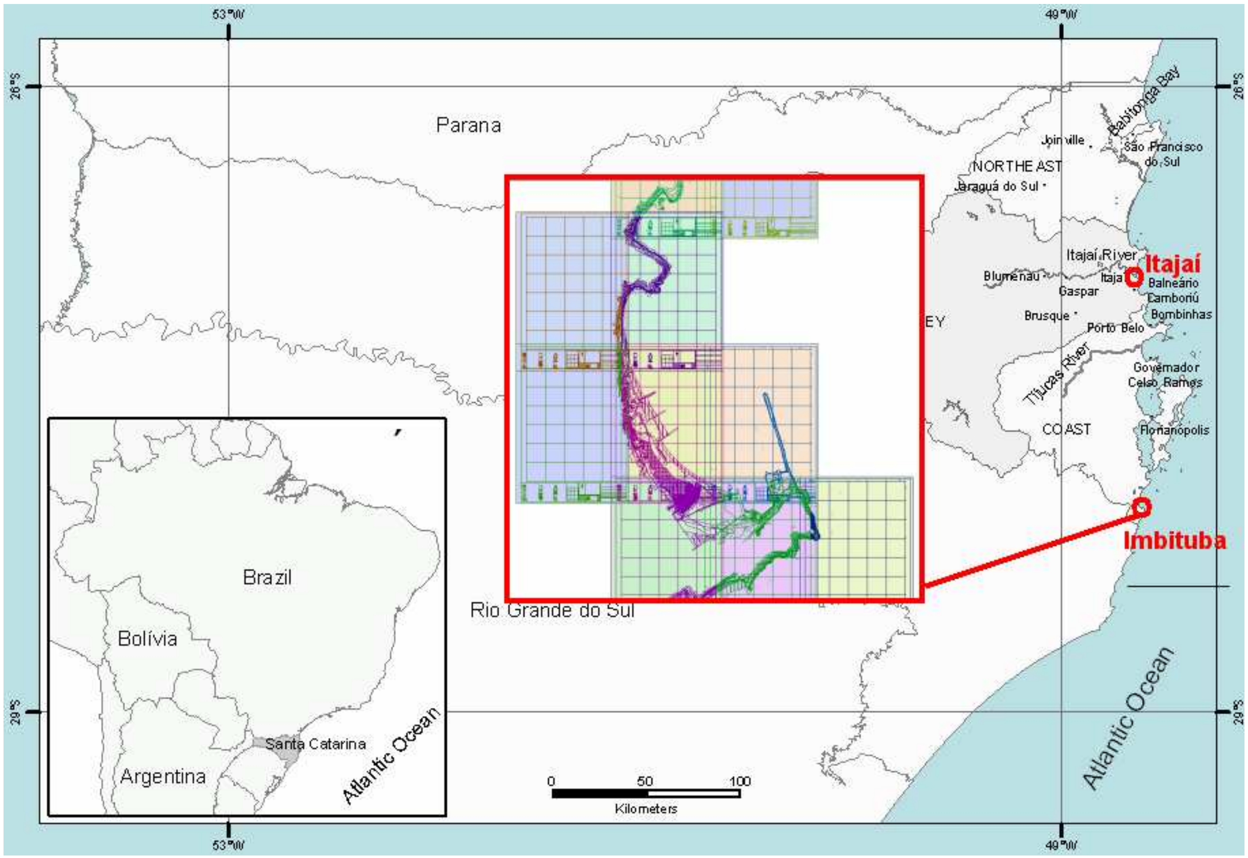


Figure A8- 1: Location of Imbituba and Itajaí

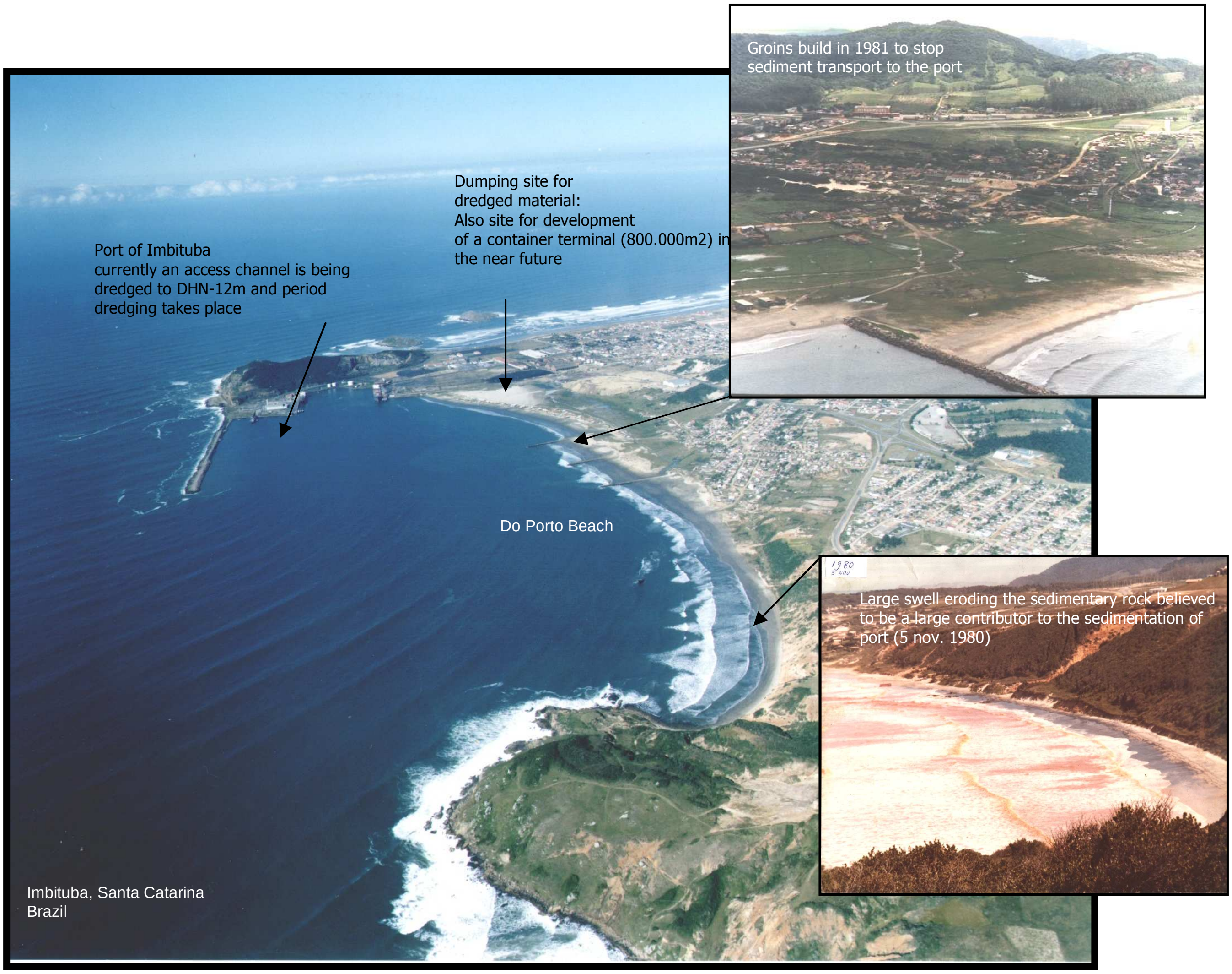


Figure A8- 2: Overview of the Bay of Imbituba, Santa Catarina, Brazil 2005.

Figure A8- 3: Northern part of the bay of Imbituba in 1980 after heavy rainfall, notice the sediment loaded water.

Figure A8- 4: Northern part of the bay of Imbituba in 2004. Notice the vegetation loss.

Figure A8- 5. Zoom in to the beach at the northern part of the Bay.

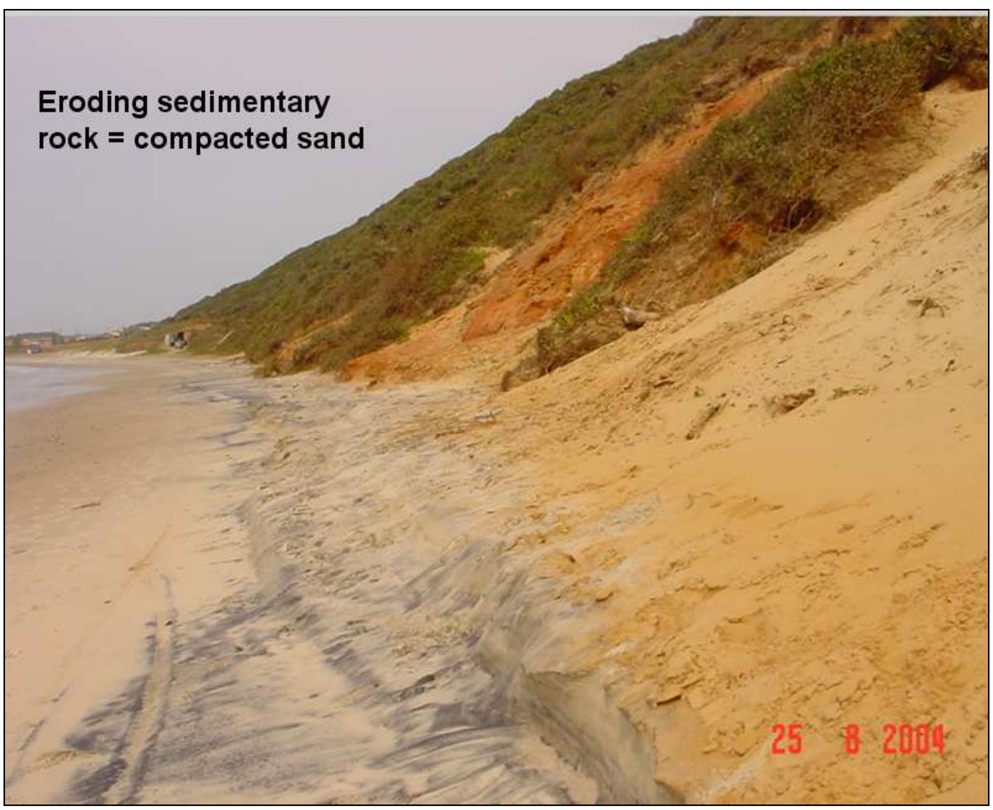


Figure A8- 6: Beach at the northern part of the Imbituba Bay. Waves can reach the toe of the eroding sedimentary rock.

Figure A8- 7: Aerial photograph showing the beach at Imbituba, part of the harbor and the 3 groins.

Figure A8- 8: Most southern groin on the beach of Imbituba.

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Uncertainty in the application of Parabolic Bay Shape Equation: A case study

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Abstract

From the several existing empirical equations that describe the planform of a bay, the Parabolic Bay Shape Equation **(PBSE)** is the only one that explicitly assesses an equilibrium bay shape. Research has been performed on the uncertainties regarding the static equilibrium planform **(SEP)** plotted by this equation but results have been more of a qualitative nature. This paper is an attempt to quantify the uncertainty in the application of the PBSE using existing bays. By means of an expert elicitation, a database consisting of the position of the control points needed to plot the SEP was generated. The elicitation was held under experts in the field of coastal/hydraulic engineering and consisted of two parts. In the Part 1 of the elicitation, twenty-two expert volunteers where asked to place the three control points needed to draw the SEP on a vertical aerial photograph of Taquaras/Taquarinhas Bay, an stable bay, approximately 1800m wide and 750m indent, in the south of Brazil.
The software program MEPBAY, which facilitates the use of the PBSE was used to translate the position of the control points into the SEP's corresponding to the bay. The distribution of the location of the SEP along four evenly spaced (200m) profiles in the southern part of the bay was determined. The overall bias of the location of the SEP calculated over the four profiles is in the order of 40m (landward) and the average bandwidth is 116 m. The bandwidth and standard deviation of the SEP increase when moving alongshore toward the curved section of the bay. This means that the uncertainty in the application of the PBSE is dependent on the particular point of interest along the bay. In Part 2 of the elicitation thirty volunteers participated. This time the consequence of the placement of the control points (the corresponding SEP) was visible. Comparing the results from Part 1 and 2, it was observed that when volunteers are directly confronted with the result of the placement of the control points (a plotted SEP) a much smaller variation in the position of the SEP occurs. This in turn means that the PBSE is a robust method provided the user sees the result of his/her choices in placement of the control points.
After quantifying the uncertainty when applying the PBSE to a stable bay an unstable situation was analyzed. For this case the bay of Imbituba in southern Brazil was chosen. The construction of a breakwater to shelter the port of Imbituba in the south of the bay was accompanied by an increase in sedimentation of the port. Superimposed plots of the coastline of the bay of Imbituba from different years confirm a general trend of accretion of the southern part of the bay accompanied with a retreat of the coastline in the northern part.
After the application of the PBSE it was clear that the breakwater caused a change in the equilibrium state of the bay. Between 1947 and 2001 the Bay of Imbituba has changed from a dynamic equilibrium to a close to static equilibrium in the northern part of the bay and an unstable equilibrium status in the southern part. The tendency of the sedimentation of the southern part of the bay can be explained by looking at the SEP belonging to the new up coast diffraction point (tip of the breakwater): The seaward position of the SEP predicts a need for sediment in order to achieve an stable planform.

Keywords: Equilibrium plan form formulations; Headland-bay beaches; Equilibrium position shoreline

1. INTRODUCTION

1.1. BAY SHAPE EQUATIONS

Rocky coasts with headland-bay beaches represent about 51% of the world coastline. Several empirical bay shape equations have been derived to verify the plan forms of these beaches. An overview of these equations is given in Table 1.

Table 1: Existing bay shape equations

Method	**Comments**
The logarithmic-spiral YASSO (1965) $r_2 = r_1 \exp(\theta \cot\alpha)$ with: r = Radii from the origin (radians) θ = Angle between the wave crest and the radius (degrees) α = Constant angle of the	Provides the best fit for beaches located between two headlands with predominant wave direction.

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tangent to the curve with radii r_1 and r_2 (degrees)	
The parabolic shape equation HSU AND EVANS. (1989)	Improved by GONZÁLEZ AND MEDINA (2001) as to the location of the control point, provides better adjustments for beaches with only one headland.
The hyperbolic tangent shape MORENO AND KRAUS (1999) $y = \pm a \tanh^m (bx)$ with: y = Distance across shore (meters) a,b,m = Empirically-determined coefficients x = Distance along shore (meters)	Simplifies the fitting procedure and reduces ambiguity in arriving at an equilibrium shoreline shape as controlled by a single headland.

The main limitations of the logarithmic spiral equation are BENEDET ET AL. (2004):

1. Due to its constant curvature the equation does not fit the relative straight section of the headland bay beach.
2. Effective wave direction and the tip of the headland (point of wave diffraction) are not used; therefore one cannot predict the effect of relocating the headland or control points (e.g. introduction of coastal structures) on beach planform.
3. The geometric centre of the log-spiral curve is offset from the headland tip and is found by trial and error or a computer program.

