Bundesanstalt für Wasserbau
Kompetenz für die Wasserstraßen

Investigation into the penetration behaviour of ships' anchors via anchor-dragging tests

Report on measurement of anchor penetration depth

Assignment number
A395 502 10088

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Bundesanstalt für Wasserbau
Kompetenz für die Wasserstraßen

Report

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Summary

In the period 29 April 2013 to 05 May 2103, a wide ranging field investigation was carried out in German Bight into the penetration behaviour of anchors, using anchor dragging tests. In addition to BAW - DH, the Federal Maritime and Hydrographic Agency [BSH], the electrical network operator Tennet and the Dutch research body Delares participated. The rationale for the investigation is the question whether marine cables in the area of shipping lanes can be buried at a reduced depth without giving rise to increased potential danger due to anchoring manoeuvres, for example as a result of shipping accidents.

In the course of the anchor dragging tests 3 anchor drags were carried out, with two different anchor types, in 3 test areas, i.e. a total of 18 anchor drags. One of these test areas was in the area of a maritime shipping lane [VTG Terschelling German Bight].

The present report refers to the contribution of the BAW-DH and the BSH to the tests, namely the measurement of the anchor tracks and anchor penetration depth using a Sediment Echo-Sounder [SES] and a Side Scan Sonar [SSS].

Using the methodology applied it was possible to investigate and record the effect of the anchor in the seabed. The results obtained are to be considered solid and thus robust and reliable.

In addition to the question of penetration depth of anchors covered by this report the scope and quality of the tests offer a good basis for further scientific analysis and evaluation. Such exploitation should be sought in cooperation with the participants or other institutions.

Federal Waterways Engineering and Research Institute.
Anchor dragging tests in German Bight.
BAW no: A395 502 10088
August 2013

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List of Tables Page

Translators' note: Unfortunately, in the original German this List does not correspond to the actual number of tables appearing in the main document - there are in fact 6 tables, not 4 as in the German List. We have corrected the list and page numbering to reflect what is in the translated main document.

List of Appendices

The abbreviations N, S and V refer to test areas North, South and VTG respectively

List of abbreviations

List of abbreviations most frequently used in the report

BAW-DH	Bundesanstalt für Wasserbau – Dienststelle Hamburg *[= Federal Waterways Engineering and Research Institute - Hamburg branch]*
BSH	Bundesamt für Seeschifffahrt and Hydrographie [= *Federal Maritime Hydrographic Agency*]
Tennet	Tennet Offshore 7. Beteiligungsgesellschaft mbH *[= Tennet Offshore 7. Associated Limited Company]*
WSD Nordwest, from 1st May 2013:	Wasser- and Schifffahrtsdirektion Nordwest
GDWS Ast NW	Generaldirektion Wasserstrassen and Schifffahrt - Aussenstelle Nordwest [= *Federal Waterways and Shipping Agency - North-West Branch*] [In the report only the new designation is used]
VTG	= Shipping lane area [Terschelling German Bight]
VWFS Wega	Vermessungs-, Wracksuch-, Forschungsschiff Wega *[= Survey, wreck-search and research vessel Wega]*
MBES	MultiBeam Echo Sounder
SSS	Side Scan Sonar
SES	Sediment Echo Sounder
ROV	Remotely Operated Vehicle

Translators' note: The [English] designations of the various organisations mentioned above are not literal translations of the German - they are the descriptions that said organisations use to describe themselves in English. For the sake of readability we have retained the German abbreviations throughout the text.

Notes

Geodetic Reference System:

All co-ordinates and map representations mentioned in the report are based upon the geodetic location reference system UTM, Zone 32 [WGS84].

Chronological Reference System:

Unless otherwise stated, time information refers to UTC [Central European Summer Time – 2 hours]

1 Rationale and nature of the project

During the period 29/04/2013 to 06/05/2013 the Federal Waterways Engineering and Research Institute - Hamburg branch [BAW-DH] participated in the "investigation into the penetration behaviour of ships' anchors" using anchor dragging tests. This resulted from an agreement between *Tennet Offshore 7. Beteiligungsgesellschaft mbH* [hereinafter Tennet] and *Generaldirektion Wasserstraßen und Schifffahrt - Ast. Nordwest [GDWS Ast. NW]* [1]. On 03/08/2012 Tennet lodged an application for a planning amendment with *GDWS Ast NW* in order to „reduce the laying depths in sea area Terschelling German Bight [hereinafter VTG] for the planned maritime cable DolWin1". Justification for this was the very high resistance to shearing of the seabed in the south of VTG. In these seabeds, laying maritime cables with the required minimum burial depth of 3 metres cannot, according to Tennet, be achieved. However, if laying depths are to be reduced in VTG, the demands of convenience and safety of shipping traffic must be taken into account, especially the danger caused by emergency anchoring or involuntary anchor-dropping in the area of the cable lines.