The hyperbolic tangent shape MORENO AND KRAUS (1999) claims to be less ambiguous than the parabolic bay shape. Similar to the logarithmic spiral curve, the hyperbolic–tangent equation excludes the use of effective wave direction and the fixed tip of the headland (point of wave diffraction), which serves as a control point. The location of relative origin of coordinates (origin of the curve) and the values of a, b and m in the hyperbolic bay shape equation are obtained by trial and error until its r.m.s.-error is minimized. Because the geometric centre of the curve is not fixed nor based on a physically existing control point related to the bay periphery (e.g. headland tip), one cannot predict the effect of changing the headland or control points (e.g. introduction of coastal structures, structure extension) will have on the beach planform configuration. Consequently, this approach limits its application for design of coastal structures or other human interventions, because this hyperbolic model was not developed to examine the beach stability condition.
On the other hand, the parabolic bay shape equation (PBSE) developed by HSU AND EVANS (1989) links the change of shoreline to the point of diffraction up coast (Figure 1). The physical location of the wave diffraction point (i.e. the tip of the headland) is used as the centre of the coordinate system for the parabolic equation. Consequently, the effect of relocating the point of diffraction, by various engineering methods, can be assessed.
KLEIN ET AL. (2003)

1.2. THE PARABOLIC BAY SHAPE EQUATION (PBSE)

The PBSE (Eq.1) is a second-order polynomial equation obtained by fitting the planform of 27 mixed cases of prototype and model bays believed to be in static equilibrium.

$$\frac{R}{R_0} = C_0 + C_1\left(\frac{\beta}{\theta}\right) + C_2\left(\frac{\beta}{\theta}\right)^2 \quad \text{Eq. 1}$$

$R_{0,\beta}$	=	Control line length
β	=	Wave obliquity
C	=	Constants generated by regression analysis to fit the peripheries of the 27 prototypes and model bays
θ	=	Angle between wave crest and radius to any point on the bay periphery in static equilibrium

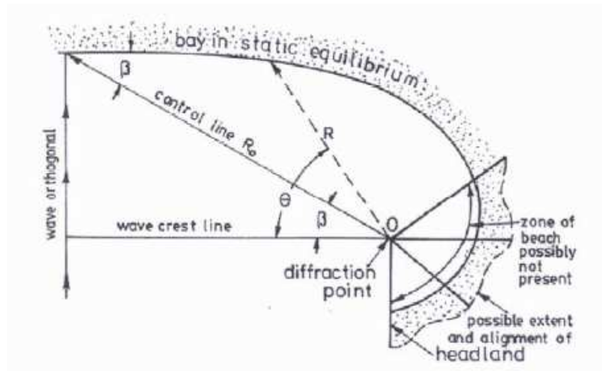


Figure 1: Definition sketch of the parabolic bay shape equation. HSU AND EVANS (1989)

R_0 is the control line length and β is the reference wave obliquity or the angle between the incident wave crest (assumed linear) and the control line, joining the up coast diffraction point to a point on the near straight down coast beach. This is how it is determined from maps, vertical aerial photographs and satellite images. The control line is also angled β to the tangent at the down coast beach end. The radius R to any point on the bay periphery in static equilibrium is angled θ from the same wave crest line radiating from the point of wave diffraction up coast.
The three C constants, generated by regression analysis to fit the peripheries of the 27 prototypes and model bays, differ with reference angle β.
Numerically, these coefficients may be expressed by forth-order polynomials as follows:

$C_0 = 0.0707 - 0.0047\beta + 0.000349\beta^2 - 0.00000875\beta^3 + 0.00000004765\beta^4$
$C_1 = 0.9536 + 0.0078\beta - 0.00004879\beta^2 + 0.0000182\beta^3 - 0.000001281\beta^4$
$C_2 = 0.0214 - 0.0078\beta + 0.0003004\beta^2 - 0.00001183\beta^3 + 0.0000000\beta^4$

These C values are bounded within 2.5 and –1.0 for the usual range of angle β from 10º to 80° applicable in most field conditions. Values of non-dimensional ratios R/R_0 versus increments of 2° of β from 20° to 80° have been tabulated for manual application by SILVESTER AND HSU (1993). For a bay beach with a given set of β and R_0, locations for pairs of R and θ can be marked on the existing waterline, and a curve can be sketched for the static bay shape prediction.

The nearness of the existing beach planform to the static equilibrium shape can then be verified. SILVESTER AND HSU (1993) proposed that in terms of beach stability, headland-bay beaches may be classified as being in:

- *Dynamic equilibrium*
- *Static equilibrium*
- *Unstable Situation*

Dynamic Equilibrium

As seen in Figure 2, bays are crenulate-shaped with a curved segment in the lee of the upcoast headland and straighter in orientation towards the downcoast limit. Whilst sediment is still passing through the bay or fed to it internally, the bay can be said to be in *dynamic equilibrium*. Figure 4 shows the Bay of Imbituba in 1947 considered to be in dynamic equilibrium.

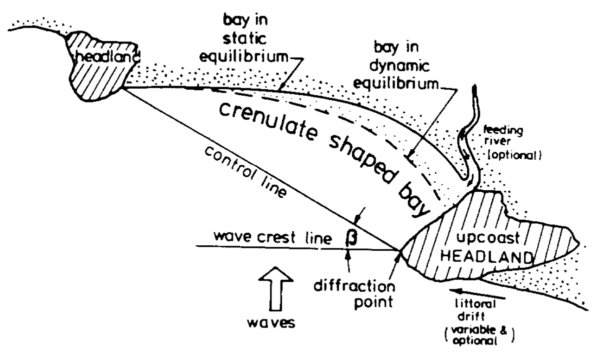


Figure 2: Dynamic and static equilibrium shape of bay formed between two headlands. (HSU ET AL. 1992)

Static Equilibrium

A bay can become more indented if the littoral drift is reduced in the longer term by natural reduction of supply or by man-induced impediments. In the event of complete cut-off, the bay will recede to a limiting indentation, as indicated in the Figure 2, by the waterline termed *static equilibrium* (HSU AND EVANS, 1989). This *static equilibrium* is reached when the dominant waves are seen to be breaking simultaneously around the whole bay periphery.

On beaches considered to be in static equilibrium the tangential section down coast is found experimentally to be parallel to the wave crests approaching the coast from offshore. Under this condition, it may be assumed that:

- No further sediment is being added or eroded from the bay, under the persistent swell condition.
- Waves break simultaneously around the bay periphery.
- Littoral drift or alongshore currents are almost non-existent.

Figure 3 shows the Bay of Taquaras/Taquarinhas, an example of a beach in static equilibrium.

Unstable Situation

On the other hand, for bays classified as *unstable* (Figure 5), often resulting from wave sheltering by a structure added to the beach, the curved shoreline experiences accretion in the lee of the structure accompanied by erosion down coast in the process of natural reshaping. KLEIN ET AL. (2003)

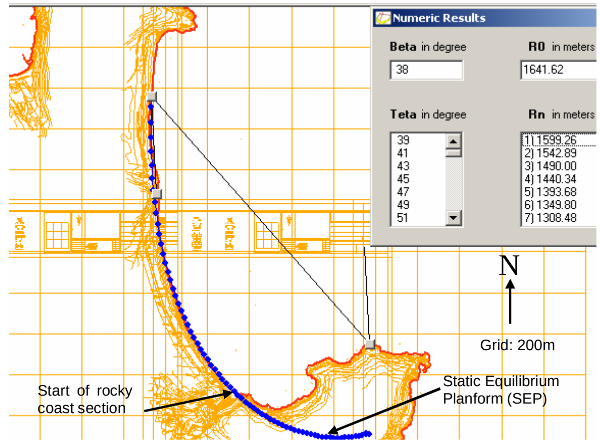


Figure 3: *Static equilibrium*: The shoreline of the bay coincides with the planform plotted by the PBSE except for the section down coast which consist of rocky coast.(Taquaras/Taquarinhas Beach, Brazil)

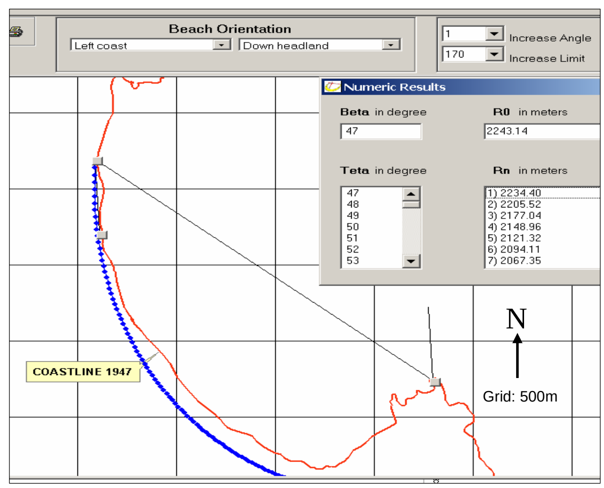


Figure 4: *Dynamic equilibrium*: The shoreline of the bay is seaward of the planform plotted by the PBSE. (Bay of Imbituba, Brazil, 1947)

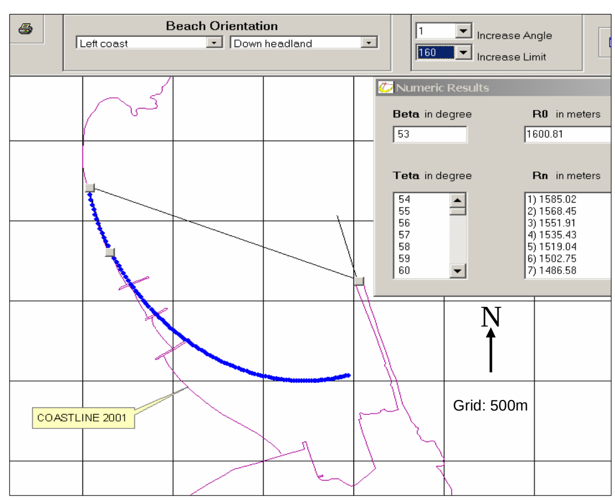


Figure 5: *Unstable situation*. Coastal constructions have changed the morphology of the bay. The southern section of the bay does clearly not coincide with the static equilibrium shape (Bay of Imbituba, Brazil, 2001)

1.2.1. PBSE: Conditions of application

The PBSE can be applied on shorelines around the oceanic margins of the world where the following conditions are in force. HSU AND EVANS (1989):

a) The sediment is predominantly sand.
b) Swell waves arrive persistently from a narrow fan of directions.
c) The tidal range is small (<2m).
d) Where headlands exist, they dictate the shape of intervening shorelines.
e) When storms arrive, the beach berm is partially or totally removed offshore as a bar.
f) Bar material is returned shoreward by milder waves such as swell.
g) Offshore bars remain as a feature for only a few days after each storm
h) If waves in (f) above are oblique to the coast, they effect a pulse of littoral drift.
i) The direction of net longshore movement of sediment is dictated by swell rather than storm waves.
j) The annual rate of littoral drift is influenced more by the number of storms than by the longshore component of swell wave energy.

In principle the PBSE can also be applied to fully enclosed and partially enclosed seas, keeping in mind the specific wave climates and tidal conditions. In fact, water levels are of little concern if shoreline shape is considered at the high water mark. (HWM)

An important condition of application of the PBSE is that at present, bays in dynamic equilibrium cannot be predicted, mainly because the littoral drift that is still occurring is difficult to asses. Thus it is only for bays in static equilibrium that a precise relationship can be found between the parabolic shape and the wave obliquity β to the control line from the upcoast headland to the downcoast limit of the bay.
In practice, this translates is an important disadvantage of the PBSE because it reduces the validity of this method significantly to only bays that do not experience sediment bypass.

When trying to understand the morphological behavior of a coastline, there are various aspects that can be investigated. Sediment characteristics, sand budgets, wave- and current climate can all be used to provide an insight into coastline behavior. Many (numerical) software programs, such as UNIBEST and DELFT3D use this data to simulate water and sediment movement. The PBSE equation uses a simpler (empirical) approach. To use the equation, relative little information is needed. The original PBSE proposed by HSU AND EVANS (1989) requires only information, which can be derived from vertical aerial photographs or charts of the bay. Based on information from these sources, the PBSE prescribes the shape of the bay considered to be in static equilibrium. The PBSE does not describe the timeframe in which the bay would reach this shape, it only gives the final result: the static equilibrium planform of the bay (SEP). Parameters such as grain size cannot be chosen explicitly but are contained implicitly in the equation.

1.3. MODEL FOR EQUILIBRIUM PLANFORM OF BAY BEACHES (MEPBAY)

Originally, the application of the parabolic model was largely in manual form, by way of hand calculation and tracing the calculated bay shape on a copy of map or aerial photograph.
To overcome this drawback, a software package called MEPBAY has been developed by the Universidade do Vale do Itajaí (UNIVALI) in Brazil. KLEIN ET AL. (2003) Starting from a copy of the plan of a bay beach and a set of basic information supplied by the user, MEPBAY calculates the idealized shoreline planform of a headland-bay beach in static equilibrium based on the parabolic bay shape model. It then presents the results in graphic form on a screen display (Figure 6). It allows the stability of a headland-bay beach, in static or dynamic equilibrium, to be assessed by comparing the existing periphery with the idealized planform.

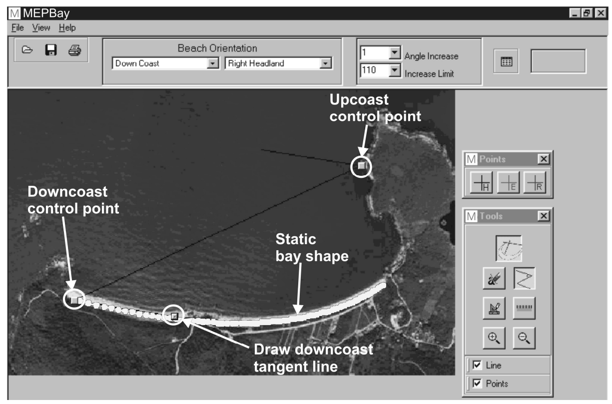


Figure 6: Input parameters of the PBSE and the plotted static bay shape. (KLEIN ET AL. 2003)

After loading the image of the planform of a bay into MEPBAY the user has to place control points on the image. These control points are the input for the calculation with the parabolic bay shape equation. The MEPBAY input parameters are:

1. Up coast control or diffraction point (Point '**H**')
2. Down coast control point (Point '**E**')
   On beaches considered to be in static equilibrium the tangential section down coast is found experimentally to be parallel to the wave crests approaching the coast from offshore. Point 'E' is to be chosen in this straight stretch of beach assumed to be perpendicular to the wave orthogonal. Point E and its positioning will be discussed further in the Discussion (Chapter 5)
3. Down coast tangent-line (Point '**W**')

1.4. PREVIOUS WORK

Since 1989 several improvements of the PBSE have been proposed. TAN AND CHIEW (1994) made simplifications in the equation with the reduction of the number of unknowns from three coefficients to one single variable. IGLESIAS ET AL. (2002) presented a method to treat the problem of multiple diffraction points.

However certain important uncertainties remained. When looking at Figure 6 it becomes clear that the placing of the control points on the figure is a subjective operation. An example of this subjectivity is the placing of the down coast control point (point E) followed by the determination of the down coast tangent-line (point W). To place these points the user must identify on the image a straight down coast segment of the beach. Since the placing of the points depends on visual interpretation a different input can be expected, when several users assess the stability of the same bay. This problem was investigated by GONZÁLEZ ET AL. (2001). González proposed a new procedure to locate the down coast starting point of the static equilibrium beach for which the parabolic planform of HSU AND EVANS (1989) is valid. The work by González and it's relationship with this paper will further be treated in the Discussion (Chapter 5)

In the past research has been performed on the uncertainties of the PBSE. Applying the PBSE to a bay on Magnetic Island, Australia (β=22.5°), SILVESTER AND HSU (1993) gauged the sensitivity of the location of the down coast control point by varying it slightly to increase R_0 with a commensurate decrease in β, or vice versa. The value of β was varied +5° and the bay curves were plotted. It was concluded that little difference occurred in the predicted waterlines. MORENO AND KRAUS (1999) performed sensitivity tests on the application of the parabolic shape and concluded that the parabolic bay shape is insensitive to β. This observation means that the control point is not well defined, i.e. uncertainty in selection of the control point and hence the radius Ro and β has little influence on the final result.