As a result, at a meeting on 26.11.2012 with representatives of GDWS Ast NW [1], the Federal Maritime Hydrographic Agency, the BAW-DH, the Dutch research institute Deltares and Tennet, a testing programme to investigate the penetration behaviours of anchors was agreed upon. Three testing areas, of which one was VTG South, and two anchor types were selected.

The procedure and the methods to be used were agreed and decided before commencement of the investigation programme in numerous discussions and tele-conferences as well as by email and the available written and printed information. According to the agreement each participant is to issue a part-report for its own contribution to the investigation, these are then to be combined in an overall report.

This report refers to the contributions of the BAW-DH and the BSH, i.e. the measurement of anchor tracks and anchor penetration using a Sediment Echo Sounder [SES] and Side Scan Sonar [SSS],

[1] In the course of a re-organisation, *WSD Northwest* was renamed on 01 May to *Generaldirektion Wasserstrassen and Schifffahrt - Aussenstelle Nordwest*, in this report the new name is used throughout

The SES measurements were to provide information about disturbances in the upper sediment layers which could be attributed to the effect of an anchor dragging on the seabed. In particular the maximum penetration depth, in relation to the level of the undisturbed seabed, was to be ascertained.

Complementary to the SES recordings, surface monitoring of the test areas was carried out.

In so far as the results of the other methods used contribute to the understanding of the SES and SSS results, these are also included in this report. For further information the specific part-reports should be consulted if required.

2 Personnel and Equipment

For the technical requirements and operation of the anchor dragging test, 3, sometimes 4, vessels were available. In addition to the required nautical personnel, technical and scientific personnel were employed to carry out measurements and produce documentation.

Vessel	*Type*	*Ship-owner*	*Used By*	*Functions*
Esvagt Connector	*Multi-purpose vessel. Offshore tug*	Esvagt A/S Denmark	*Tennet*	*Anchor handling, anchor drags*
Guardian	*Survey ship*	Braveheart Shipping, Netherlands	*Tennet*	*Submersible robot, multi-beam measurement*
VWFS WEGA	*Survey ship*	BSH	*BSH, BAW*	*Side Scan Sonar Sediment Echo Sounder*
Karen	*Patrol vessel*	BSH	*Tennet*	*Traffic security, temporarily in VTG*

Table 1: Overview of the vessels participating in the anchor dragging tests

2.1 BAW, BSH aboard VWFS Wega

VWFS Wega was made available as a carrier platform for the SES and SSS measurements [Plate 1]. The SSS equipment is built into the side of the ship; the SES is temporarily installed and attached to the ship's measuring equipment.

Plate 1. Survey, wreck-search and research vessel Wega [BSH]

A hydrographic shaft [Plate 2] was available to accommodate the SES oscillator [underwater unit], the shaft was integrated into the ship's co-ordinates system and could be calibrated with the other sensors of the hydrographic measurement system [position, ship's movement, side scan sonar]. Measurement planning and profile navigation was carried out by VWFS Wega's own on-board systems and the data recording of the SES with the Seswin software belonging to the system. Data relating to the ship's position and orientation [heave, roll, pitch, heading, position] were transferred by the measurement system of VWFS Wega, via splitters, to the Seswin software.

Plate 2: Hydrographic shaft on VWFS Wega accommodating the SES oscillator

Measurement operations on the Wega were carried out and co-ordinated by BAW-DH and BSH personnel [individual tasks allocated ad hoc]   Tennet was represented by a qualified observer. GDWS Ast NW did not participate.

Table 2 shows the relevant hardware components of the measurement system used and Table 3 the responsibilities on board the VWFS Wega. Plate 3 shows the measurement workstation on VWFS Wega.