1.5. OBJECTIVE OF THE PAPER

In this paper an attempt is made to better understand the uncertainty in the application of the PBSE when applied to an existing stable bay. The main objective is to quantify the sensitivity of the orientation of the Static Equilibrium Planform (SEP) to variations in the position of the control points. The original work of HSU AND EVANS (1989) is tested. This means that all the information needed to asses the stability of the bay is obtained from vertical aerial photographs or charts of the bay.

Two bays where analyzed in this paper. The first bay is Taquaras/Taquarinhas beach. (Figure 7) Taquaras/Taquarinhas beach is located in the state of Santa Catarina, southern Brazil and is subject to predominant swell from the Southeast. The bay is considered to be in static equilibrium.

An expert elicitation carried out by volunteers having affinity with coastal engineering was performed to obtain possible realistic locations of the control points. These control points served as input for the MEPBAY model, which plotted the static equilibrium planform corresponding to the control point configuration. With this information it was then possible to obtain the distribution function of the position of the predicted coastline along several beach profiles.

After applying the PBSE to the bay of Taquaras/Taquarinhas and examining the sensitivity of the PBSE in this stable situation, the next step was to apply the PBSE to a bay, which is not stable. For this purpose the Bay of Imbituba also in southern Brazil was chosen, where a 850m long breakwater was constructed to shelter part of the bay serving as a port.

Figure 7: Location of Taquaras/Taquarinhas Beach, Brazil. GoogleEarth (2005)

Figure 8: Location of Bay of Imbituba, Brazil. GoogleEarth (2005)

2. AREA DESCRIPTIONS, METHODS AND MATERIAL STUDIED

2.1. DETERMINATION OF UNCERTAINTY IN THE APPLICATION OF THE PBSE

2.1.1. A Stable Bay: Taquaras/Taquarinhas Beach

As mentioned in the last paragraph the stable bay of Taquaras/Taquarinhas was used in the determination of the uncertainty in the application of the PBSE. This is important for only bays in static equilibrium can be used when examining the uncertainty of the application of the PBSE. An aerial photograph from 2002 (Figure 9) was used to plot the static equilibrium profiles with the help of the MEPBAY software.

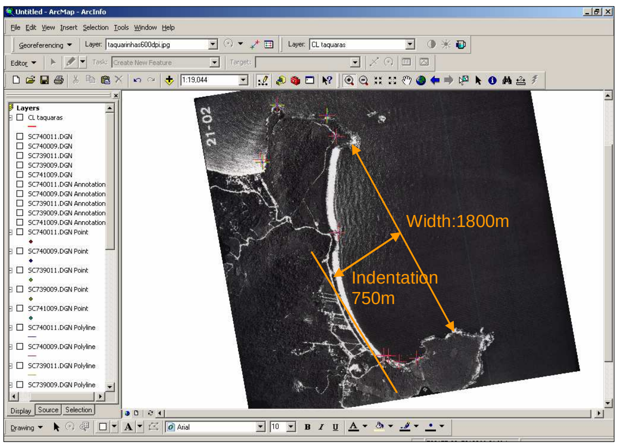


Figure 9: Aerial Photograph of Taquaras/Taquarinhas Beach in 2001, a stable bay 1800m wide and with and indent of 750m.

The aerial photograph was georeferenced using the GIS software program Arcmap 9 to an accuracy of (r.m.s.: 1.45 m).
As basis for the georeferencing a digital chart from the Secretaria Do Patrimônio Da União (SPU) was used. (Figure 10) This is a digital chart composed from nautical charts of 1995 of the coast of Santa Catarina.

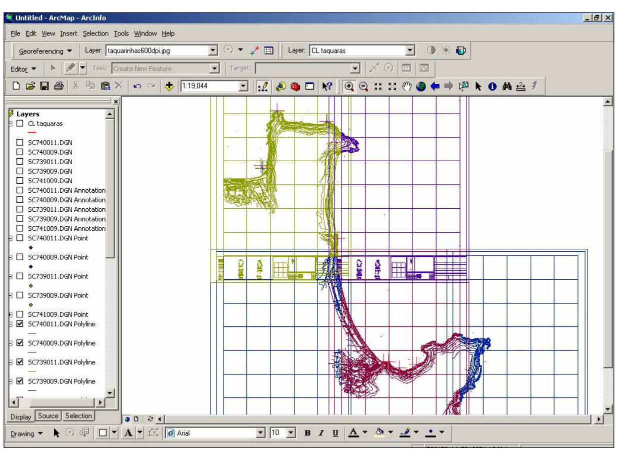


Figure 10: SPU chart of Taquaras/Taquarinhas Beach.

2.1.2. The NASA Clickworkers Pilot Study

Since the shape of the plotted static equilibrium profile is directly dependant on the position of the three chosen control points H, E and W, it is interesting to know how the location of these points is chosen on an aerial photograph or chart. This is where a pilot study by the NASA Ames Research Center comes into attention.
KANEFSKY ET AL. (2001) set up a website where public volunteers (clickworkers) where asked to identify craters on satellite images from Mars (http://clickworkers.arc.nasa.gov/top). An interactive interface was provided in which the clickworker clicks on four points on a crater rim and watches a circle draw itself around the rim. This pilot study was the inspiration for the idea to apply this same principle to coastal morphology. In this context an expert elicitation was developed which was distributed under potential MEPBAY users. The participants where members of the section hydraulic engineering at the Delft University of Technology, students in the last phase of the study hydraulic engineering and experts involved in the development of the PBSE.

2.1.3. Expert elicitation

The expert elicitation had as objective to generate realistic input for the MEPBAY model so that the spread of the output parameter (SEP) could be determined. The elicitation consisted of two parts:

Part 1 of the elicitation: Choose the best location of the control points

The first part of the elicitation presented the volunteer with an aerial photograph of Taquaras/Taquarinhas bay. (Figure 11 and Appendix 1)

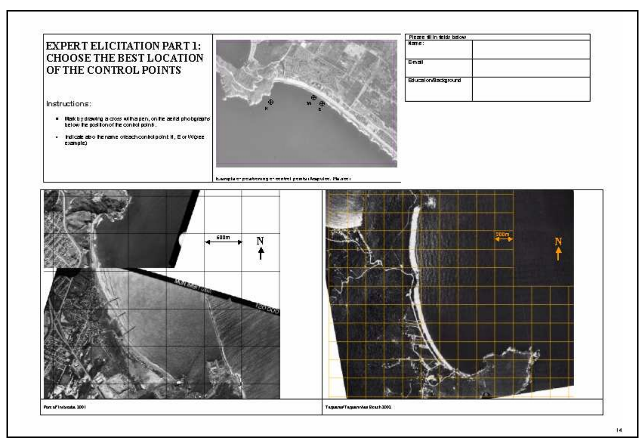


Figure 11: Expert Elicitation Part 1, where the volunteers were asked to choose the best location of the control points by marking their locations with a pen.

After reading the background theory on the PBSE (Appendix 2) the volunteer was asked to identify the three control points on the aerial photograph, by marking their locations with a pen. The volunteer did not see the consequence of his choices i.e. the SEP corresponding to the location of the points was not plotted.

Part 2 of the elicitation: Choose the best Static Equilibrium Profile

In the second part of the expert elicitation eight figures of the Taquaras/Taquarinhas bay where presented. See Figure 12 and Appendix 1. Each figure contained a plot of the static equilibrium profile. The configurations of the control points varied slightly throughout every figure. The volunteer was asked to choose one of the figures which best represent the location of the control points and the corresponding SEP.

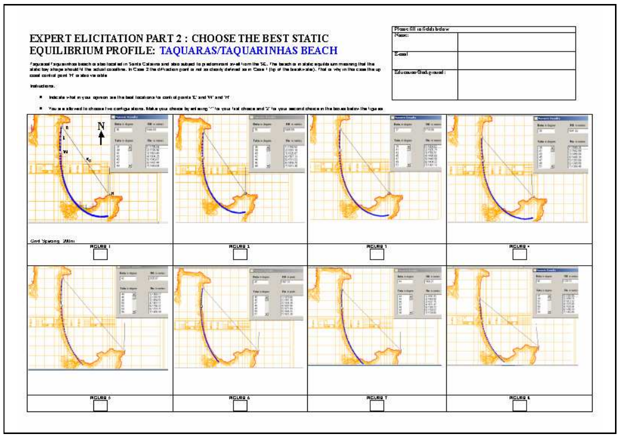


Figure 12: Expert Elicitation Part 2

The order in which the two parts of the expert elicitation where filled in by the volunteers was important. Part 1 had to be completed before filling in Part 2. The reason for this being that the plots in Part 2 could influence the choices of the volunteers regarding the positioning of the control points.

3. RESULTS AND ANALYSIS

3.1. STATISTICAL ANALYSIS OF THE EXPERT ELICITATION

3.1.1. Results expert elicitation Part 1: Choose the best location of the control points

Twenty-two volunteers participated in Part 1 of the elicitation. The positions indicated by the different users marked on the aerial photograph were translated into MEPBAY to obtain the corresponding SEP plots (Figure 13). This created twenty-two SEP plots of the bay of Taquaras/Taquarinhas.

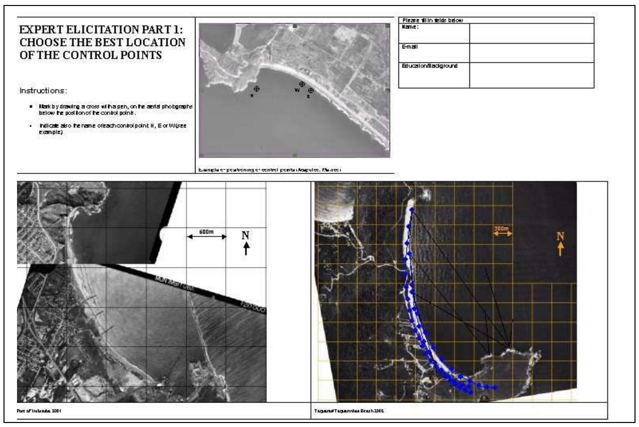


Figure 13: Plotted Static Equilibrium Planforms corresponding to control points chosen by the volunteers

Four profiles at a fixed positions along the bay where chosen to perform statistical analysis. To facilitate the reading of the coordinates of the SEP along the chosen profiles, the profiles where taken along certain latitudes and the location of these latitudes was chosen such that the profiles intersected all the SEP plots. All volunteers chose the diffraction point (point H) along the southern headland and eleven of the twenty-two volunteers chose point E halfway along the bay. This means that the 4 profiles had to be defined in the southern part of the bay. (Figure 15)

Using the georeferenced chart of the bay in Arcmap 9 the coordinates of the intersection of each SEP plot with the latitude was determined. With the help of Microsoft Excel's FREQUENCY function these coordinates where divided into 5 categories and plotted in a histogram. The number of categories in which the data was distributed was determined according to data based general guidelines (Equation 2) provided by DEKKING ET AL. (2004).

$$m = 1 + 3.3\log_{10}(n) \qquad \text{Eq. 2}$$

with:

m: Number of categories (bins)

n: Total number of elements in dataset

A continuity correction of half bin at each limit of the data set was included to ensure that all the coordinates where taken into account. The results can be seen in Figures 17-21.

3.1.2. Expert elicitation Part 2: Choose the best SEP

In part 2 of the expert elicitation thirty volunteers participated in choosing the best configuration of the control points and corresponding static equilibrium planform. More volunteers participated than in Part 1. The reason for this being that part 1 could easily be distributed by email to experts abroad and part 2 not. To compare the results from the different parts of the elicitation, the position of the SEP's along the same four profiles as in Part 1 of the elicitation where analyzed. Along with the choices of the volunteers (Figure 14), this generated a distribution function of the position of the coastline along the different profiles. The results can be seen in Figures 21-25.

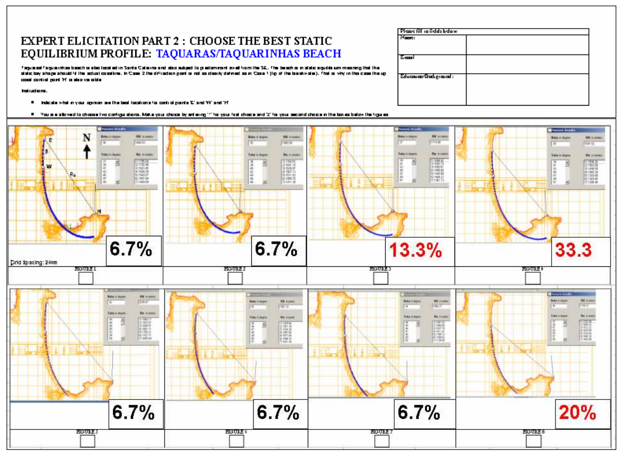


Figure 14: Choices of the volunteers (percentages), Expert Eliciation Part 2

RESULTS EXPERT ELICITATION PART 1

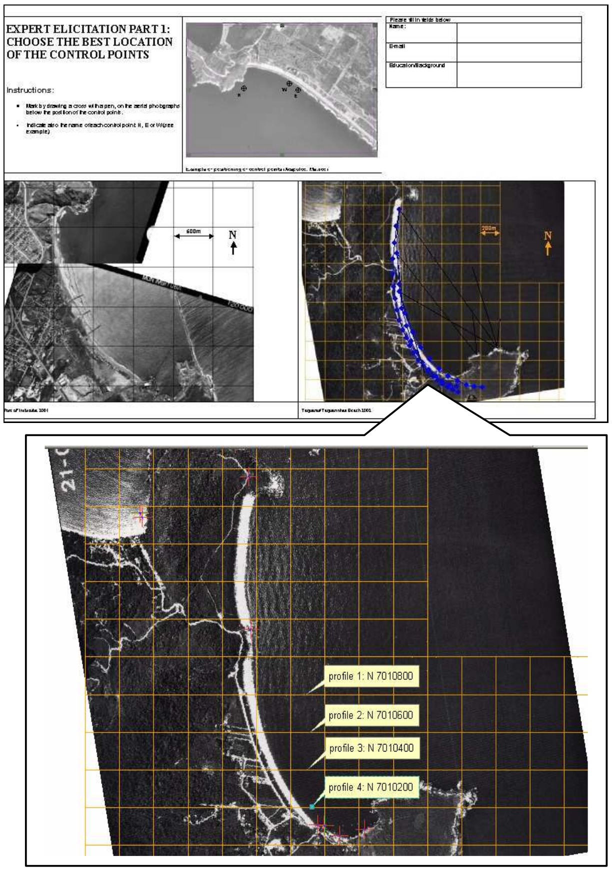


Figure 15: Location of the four profiles, Taquaras/Taquarinhas Bay

PART 1 PROFILE 1

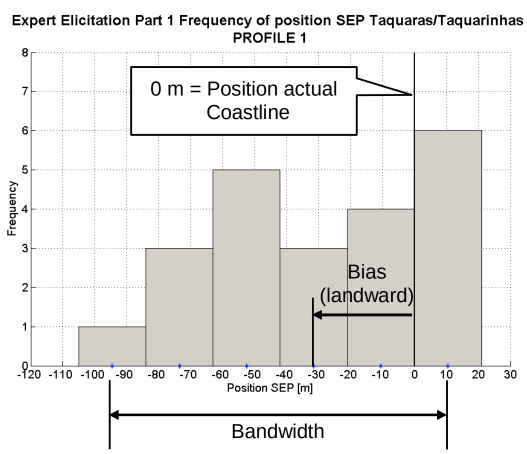


Figure 16: Results Expert Elicitation part 1, profile 1

RESULTS EXPERT ELICITATION PART 2

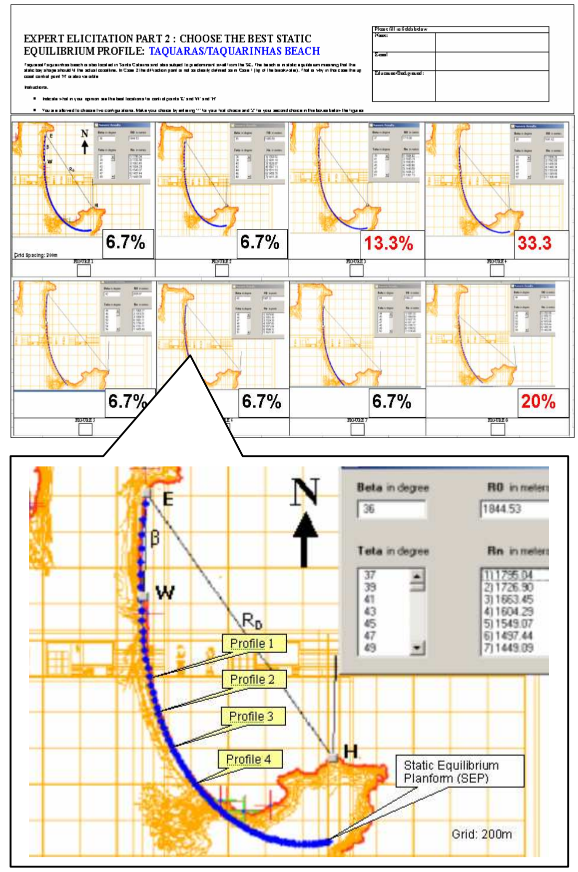


Figure 20: Location of the four profiles and the Static Equilibrium Planform Taquaras/Taquarinhas Bay