1	Side Scan Sonar	Edgetech MPX 4300	410 KHz, typically 75 m beam width
2	Sediment Echo Sounder	Innomar SES2000 Standard	LF 4 – 15 KHz, HF ca. 100 KHz, Open angle < +/- 2°
3	Positioning	Leica GPS1200	Differential via NavBeacon Receiver Heligoland
4	Ship motion	Seatech MRU5 plus	Heave, Roll, Pitch
5	Orientation	Anschütz Standard 20	Ship’s heading
6	Tide	Javad Sigma GPS	GPS-Raw data [Post-processing]

Table 2: Hardware components of the measuring system on VWFS Wega

Name	Institution	Function
Hartmut Brunn	BSH	Skipper of the Wega, measurement planning
Maria Lambers Huesmann	BSH	Sonar operator
Peter Hümbs	Innomar Technologie GmbH	SES Operator
David Sinclair	Tennet	Expert Observer, Tennet
Christian Maushake	BAW	Co-ordination

Table 3: Participants and responsibilities on board VWFS Wega

Plate 3: Hydrographic Workstation on board VWFS Wega

Glossary:
Measurement planning
SES transmitter/receiver unit and control processor

2.1 Tennet aboard *Guardian* and *Esvagt Connector*

Carrying out the anchor drags and mobilisation of the necessary vessels was organised and supervised by Tennet. The anchor drags were carried out by the multi-purpose vessel *Esvagt Connector* whose static pull specification as an offshore tug is 107 tonnes maximum. On board the survey ship *Guardian* the anchor drags were recorded and documented by ROV Video and MBES. For anchor drags in southern VTG the patrol vessel Karen stood by for traffic safety purposes.

The project manager with overall responsibility [M. Petzold, Tennet] was stationed on the *Guardian*. In addition, expert observers from Tennet [Frau V. Schwamborn, Frau A. Drews] and Deltares [D. Luger, H. v. Lottum] were employed on the *Esvagt Connector*. Further details and a description of the test procedures on *Guardian* and *Esvagt Connector* can be found in the relevant Tennet or Deltares part-reports.

Plate 4: Tennet participating vessels Left: Survey ship Guardian [22.2 x 6.6 x 1.3 m]
Right: Multipurpose vessel and offshore tug Esvagt Connector [56.4 x 14.5 x 6 [max.] m]

3 Test areas

As there is an interaction of the penetration behaviours of anchors with the composition of the sediments in the seabed along with geo-technical parameters, a total of 3 test areas in German Bight were designated for the anchor dragging tests, with different seabed compositions. For the purposes of the investigation programme, these were designated „BSH North“, „BSH South and „VTG“ [Plate 5].

In this respect the area “VTG“, in which the problems mentioned with the required minimum burial depth of 3m in the laying of marine cables manifest themselves, is of special interest.   According to previously available examinations of the seabed in the southern area of VTG especially, very solid layers of clay force themselves upwards in “folds” very close under the surface of the seabed. These structures cause particular technical problems for cable-laying [according to statements from Tennet, see measurement project plan].

In the other two areas BSH Nord“ and „BSH South" the sediment composition is rather more homogeneous: In „BSH Nord“ mainly loose to very loose layers of sand and in „BSH South“ loose to moderately dense fine sands with coarse clay particles [according to the measurement project plan].

Within the 3 areas envisaged „BSH North“, „BSH South“ and „VTG“ „measurement boxes“ were defined, within which, prior to the anchor dragging tests, base measurement was carried out by VWFS Wega and within which the anchor drop positions were specified.