PART 2 PROFILE 1

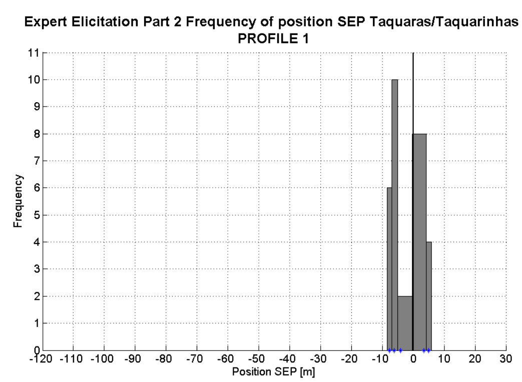


Figure 21: Results Expert Elicitation part 2, profile 1

Statistical Analysis Profile 1

Number of volunteers	22
Bandwidth plotted static equilibrium profiles	105 m
Weighted distance from SEP's to actual coastline	-30 m (landward bias)
Standard deviation of 22 plots:	31.9 m

PART 1 PROFILE 2

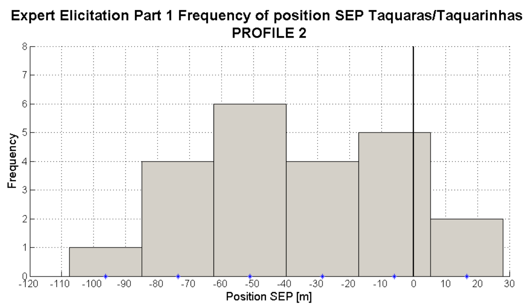


Figure 17: Results Expert Elicitation part 1, profile 2

Statistical Analysis Profile 2

Number of volunteers	22
Bandwidth plotted static equilibrium profiles	113 m
Weighted distance from SEP's to actual coastline	-37 m (landward bias)
Standard deviation of 22 plots:	32.7 m

PART 1 PROFILE 3

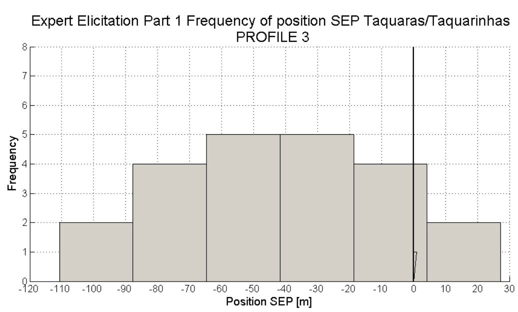


Figure 18:Results expert elicitation part 1, profile 3

Statistical Analysis Profile 3

Number of volunteers	22
Bandwidth plotted static equilibrium profiles	115 m
Weighted distance from SEP's to actual coastline	-42 m (landward bias)
Standard deviation of 22 plots:	33.8 m

Statistical Analysis Profile 1

Number of volunteers	30
Bandwidth plotted static equilibrium profiles	13 m
Weighted distance from SEP's to actual coastline	-2 m (landward bias)
Standard deviation of 30 plots:	5.3 m

PART 2 PROFILE 2

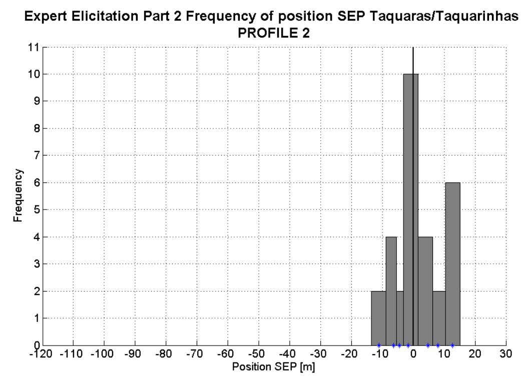


Figure 22: Results Expert Elicitation part 2, profile 2

Statistical Analysis Profile 2

Number of volunteers	30
Bandwidth plotted static equilibrium profiles	24 m
Weighted distance from SEP's to actual coastline	1 m (seaward bias)
Standard deviation of 30 plots:	7.5 m

PART 2 PROFILE 3

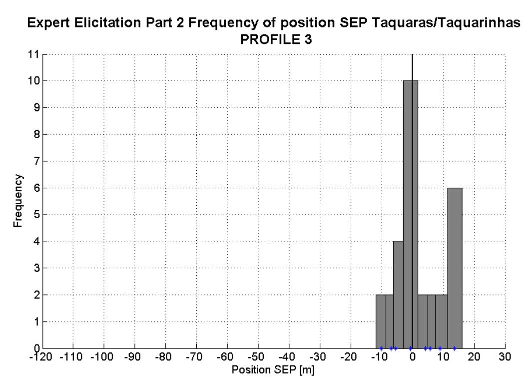


Figure 23: Results Expert Elicitation part 2, profile 3

Statistical Analysis Profile 3

Number of volunteers	30
Bandwidth plotted static equilibrium profiles	24 m
Weighted distance from SEP's to actual coastline	2 m (seaward bias)
Standard deviation of 30 plots:	7.7 m

PART 1 PROFILE 4

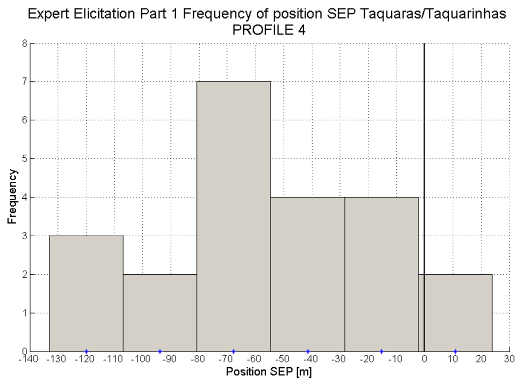


Figure 19:Results expert elicitation part 1, Profile 4

Statistical Analysis Profile 4

Number of volunteers	22
Bandwidth plotted static equilibrium profiles	130.8 m
Weighted distance from SEP's to actual coastline	-56 m (landward bias)
Standard deviation of 22 plots:	39.4 m

Statistical Analysis all profiles

Overall bias*: ($B_{overall}$)	**-41 m (landward bias)**
Overall standard deviation**: ($\sigma_{overall}$)	**34.4 m**

PART 2 PROFILE 4

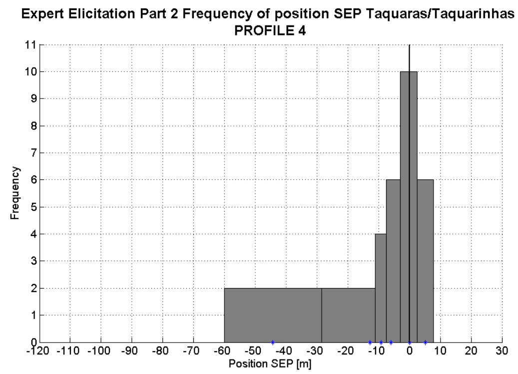


Figure 24:Results expert elicitation part 2, Profile 4

Statistical Analysis Profile 4

Number of volunteers	30
Bandwidth plotted static equilibrium profiles	49 m
Weighted distance from SEP's to actual coastline	-5 m (landward bias)
Standard deviation of 30 plots:	12 m

Statistical Analysis all profiles

Overall bias*: ($B_{overall}$)	**-1.1 m (landward bias)**
Overall standard deviation**: ($\sigma_{overall}$)	**8.1 m**

* Overall bias: ($B_{overall}$)

$$B_{overall} = \frac{B_{p1} + B_{p2} + B_{p3} + B_{p4}}{4}$$

With:
B_{px} = Bias profile number x

** Overall standard deviation: ($\sigma_{overall}$)
If the profiles would be statistically independent $\sigma_{overall}$ would be:

$$\sigma_{overall} = \frac{1}{2}\sqrt{\sigma_{p1}^2 + \sigma_{p2}^2 + \sigma_{p3}^2 + \sigma_{p4}^2}$$

But this is not the case, the positions where the SEP crosses the different profiles are indeed statistically dependent, so another formula must be used:

$$\sigma_{overall} = \frac{\sigma_{p1} + \sigma_{p2} + \sigma_{p3} + \sigma_{p4}}{4}$$

3.2. CONCLUSIONS OF THE STATISTICAL ANALYSIS OF THE EXPERT ELICITATION

3.2.1. Expert elicitation Part 1

Twenty-two expert volunteers where asked to place the three control points needed to draw the SEP on a vertical aerial photograph of the existing stable bay of Taquaras/Taquarinhas Beach. By strictly adhering to the definitions of the control points (definitions Point H, E and W in Paragraph 1.3 of this paper) and not seeing the result of their control point configuration the following can be concluded:

- In the particular case of a stable bay, 1800 m wide and 750 m indentation, the overall bias of the location of the SEP calculated over 4 evenly spaced (200m) profiles in the southern part of the bay is in the order of 41m (landward) with an average bandwidth of 116 m.

- The bandwidth and standard deviation of the SEP increase when moving alongshore from profile 1 to 4. Meaning that the uncertainty in the application of the PBSE is dependent on the particular point of interest along the bay. This behaviour was already noticed by MARTINO ET AL. (2005) and will be elaborated upon in the Discussion (Chapter 5)

3.2.2. Expert Elicitation Part 2

The location of the SEP along the same profiles as in Part 1 of the elicitation where analyzed. In part 2 of the elicitation the volunteers where presented with figures of the bay that included the SEP, now the volunteers could see the effect of the location of the control points. The results from part 2 of the elicitation are presented using the same horizontal scale as the results in Part 1. It is immediately clear that the variation of the position of the SEP along the 4 profiles is much smaller than in Part 1.

Therefore the following can be concluded:

- Provided the volunteer sees the consequences of the placement of the control points (the corresponding SEP), the variation of the position of the SEP along the four profiles is much smaller. This in turn means that the PBSE is a **robust** method provided the user sees the result of his/her choices in placement of the control points.

3.2.3. Motivation and comments of volunteers

Beside the statistical results from the expert elicitations some valuable comments were received from the participating volunteers. The most important comments are given here. These comments might be particularly useful for the development of the next version of MEPBAY.

Location of control point W

Several volunteers remarked that the positioning of control point W, upcoast of control point E should be made possible. Especially since this is physically more justifiable when looking at the precise definitions of the control points. In the actual version of MEPBAY an upcoast positioning of control point W from control point E is not possible.

Distance between the control points E and W.

This varied greatly between the volunteers. A general assumption is that the larger the distance the smaller the relative error of the positioning of control point W.

4. APPLICATION OF THE PBSE ON A BAY MODIFIED BY COASTAL STRUCTURES

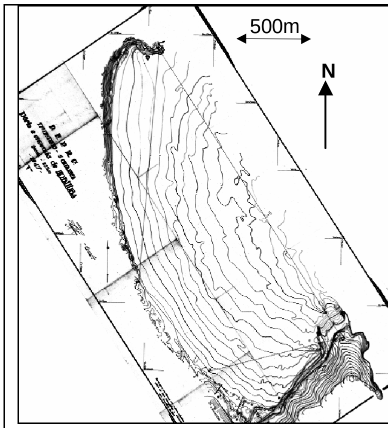
In the last paragraph the PBSE was applied to a bay in static equilibrium and the variation of the orientation of the SEP corresponding to different realistic orientations of the control points was quantified.
The next step is to make matters more complex by applying the PBSE to a bay, which has undergone change by human intervention in the form of coastal construction works and to analyze the results of the application of the PBSE in this situation.

4.1. BAY OF IMBITUBA: HISTORY OF COASTAL WORKS CONSTRUCTION

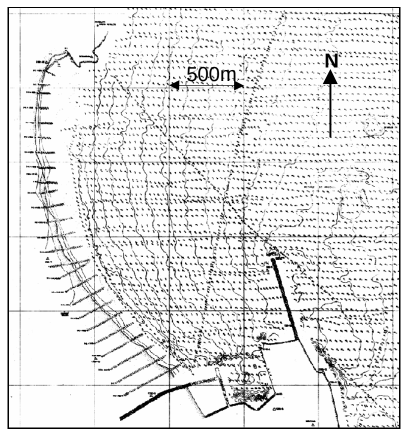
The Bay of Imbituba is located in the state of Santa Catarina, Southern Brazil. The strategic location of the bay was the main reason for the construction of a port in 1919 and works where started in the south of the bay to accommodate the export of coal from the mainland.
To protect the port against incoming waves a breakwater was built. The construction was carried out in two phases, initially 550m of breakwater was constructed in 1972 and later the breakwater was extended to its actual 850m. The history of the major coastal works constructions is described in Table 2 and illustrated in Figure 25.
With the construction of the breakwater an increase in sedimentation of the portual area was noticed. The breakwater has changed the wave diffraction pattern in the bay, exposing the soft sedimentary rock in the north of the bay to increased wave attack. It is the erosion of this soft sedimentary rock that is considered to be the major contributor to the sedimentation in the port. The port authority commissioned the construction of three groins in 1980 on Do Port Beach to combat the sedimentation in the port. A cutter suction dredge, owned by the port authority, performs periodic dredging of the bassin and access channel and recently, the port authority has decided to extend its operation also to the handling of containers with the construction of a 800.000m^2 container terminal in the south of the bay.