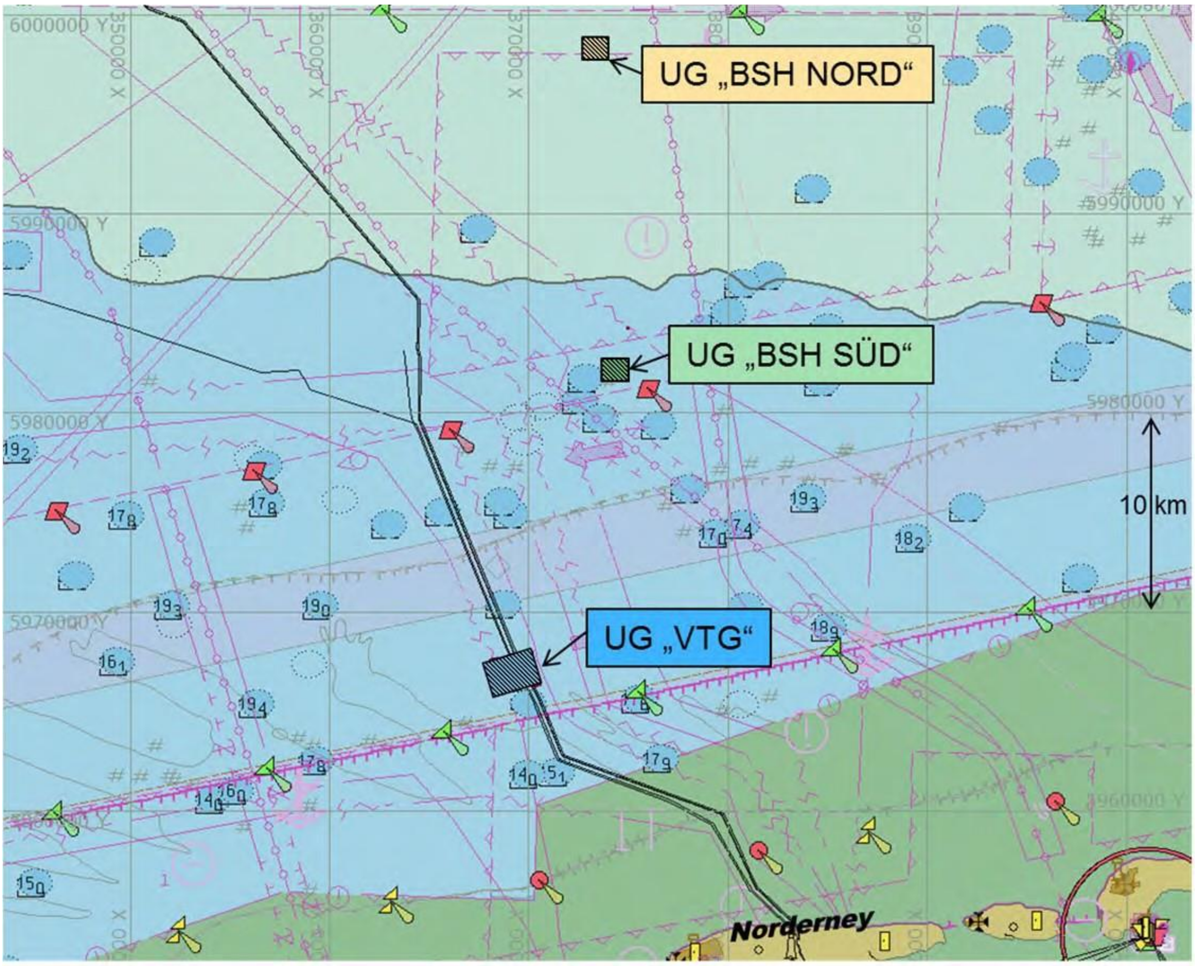

Plate 5: Location of the test areas in German Bight

Glossary
Test area BSH North
Test area BSH South
Test area “VTG”

Plate 5 shows an overview of the test areas; the exact location and a list of co-ordinates can be found in appendices 2N, 2S, and 2V.

4 Anchor dragging tests

For the tests, very strict organizational and logistic requirements and limitations had to be observed in the investigation. The measurement project plan agreed with all participants could, in essence, be adjusted as envisaged*. Accordingly, in each of the test areas 3 anchor drags with the two anchor types under investigation were carried out, thus a total of 18 anchor drags.

Translators’ note* Is the word NOT missing from this sentence here?

4.1 Test anchors

In accordance with the measurement project plan and in agreement with GDWS Ast. NW, two test anchors were selected which meet the regulations of German Lloyd for container ships of 294m in length and a capacity of 80.000 tdw. One anchor of „Hall“ type weighing 11.7 tonnes and one anchor of Type „HHP AC14“ weighing 8.3 tonnes suitable for the survey ship were used [Plate 6], As an anchor chain for both test anchors an 81mm Gr.III chain ca. 60m in length and weighing ca. 2 tonnes was used. Anchor handling, i.e. anchor drops and drags as well as re-shackling and preparation of the dragging tests, was entirely carried out by the offshore tug Esvagt Connector.