Table 2: History of major coastal works construction in the Port of Imbituba (source: Eng. Candido, Companhia Docas de Imbituba)

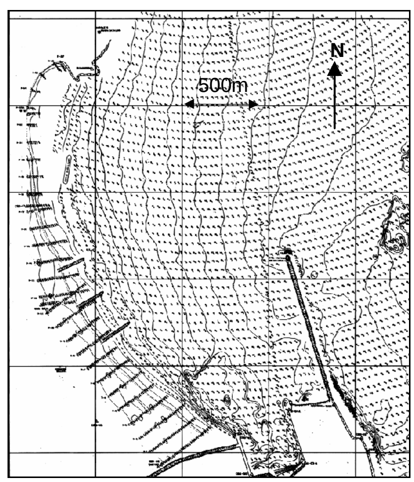
Date	Construction phase
24 /10 /1972	Start of construction of the breakwater
17 /09 /1975	End of construction: 550m
15 /08 /1980	Start of extension of the breakwater and construction of 3 groins on Do Porto Beach
03 /12 /1982	End of construction works. Total breakwater length: 850m



Nautical chart Imbituba 1947



Bathymetric chart Imbituba 1979:
Notice that 550m of breakwater is in place



Bathymetric chart Imbituba 1983:
Notice that the breakwater has been extended to its actual (850m) length and 3 groins are in place on Do Porto Beach

Figure 25: History of coastal works construction in Imbituba.

4.2. EVOLUTION OF THE IMBITUBA COASTLINE

Different data, ranging from bathymetric charts to aerial photographs from as early as 1947 to 2001 were obtained at the Companhia Docas de Imbituba (CDI), Imbituba's Port Authority.
An overview of the obtained data is given in Appendix 4. The data covers a time span of 54 years. In this period large morphological changes took place between 1972 and 1982, the most important being the construction of the 850m breakwater in the south of the bay and three groins on Do Porto beach
To analyze the effect of the coastal structures on the morphology of the bay, preparation of the data was needed. This included using the GIS software program ArcMAP 9 to designate the correct UTM coordinates to the images (georeferencing) and to digitalize the coastline. A chart from the Secretaria Do Patrimônio Da União (SPU) was used as basis for the georeferencing. The projected coordinate system applied was: South American 1969 UTM Zone 22S and the average error of the aligning was 1,57 meters (r.m.s.). In Appendix 5 a more elaborate account of the georeferencing of the data is given.
Once georeferenced the coastline could be digitalized and the coastlines from different years could be superimposed on each other, yielding a visual representation of the morphological evolution of the bay. Coastlines from 1966 and 2001 can be seen in Figure 27. More plots are given in Appendix 6.
What is immediately clear from Figure 27 is the accretion in the southern part of the bay. According to the port authority this accretion is not entirely due to natural causes such as sediment transport. During the construction of the berths material from the port bassin and access channel was dredged and used as landfill material behind the berths. Nevertheless, after the completion of the first 550m of the breakwater, sedimentation of the port area was experienced and in 1981 three groins where built with the purpose to stop further sedimentation of the harbor. It is suspected by the port authority that the material needed for this sedimentation came from the northern part of the bay. This seems plausible when looking at Figure 27.
The difference in size of the erosion and accretion area could be explained by the fact that the erosion area consists of an eroding active sea cliff (comparable to a high (± 40 m) dune at some places) and the accretion area a flat beach. (Figure 26)

Figure 26: Erosion and accretion area in the Bay of Imbituba.

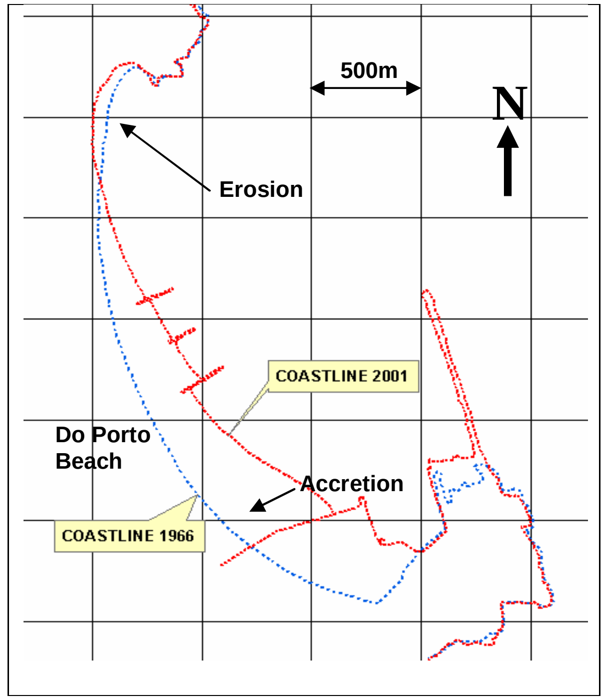


Figure 27: Coastline of the Bay of Imbituba in 1966 and 2001.

4.3. RESULTS OF THE APPLICATION OF THE PBSE ON THE BAY OF IMBITUBA

The most important results of the application of the MEPBAY model on the Bay of Imbituba are presented in this paragraph.
It is clear from the previous paragraph that the coastal structures in the bay of Imbituba have had a significant impact on the morphology of the bay.
After application of the PBSE to the Bay of Imbituba it was observed that as a consequence of the construction of the breakwater and groins the equilibrium status of the bay has changed from dynamic to close to static in the north and unstable in the south (Table 3). More detailed simulations can be found in Appendix 7.

Table 3: Equilibrium status, wave obliquity and length of the control line throughout time in the Bay of Imbituba

Date	Equilibrium status	β (degrees)	R_o (meters)
1947	Dynamic*	47	2243.14
1966	Dynamic	49	2235.61
1979	Close to Static (North***) Unstable** (South***)	52	1783.03
1983	Close to Static (North) Unstable (South)	60	1569.45
1988	Close to Static (North) Unstable (South)	60	1591.43
1995	Close to Static (North) Unstable (South)	54	1586.21
2001	Close to Static (North) Unstable (South)	53	1600.81

* :Dynamic: SEP is landward of actual coastline
** :Unstable: SEP is seaward of actual coastline
*** :North: Northern part of the Bay. (See also Figure 30)
:South: Southern part of the Bay

Noticeable is also that β changes over time (Figure 28) This is understandable since with the construction of the breakwater the diffraction point has been moved northwards into the bay, decreasing the length of the control line (Figure 29)

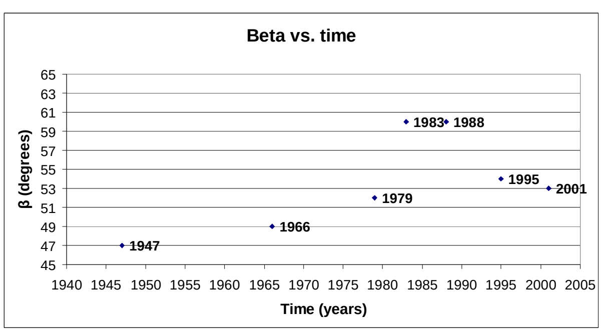


Figure 28: Wave direction (β) plotted throughout time. β increases until 1983 (completion of breakwater) and then decreases as the beach planform adapts itself to the new diffraction point.

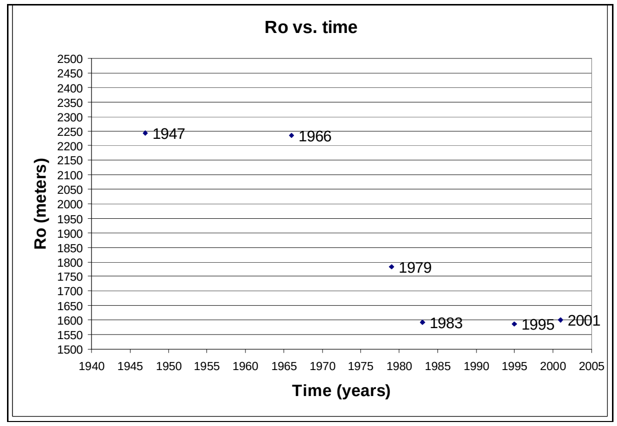


Figure 29: **Control line length (R_o) plotted throughout time. Noticeable is that with the construction of the breakwater the R_o decreases**

If the beach would not adapt itself to the new situation i.e.: position of point E remains the same, then β would **increase** just by the translation of the up coast diffraction point alone. Since β is defined as the angle between the wave crest line and the control line. But as can be seen in Figure 27 the orientation of the beach has indeed **changed.** This complicates matters because it implies that the position of point E does not remain the same throughout time. If one looks at Figure 30 (coastlines 1988 and 2001) the increase of β by the translation of the diffraction point is left out. In theory the only factor influencing the change of β now would be the adaptation of the beach planform. This can be seen in Figure 28 where after completion of the extension of the breakwater in 1982, β seems to **decrease** as the beach planform adapts itself to the new diffraction point.

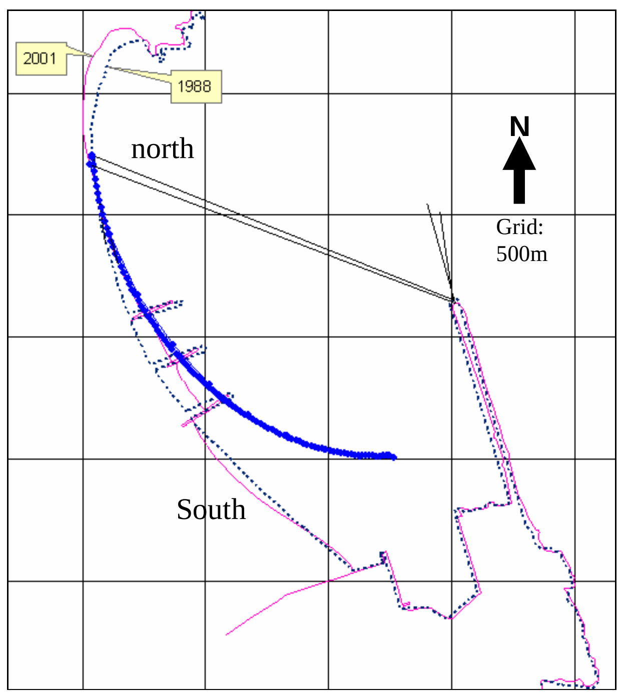


Figure 30: Coastlines 1988 and 2001 with the application of the parabolic bay shape equation. β now decreases as the coastline adapts to the presence of the breakwater.

Besides the translation of the diffraction point and the adaptation of the beach line to the presence of the breakwater, the cause for the variations in β could also be:

1. Inaccuracies in the plotting of the coastline. Poorly visible sections of beach on the aerial photographs make identification of the waterline difficult.
2. Round-off error of MEPBAY when determining β. According to A. Raabe (co-developer of MEPBAY) this error could be up to 1%.
3. The Port of Imbituba operates its own cutter suction dredge, which performs regular dredging of the access channel (Figure 31) and port bassin. The effect of this dredging on the coastline is not taken into account by MEPBAY.

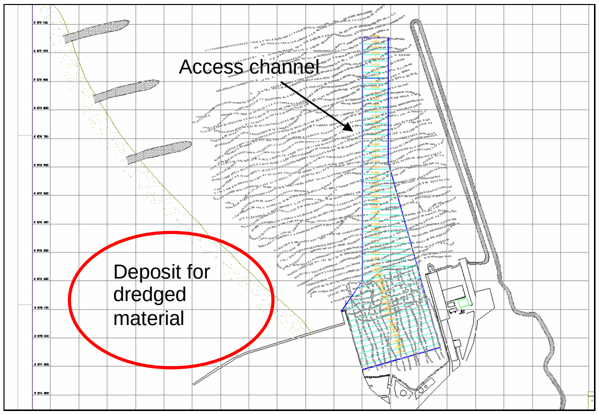


Figure 31: Orientation of the access channel in the port of Imbituba (2004). The material from the access channel is pumped inland in a deposit area where a container terminal is planned.

The tendency of the sedimentation of the port stated in Paragraph 4.2 can be explained by looking at the SEP belonging to the new up coast diffraction point (the tip of the breakwater). To reach this new SEP the southern part of the bay requires massive accretion.

4.4. EXPERT ELICITATION RESULTS FOR THE BAY OF IMBITUBA

In the previous paragraphs the evolution of the coastline of the bay of Imbituba was analyzed and it's behavior explained with the help of the PBSE.

To investigate the behavior of the PBSE when applied to an unstable situation, the bay of Imbituba was also included in the expert elicitation. It is important to note that for the investigation of the uncertainty of the PBSE only bays in static equilibrium must be used. But even though the results from the expert elicitation regarding the Bay of Imbituba may not be used to determine the uncertainty of the PBSE some useful comments can be made regarding the behavior of MEPBAY users when applying the PBSE to a bay where coastal structures have been placed.

4.4.1. Expert elicitation part 1: Choose the best location of the control points

Twenty-two volunteers participated in this part of the expert elicitation and 1 person refused to participate, stating that the right answer was not included. In Figure 32 the choice of the positioning of the control points by the 21 volunteers can be seen.

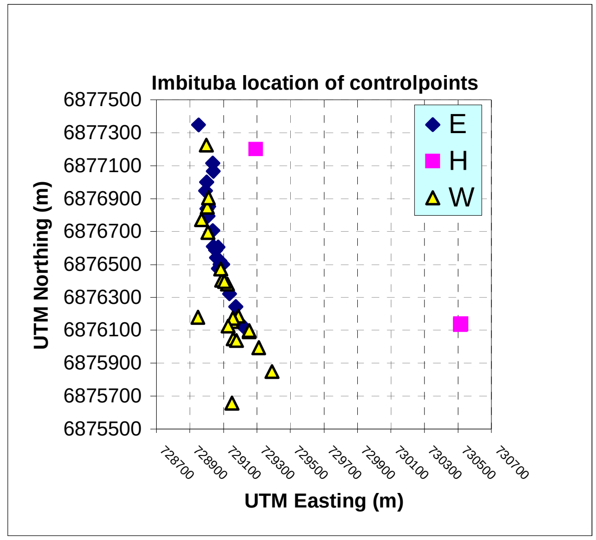


Figure 32: Results from the Part 1 of the expert elicitation, Imbituba.

Regarding Figure 32, the following comments can be made:

Control point H:

Twenty-one of the twenty-two volunteers choose the tip of the breakwater as the up coast diffraction point. One person chose the down coast headland (Ponta da Ribanceira) as diffraction point. (Figure 33)

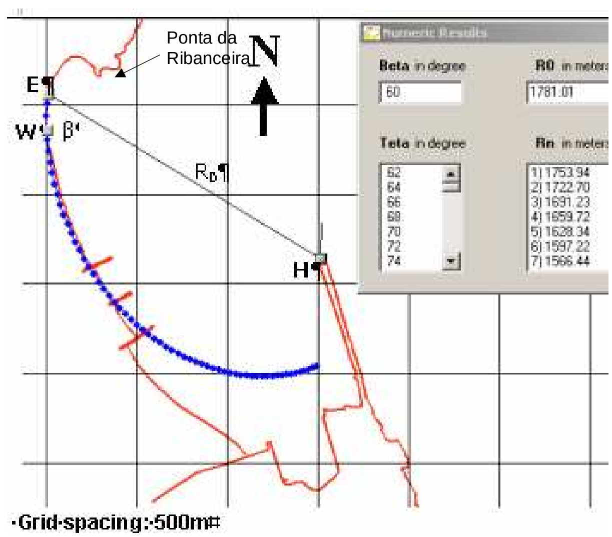


Figure 33: Location of Ponta da Ribanceira.

Control point E

The highest percentage of the volunteers (43%) chose point E between northing: 6876490.285 and 6876735.555. This can be seen in Figure 34, where Do Porto Beach is divided into 6 sections. The percentage of the positioning of the control point E is given for each section.

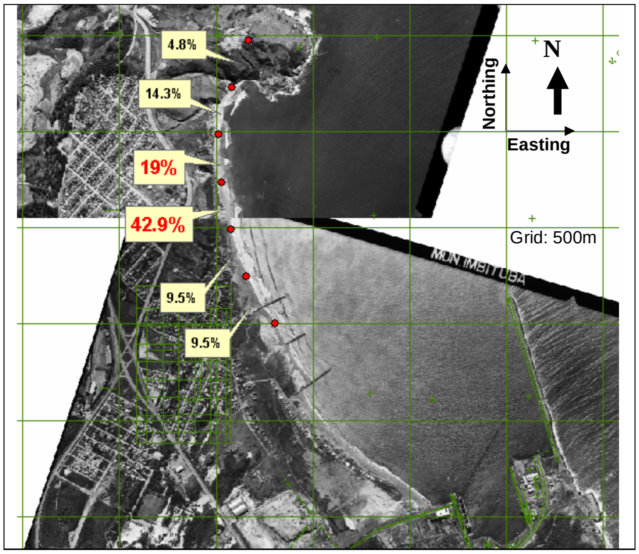


Figure 34: Percentage of the positioning of the control point E given for the various sections.

Control point W

Point W varies too much to be able to derive a general behavior. This is in part logical because W is in fact a direction and could be chosen on any point along the line, which the volunteer chose as the tangent to point E.

4.4.2. Expert elicitation part 2: Choose the best SEP

In this part of the expert elicitation 30 volunteers participated. One volunteer refused to apply the PBSE to the case of Imbituba, stating that the PBSE cannot be applied to the bay. The most important reason being that control point E could not exist in the bay. This statement was the motive for further research into the positioning of the control point E in the Bay of Imbituba and will be elaborated upon in the Discussion (Chapter 5)

5. DISCUSSION

There are certain aspects regarding the application of the PBSE that are worthy of discussion. These aspects were mentioned in the preceding paragraphs but were not fully elaborated upon. This is done in the following paragraphs.

5.1. THE DOWNCOAST CONTROL POINT (POINT E): A CLOSER LOOK AT WAVE DIFFRACTION

The statement given by one expert during the expert elicitation that point E cannot exist in the Bay of Imbituba (Paragraph 4.4.2) was the motive to conduct more research. The location of the down coast control point on a headland-bay beach has always been difficult to asses (SILVESTER AND HSU 1993). In an attempt to better understand the positioning of the downcoast control point in the Bay of Imbituba a study was performed, targeting specifically the interpretation of the downcoast control point and their context in literature throughout time. The result of this literature study is given in Table 4.

Table 4: Interpretations of the down coast control point in literature

Author	Interpretation of the downcoast control point.
HSU ET AL. (1992)	*The down coast limit of the bay: generally the limit of the straightening beach*.
SHORT (1999)	*The second control point (downcoast control point) may be a second headland or, if the latter is not present, can be taken as the start of the straight section of the coastline where the shoreline orientation is parallel to the incident wave crests*
KLEIN ET AL. (2003)	*It is worth noting that any point on or near at the straight down coast segment of the beach could be conveniently chosen as a downcoast control point, for which the convenience and insensitivity was noted in SILVESTER AND HSU (1993, 1997)*
BENEDET ET AL. (2004)	The selection of the point of origin, or upcoast control point, and the end point, or downcoast control point and wave obliquity must be made from careful interpretation and understanding of coastal morphology as viewed from aerial photographs or maps. Automatic curve fitting is not an option. The point of origin is relatively straightforward because it is the point where waves first diffract against the headland. *The end point is located when the beach starts to become straight therefore free from the direct influence of the headland*. Some bay beaches may have double curvature and, thus with two facing control points, or two different levels of control within the same headland may occur. At beaches with two long headlands, there will be two facing end points in the middle of the embayment, the transitional zone between opposite headlands.
MARTINO ET AL. (2005)	*For the parabolic shape, the control point is a boundary for the curved section of the beach controlled by diffraction and the straight section of beach perpendicular to the assumed predominant wave direction.* GONZÁLEZ AND MEDINA (2001) provided guidance on the location of the control point, proposing a parameter called α_{min} as a function of the relative location of the structure and the original shoreline and the wavelength. Problems arise with short or incomplete plan shapes, meaning that the straight stretch of coast is lacking, and therefore, the control point becomes a 'virtual' point. Distance to the original shoreline is difficult to asses in some situations. (MORENO 1997) performed sensitivity tests regarding the location of the control point and showed that the plan shape is slightly sensitive to the location of the control point.

5.1.1. Wave diffraction in the Bay of Imbituba

An interesting point in the interpretations in Table 4 is the mentioning of wave diffraction (MARTINO ET AL. 2005 and indirectly BENEDET ET AL. 2004). A relationship between the wave diffraction and position of the downcoast control point is suggested. This lead to a study with the objective to investigate this relationship

In 2001 the INHP (Institute for waterway research, Rio de Janeiro) performed a study to model the wave propagation in the port of Imbituba. INHP (2001)
Wave refraction and diffraction was modeled with the help of the software program MIKE 21 (PMS&BW). Wave data was obtained from measurements performed by the INPH between July 1982 and March 1985. These measurements where obtained from an OSPOS wave recorder located approximately 1,5 km offshore from the port and wave directions where obtained visually from an observation point on Ponta de Imbituba.
In the INHP report the wave propagation inside the bay of Imbituba was modeled using several wave directions. The most relevant figures from the report are displayed in Figure 35 and Figure 36. The wave directions are given in degrees with respect to the north (0^o) and turning clockwise being positive.

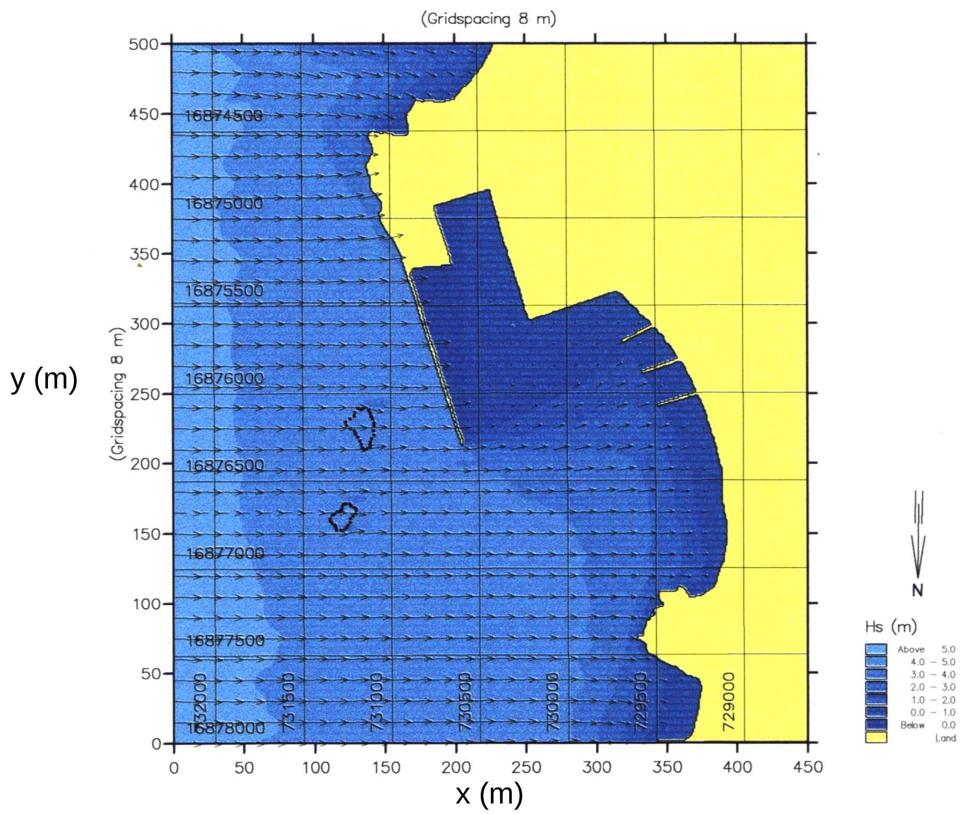


Figure 35: Wave propagation (90°) in the bay of Imbituba. The x-axis has been chosen such that it coincides with the wave direction (INHP 2001)

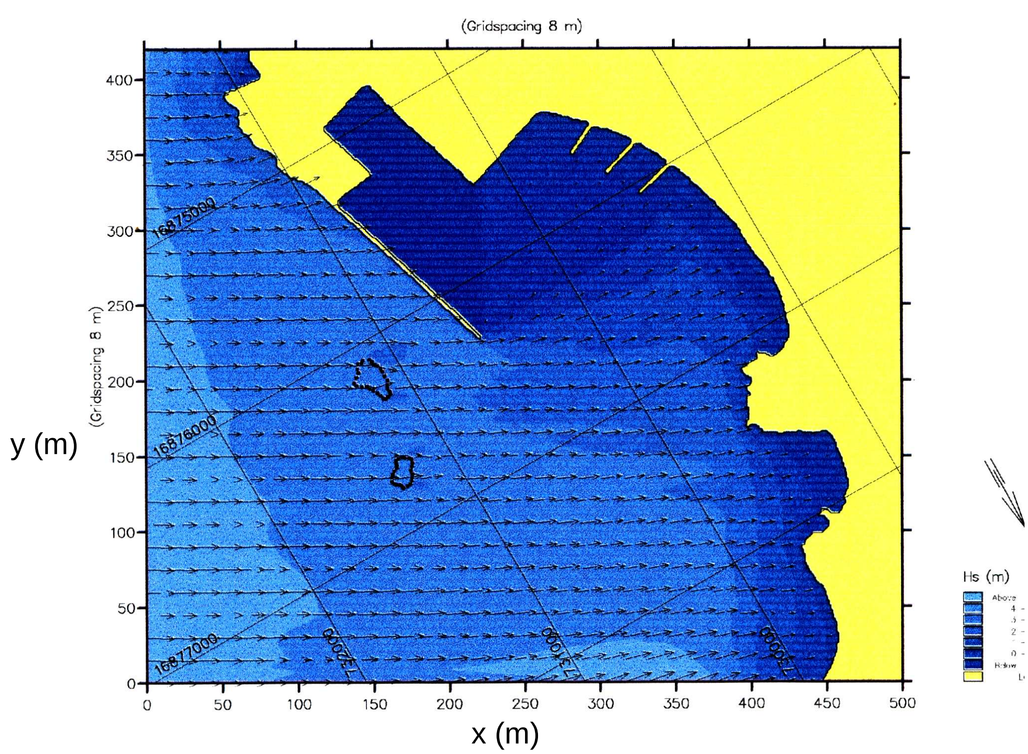


Figure 36: Wave propagation (120°) in the bay of Imbituba. The x-axis has been chosen such that it coincides with the wave direction. (INHP 2001)

In Figure 35 and Figure 36 the wave direction is represented by arrows. In areas where arrows are parallel to each other the direction of the wave propagation does not change. In Figure 35 the wave direction at the offshore boundary (x = 0m) is 90^o it can be seen that waves traveling between y = 100 m and y =160 m arrive at the beach without any change in wave *direction*.
However, the wave *height* along this section of the shore can change due to diffraction of the breakwater. Unfortunately this is not illustrated in the Figure 35 and Figure 36, in these figures only change in wave *direction* is given. A relatively simple way to analyze wave *height* variation due to diffraction is by means of the Cornu spiral (Figure 37)

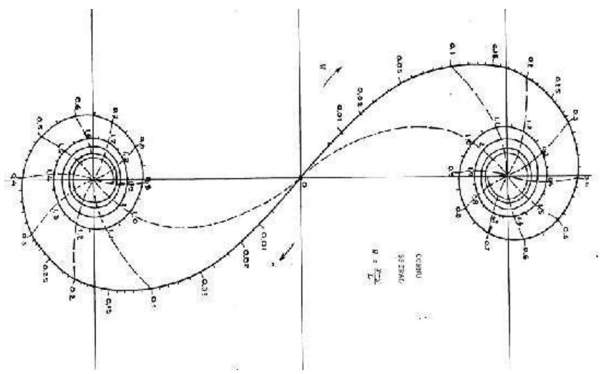


Figure 37: The Cornu Spiral

To calculate the wave height at the point of interest (point P) the Cornu spiral requires parameters W, L, y, r, β and H, which are clarified in Figure 38 and Table 5.

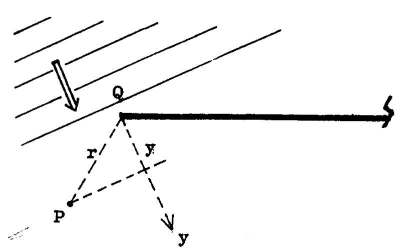


Figure 38: Distances r and y used in the Cornu Spiral

Table 5: Parameters needed for wave diffraction calculations using the Cornu Spiral

Parameter	Description and Value
W (-)	Parameter plotted along the Cornu spiral $$W = \frac{r - y}{L}$$
L (m)	Wavelength at point of diffraction. Calculated based on the INPH report (2001) Where the significant wave is: • H_s= 5.16 m at 15 m depth (location pressure buoy) • T= 8s Propagated to the depth of the diffraction point (h=13m) this leads to: L= 78 m
y (m)	y-coordinate of point P
r (m)	Radial distance from point Q to the point P considered
β (^{o}):	Wave direction. Obtained from the orientation of the coastline in the southern part of the bay The wave direction taken was: 90^o (East)
H (m)	Wave height at point of diffraction Obtained from the INPH report (2001) and propagated to the depth of the diffraction point (h=13m) leads to: H= 4.7 m

Using the Cornu spiral we can calculate the diffraction coefficient (K_D) along any point on the Bay of Imbituba. In this particular case we are interested in finding the location of the point along the Imbituba beach where waves do not experience diffraction (K_D=1) (Point C in Figure 39)

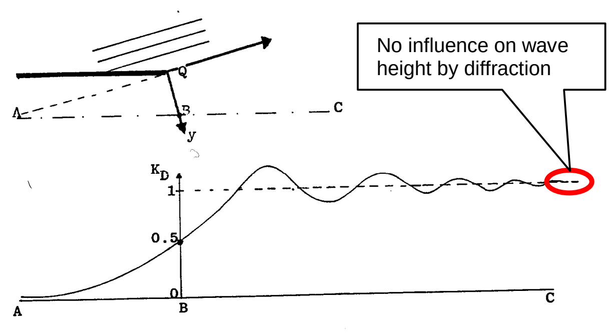


Figure 39: Value of diffraction coefficient K_D along line A-B-C

Through trail and error a value of W= 4.59 was found with an r =1779.88 m and β = 53^o (Figure 40). The corresponding diffraction coefficient at point E is: K_D= 1.01. Resulting eventually in a variation of the wave height at Point E of 1% compared to the wave height at the diffraction point (Point H)

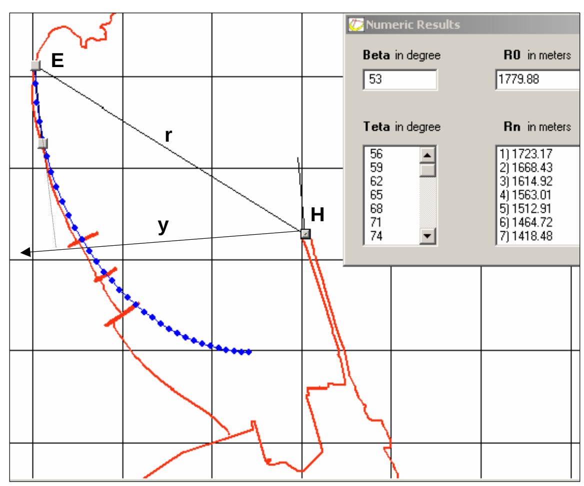


Figure 40: Location of Point E corresponding to W= 4.59

Calculations using the Cornu spiral where performed manually. Software programs such as REFDIF (Kirby et al. 1994) facilitate wave diffraction and refraction calculations. To study the wave diffraction in the Bay a simplified topography of the bay was used:

- Uniform bottom profile of 1:100 (INHP 2001)
- The breakwater was considered as impermeable. (no wave transmission)
- The coastline was represented as straight.
- The wave height was reduced to 0.1m, so that the waves break closer to the actual shoreline.
- Wave period: 8 s (INHP 2001)
- Wave direction: 90^o (East) (INHP 2001)

Results of the REFDIF calculations can be seen in Figure 42. In this figure four points along the coastline have been introduced to facilitate the interpretation of the results. The orientation of the points is displayed in Figure 41.

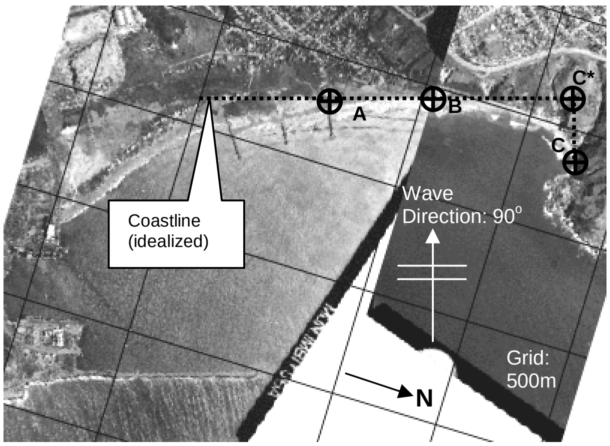


Figure 41: Location of points for the interpretation of the REFDIF calculation in the Bay of Imbituba

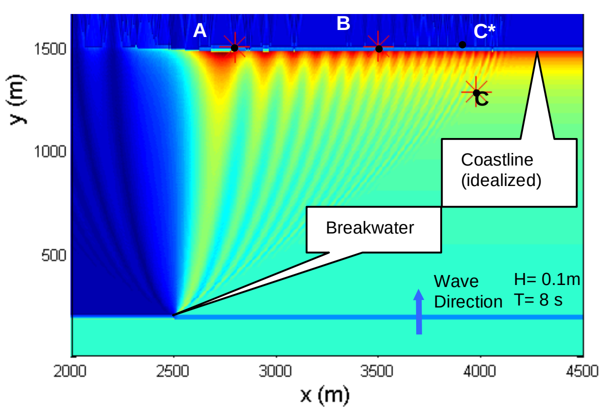


Figure 42: Wave diffraction/refraction pattern in an idealized Bay of Imbituba. Wave direction: 90^o

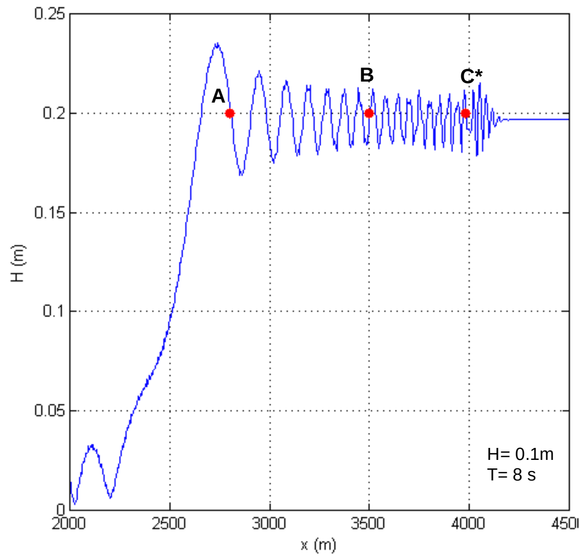


Figure 43: Variation of wave height along the idealized coastline (y=1500m). Wave direction: 90^o

The variation of wave height along the idealized coastline is represented in Figure 43. Noteworthy in this figure is the section of coastline between points B and C*: the envelope of the wave height variation in this area is practically constant. (Figure 44)

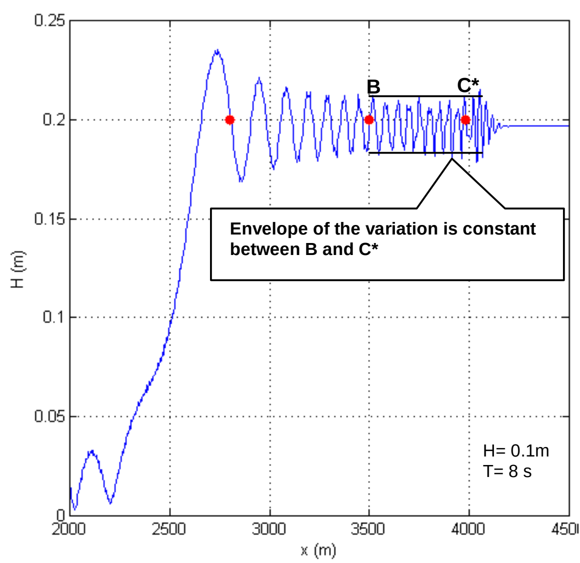


Figure 44: Variation of wave height along the idealized coastline. Wave direction: 90^o
Notice that the variation between B-C* is practically constant

When looking more closely at Figure 41 it is clear that when waves approach the bay at an angle of 90° they will also diffract along the northern headland (Ponta da Ribanceira). This situation has also been modeled in REFDIF and the results can be seen in Figure 45. The northern breakwater has in this case been modeled as a 100 m wide breakwater.

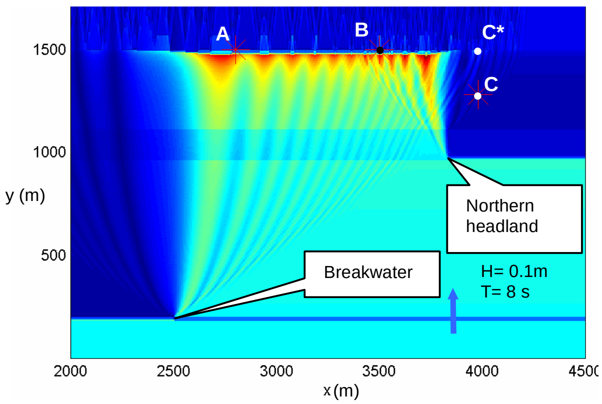


Figure 45: Wave diffraction/refraction pattern in an idealized Bay of Imbituba taking also in account diffraction around the northern headland. Wave direction: 90°

In Figure 45 the two diffraction/refraction patterns overlap each other creating an increase of wave height around x= 3750 m
This can clearly be seen in Figure 46. Remarkable is also the large drop in wave height around x = 3800 m.

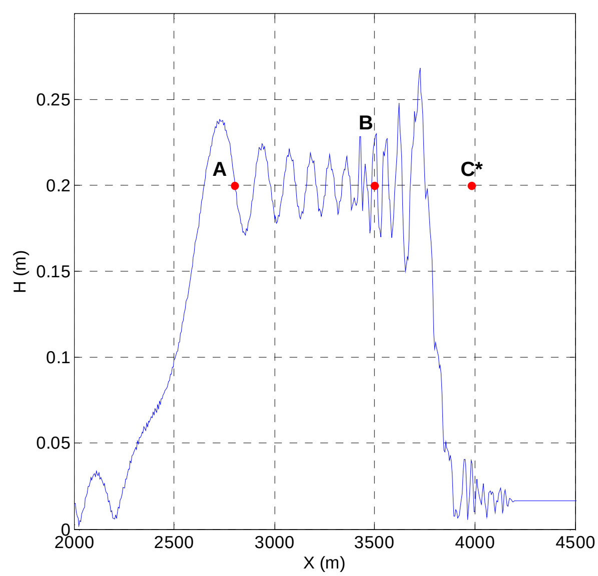


Figure 46: Variation of wave height along the idealized coastline of Imbituba taking into account diffraction around the breakwater and northern headland. Wave direction: 90°

5.1.2. Wave diffraction in the Bay of Taquaras/ Taquarinhas

To determine a relationship between the location of the downcoast control point and the diffraction pattern proved difficult in the case of the Bay of Imbituba. That is why also the diffraction/refraction pattern of the stable Bay of Taquaras/Taquarinhas was modeled
As was the case with the modeling of wave propagation in the bay of Imbituba here too a simplified topography of the bay was used :

- Uniform bottom profile of 1:40 (KLEIN ET AL. 2001)
- The southern headland was modeled as a 600m wide impermeable (no wave transmission) breakwater.
- The coastline was represented as straight.
- Wave height: 0,1m
- Wave period: 8 s
- Wave direction: 90° (East)

A point 'E' was introduced along the bay to facilitate interpretation of the calculation (Figure 47). The results of the REFDIF calculation can be seen in Figure 51.

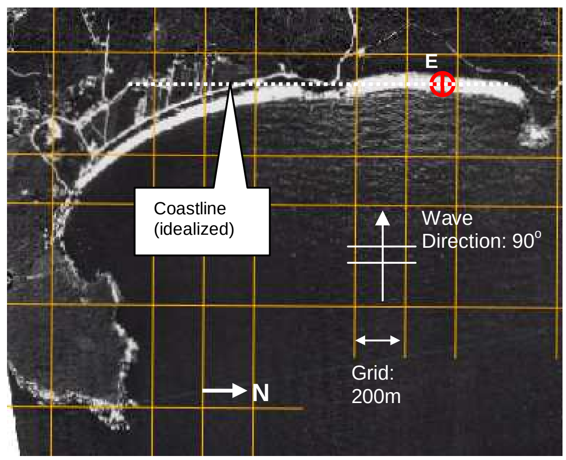


Figure 47: Location of point E and the idealized coastline for the interpretation of the REFDIF calculation in the bay of Taquaras/Taquarinhas.

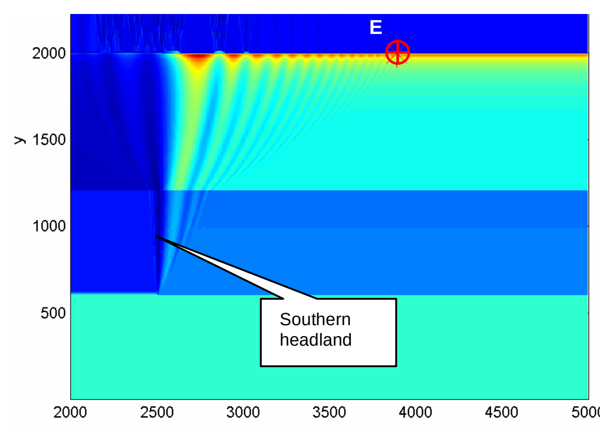


Figure 48: Wave diffraction/refraction pattern in an idealized Bay of Taquaras/Taquarinhas. Wave direction: 90°

The variation of wave height along the idealized coastline is represented in Figure 49. Remarkable in this figure is that point E is on the boundary between the area where there is influence on wave height by diffraction and the area where there are no diffraction effects. (Figure 39)

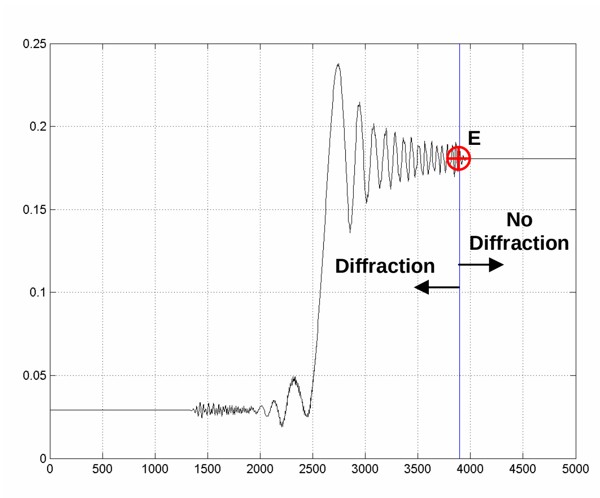


Figure 49: Variation of wave height along the idealized coastline of Taquaras/Taquarinhas. Notice that Point E is located on the boundary between the 'diffraction' and 'no diffraction' zone.

Point E was not chosen randomly, it is the location of the downcoast control point (Point E) in Figure 4 of the Expert Elicitation Part 2 (Figure 50 and Appendix.1). This figure was chosen by 33% (highest percentage of the figures) of the expert volunteers during the elicitation as the figure, which best represented their choice of positioning of the control points and corresponding SEP.

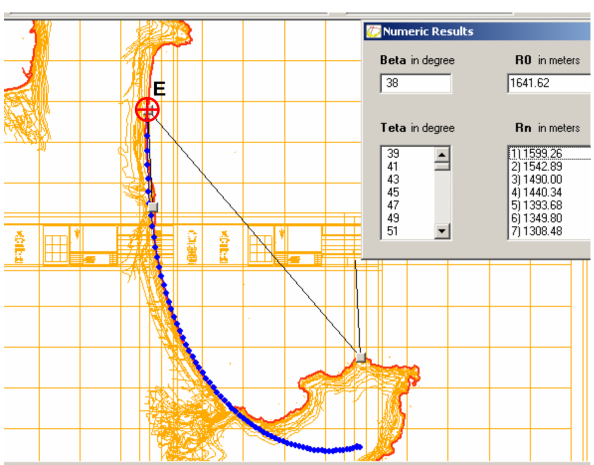


Figure 50: Figure 4 from the Expert elicitation part 2. The location of point E portrayed in the REFDIF results, is the same as the location of the control point E in the Figure 4 of the Expert elicitation Part 2.

5.1.3. Conclusions from the wave diffraction calculations

From the preceding paragraphs concerning wave diffraction the following can be concluded:

- The Cornu Spiral is not a suitable tool to investigate the limits of the diffraction effects. The objective in this study was to find the point where there was no more diffraction. This requires high (W>4) values of the Cornu parameter W, which are not accurately represented in the spiral.

- Initial wave diffraction/refraction simulations where performed with the software program REFDIF (KIRBY ET AL. 1994), which provided insight in the diffraction/ refraction pattern in the Bay of Imbituba
  These simulations were performed with simplified bottom profiles; straight coastlines and headlands schematized as wide breakwaters.

- In the case of the Bay of Imbituba:
  It is difficult to derive a relationship between the position of the control point E and the diffraction pattern.
  The REFDIF simulation with only the breakwater as diffraction point placed the area where no diffraction effect occurred outside of the bay of Imbituba. A section where the envelope of the wave height variation is constant occurs between points B and C*.
  More research into the significance of this envelope and it's relationship with the position of the control point E is needed.
  REFDIF calculations including the diffraction from the Ponta da Ribanceira, which represents reality more accurately, give a more complicated representation of the wave height behaviour. The bay experiences diffraction from two headlands, which causes overlapping diffraction patterns. Also here more research is needed to better understand the position of the control point E in a bay with multiple diffraction points.

- In the case of Taquaras/Taquarinhas Beach:
  In this particular case the separation point along the bay between the area under influence of diffraction (wave height variation) and the area free from influence of diffraction coincides with control point E. Control point E being the downcoast control point in the most frequently chosen figure in the Expert Elicitation Part 2.This supports the supposition by (MARTINO ET AL. 2005) in Table 4.

5.2. THE INTRODUCTION OF NEW PARAMETERS IN THE PBSE: DO MORE PARAMETERS MEAN BETTER RESULTS?

As mentioned in Paragraph 1.4 and Table 4 GONZÁLEZ ET AL. (2001) provided guidance on the location of the control point, proposing a parameter called α_{min} (Figure 51) which defines the down coast limit from which the parabolic model is applicable in beaches with dominant refraction-diffraction effects. The proposed model by GONZÁLEZ ET AL. (2001) does not use the orientation of the coast to obtain the wave direction but uses the definition of the wave front's orientation at the diffraction point in relation to the direction of the mean wave energy flux in the area (MWEF). Which is defined as follows:

- All the waves in any year are propagated with a propagation model until the diffracting point.
- An energy flux vector is composed for each wave (intensity of the vector = energy flux EC_g with the corresponding wave angle).
- Adding all of these vectors, results in the direction of the mean energy flux in that position. According to González, this is the real wave front to apply in the PBSE.

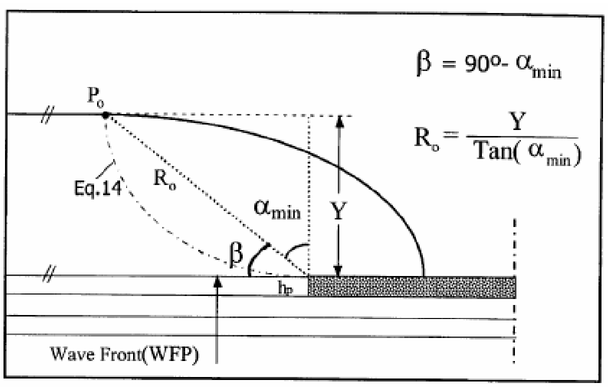


Figure 51: Definition sketch showing the relationship between the variables β and R_0, which are used in Hsu and Evans's (1989) equilibrium shape formulation and the variables α_{min} and Y used in the proposed methodology. Y is the distance from the control point to the prolongation of the straight alignment down coast. α_{min} is related to β through β= 90°- α_{min} (GONZÁLEZ ET AL. 2001)

Figure 52 shows the measured α_{min} versus Y/L_s for 26 beaches along the Atlantic and Mediterranean coasts of Spain. The selected beaches are fully developed beaches with a straight alignment downcoast

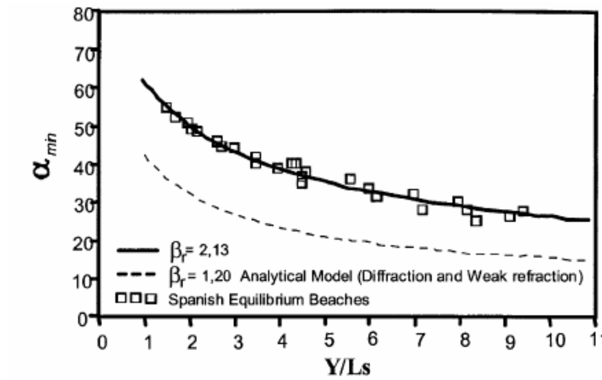


Figure 52: Value of the angle α_{min} for different dimensionless distances from the control point to the prolongation of the straight alignment downcoast Y/L. These values have been obtained using data from 26 beaches along the Atlantic and Mediterranean coasts of Spain. The analytical expression for α_{min}, for the case of diffraction with weak refraction derived by González (1995) is also graphed with a dashed line. (GONZÁLEZ ET AL. 2001)

A possible question that is raised when analyzing the work by GONZÁLEZ ET AL. (2001) is whether the introduction of more parameters into a bay describing equation such as the PBSE reduces the uncertainty in the predicted static equilibrium planform. When looking at Figure 52 a spread in the data from the Spanish beaches can be seen. This spread is largest around Y/Ls = 4.5.The spread in the value of α_{min} is approximately 5°.

In this paper it was shown that a spread in β of up to 10° (Taquaras/Taquarinhas Bay, Expert Elicitation part 2 in Appendix 1) can give an acceptable fit of the SEP on the coastline in static equilibrium. Meaning that larger variations in α_{min} can be possible, reducing the certainty of the position of the downcoast control point.

Another example of uncertainty caused by introduction of parameters into the PBSE is the determination of the Parameter Y, defined as the distance from the control point to the prolongation of the straight alignment down coast. (Figure 51)

The determination of Y is still based on visual estimation. In a case where there is a straight section downcoast of the bay the determination of the prolongation of the straight alignment is not a problem. The matters are more complicated in cases where a straight section downcoast is not obvious. Like in the example of Eaglehawk Neck Beach in Pirates Bay, Tasmania, Australia, a large embayment with upcoast control points at both ends. (Figure 53)

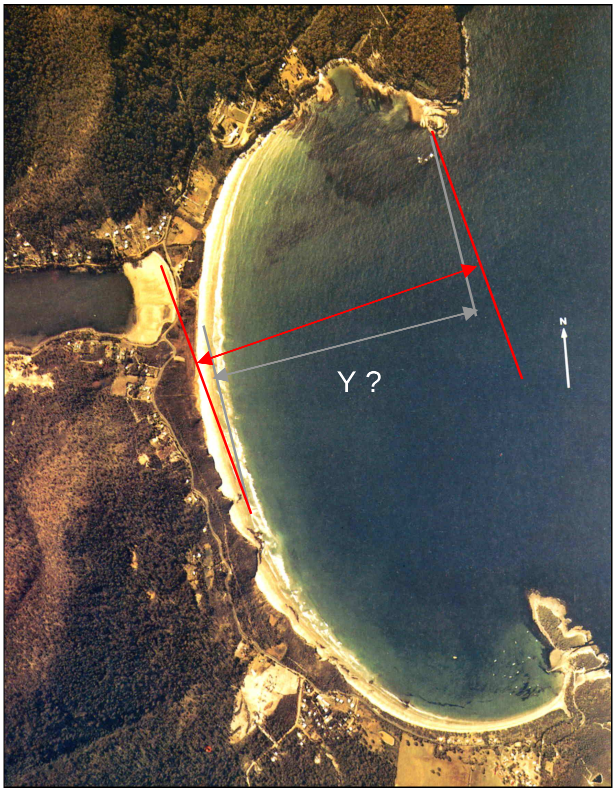


Figure 53: Eaglehawk Neck Beach (READER'S DIGEST, 1983). Finding the prolongation of the straight alignment down coast to determine Y is still based on (subjective) visual estimation.

Determining the length of Y would be simple if the wave direction is known beforehand as suggested with the use of the MWEF. After all the prolongation of the straight section of the coastline would be parallel to this wave direction.
However regarding the use of the mean wave energy flux (MWEF) as the wave front to apply in the PBSE the following comment can be made:
With advances in wave measurement techniques like the use of satellite data and wave measurement buoys, *momentary* wave data maybe available for most locations around the world.
But it is certainly not so that long-term (historical) wave direction data measured over sufficient time is available at any location and it is *only* from long-term wave direction data that an correct wave direction to be used in the PBSE can be determined.
With this data not readily available, the process of obtaining the wave direction from the orientation of the downcoast section of a bay (as proposed in the original PBSE by Hsu and Evans 1989) remains a valuable technique.

5.3. THE DEPENDENCY OF THE UNCERTAINTY ON THE POSITION ALONG THE BAY

In the conclusions of the statistical analysis of the expert elicitation (Paragraph 3.2.1) the following remark was made:
The bandwidth and standard deviation of the SEP increases when moving alongshore from profile 1 to 4. Meaning that the uncertainty in the application of the PBSE is dependent of the position along the bay. This behaviour was already noticed by MARTINO ET AL. (2005)

MARTINO ET AL. (2005) concluded the following:

"Neglecting second-order terms in a Taylor series expansion of the PBSE the following expression for the change in radius vector is obtained, as induced by an uncertainty $\Delta\beta$ in estimation of β:

$$\Delta R = R_0 \left(C_1 + C_2 \frac{2\beta}{\theta} \right) \frac{\Delta\beta}{\beta}$$

In particular, at the control point ($\theta = \beta$), this equation reduces to:

$$\Delta R = R_0 \, (C_1 + 2\, C_2) \frac{\Delta\beta}{\beta}$$

Uncertainty depends in a multiplicative way on three parameters, R_0, β, and θ, and on two empirical coefficients that depend on β. The larger the size of the beach (R_0), the larger ΔR.
Similarly, for larger θ (points located more towards the "shadow area"), the uncertainty ΔR decreases. Figure 54 shows how an error in β of ±1% implies an error in R that decreases with θ; that is, it depends on the particular location of the point of interest within the curve. The error also depends on the size of the bay, inversely on the angle θ and in a complex way on the angle β furthermore the error is smaller in the area strongly controlled by diffraction"

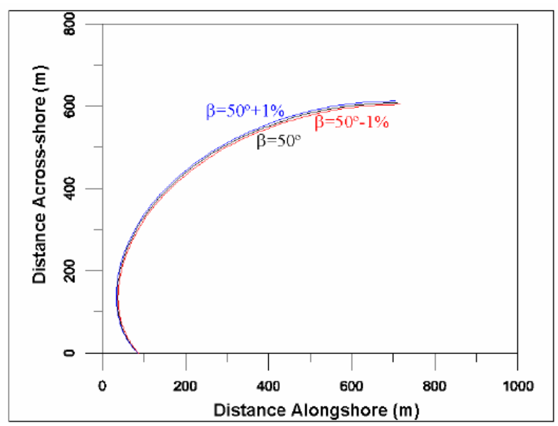


Figure 54: Parabolic (β=50°) sensitivity to ± 1% variation in β (Martino et al. 2005)

What is striking from the results of the Expert Elicitation (Paragraph 3.2.1) is that the *opposite* behavior seems to be the case. In the Bay of Taquaras/Taquarinhas the error increases when θ increases. More research on this topic is needed to test verify the general relationship between error and position along the bay.

6. CONCLUSIONS

This chapter presents the overall conclusions that can be drawn from the research conducted in the framework of this paper.

With the help of an expert elicitation an attempt was made to quantify the sensitivity of the Parabolic Bay Shape Equation applying it to the existing stable bay of Taquaras/Taquarinhas. The following can be concluded from the analysis of the results from this expert elicitation:

- When strictly adhering to the definition of the control points and not seeing the result of the control point configuration, twenty-two expert volunteers provided the following:
    - In the particular case of a stable bay, 1800m wide and 750m indentation, the overall bias of the location of the SEP calculated over 4 evenly spaced (200m) profiles in the southern part of the bay is in the order of 41m (landward) with an average bandwidth of 116 m.
    - The bandwidth and standard deviation of the SEP increase when moving alongshore from profile 1 to 4. Indicating the following behaviour:
        - The uncertainty in the application of the PBSE is dependent on the particular point of interest along the bay.
        - When moving along the SEP from the downcoast control point to the more strongly curved area of the bay the uncertainty of the PBSE increases. This behaviour is opposite of the relationship found earlier by MARTINO ET AL. (2005), where the uncertainty decreases when moving along the SEP from the downcoast control point to the more strongly curved area of the bay
- Provided the volunteer sees the consequences of the placement of the control points (the corresponding SEP) the variation of the position of the SEP along the four profiles is much smaller. This in turn means that the PBSE is a **robust** method provided the user sees the result of his/her choices in placement of the control points (SEP plot)

Applying the PBSE on the Bay of Imbituba lead to the following conclusions

- As a consequence of the construction of the breakwater and groins the equilibrium status of the Bay of Imbituba has changed from dynamic to close to static in the north and unstable in the south
- The tendency of the sedimentation of the port can be explained by looking at the SEP belonging to the new upcoast diffraction point (the tip of the breakwater):
  To reach this new SEP the southern part of the bay requires massive accretion.

The statement given by one expert during the expert elicitation that point E cannot exist in the Bay of Imbituba was the motive to conduct more research on the relationship between the positioning of control point E and the wave diffraction pattern in the bay. The conclusions of this research are:

- The Cornu Spiral is not a suitable tool to investigate the limits of the diffraction effects. Finding the point where there is no more diffraction, requires high (W>4) values of the Cornu parameter W, which are not accurately represented in the spiral.
- In the case of the Bay of Imbituba:
  It is difficult to derive a relationship between the position of the control point E and the diffraction pattern.
  The REFDIF simulation with only the breakwater as diffraction point placed the area where no diffraction effect occurred, outside of the bay of Imbituba. A section where the envelope of the wave height variation is constant occurs between points B and C*.
  More research into the significance of this envelope and it's relationship with the position of the control point E is needed.
  REFDIF calculations including the diffraction from the Ponta da Ribanceira, which represents reality more accurately, give a more complicated representation of the wave height behaviour. The bay experiences diffraction from two headlands, which causes overlapping diffraction patterns. Also here more research is needed to better understand the position of the control point E in a bay with multiple diffraction points.
- In the case of Taquaras/Taquarinhas Beach:
  In this particular case the separation point along the bay between the area under influence of diffraction (wave height variation) and the area free from influence of diffraction coincides with control point E. Control point E being the downcoast control point in the most frequently chosen figure in the Expert Elicitation Part 2.This supports the supposition by (MARTINO ET AL. 2005) That the control point E is a boundary for the curved section of the beach controlled by diffraction and the straight section of beach perpendicular to the assumed predominant wave direction.

After having numerously applied the software program MEPBAY to the several bays the following general conclusions on the application of MEPBAY version 1.0 can be made:

- In using MEPBAY as an engineering tool there are several sources of uncertainty that are more related to image processing than coastal engineering. One of these uncertainties is the distortion of data introduced by conversion by different software programs. It is of utmost importance that the images are not distorted. An alteration of the coastline by a software operation could lead to erroneous conclusions about the state of equilibrium when comparing the plotted static equilibrium with the (distorted) coastline. Although there was no ‘visible’ distortion of the images, no quantitative method was applied to prove that the image was not distorted.

- Another source of uncertainty is the aspect of image size (in KB). It is possible to place the control points more precisely when using large (>12.000KB) images. But there is a limit to the amount of KB that you can load and the coastline is poorly visible when zoomed out to the extend of the whole bay. Also here quantification of the difference in accuracy is needed when working with different size images.

- It is evident that like in all software programs the quality of the results obtained from MEPBAY are as good as the quality of the input. When using charts the vertical datum must be known and with aerial photographs the exact time and local conditions of taking of the photograph have to be recorded so that the *shoreline indicator* can be related to other data using tidal charts.
  So even though the MEPBAY program can be accurate in its functioning, complete and exact data is of crucial importance especially when considering a flat beach slope and high tidal difference, as is the case in the Bay of Imbituba.

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8. APPENDICES

Appendix 1: Expert elicitations
Appendix 2: Theoretical background on the PBSE
Appendix 3: Participants expert elicitation
Appendix 4: Data from Imbituba
Appendix 5: Georeferencing of the data
Appendix 6: Evolution Of The Coastline Of Do Porto Beach
Appendix 7: Application of the PBSE to Imbituba

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