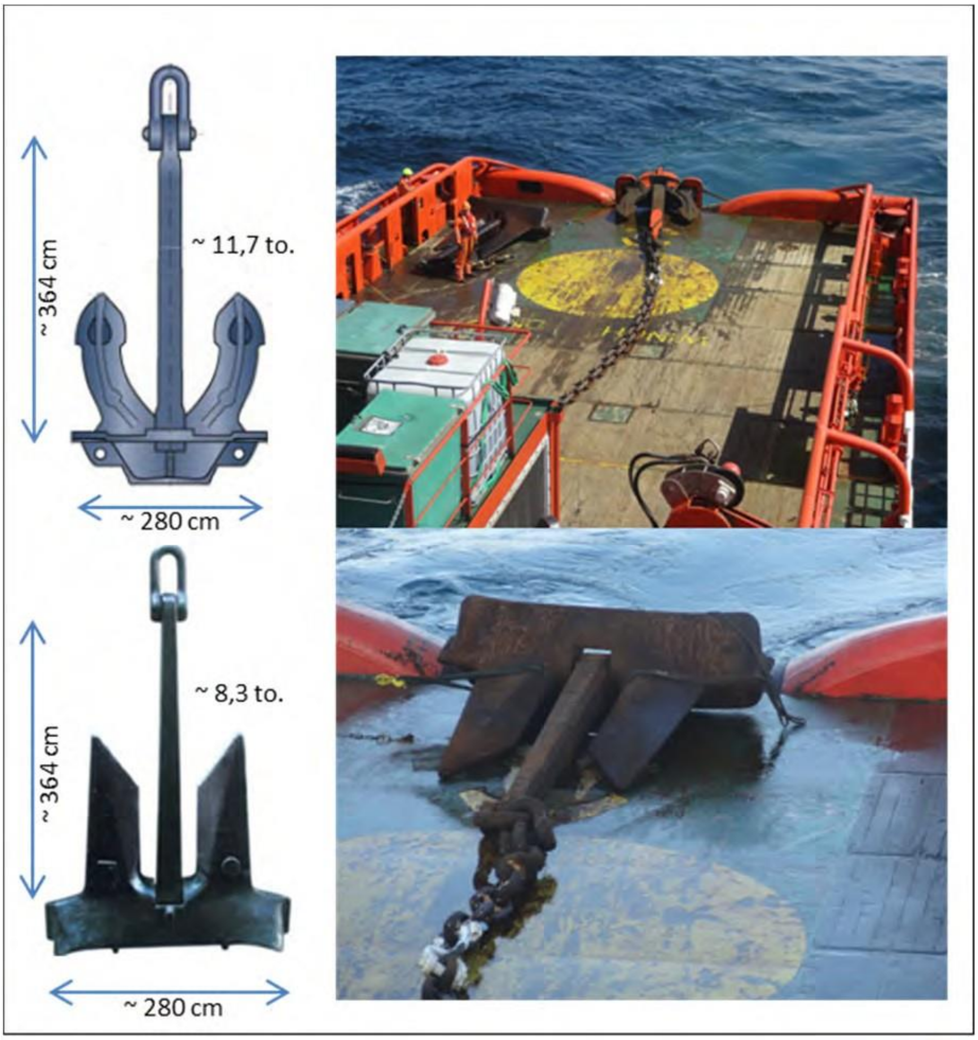

Plate 6: Test anchors used: above: Hall – Anchor, below: HHP AC14 – Anchor

4.2 Test procedure

The individual test phases should at this point again be presented schematically and in abbreviated form [Details in the measurement project plan or in the relevant part-reports]:

1. Base measurement [SES, SSS] by VWFS Wega in the test area
   [Detection of possible obstacles, inspection of the planned drop positions and sediment structures in the upper seabed layers]
2. Positioning of *Esvagt Connector* over the prescribed drop position
3. Anchor drop
4. Inspection of the anchor position by ROV – Video [*Guardian*]
5. Anchor drag, up to a maximum drag* [80 tonnes] or until anchor breakout
   * The maximum drag is specified in the measurement project plan
6. Inspection or measurement of the anchor position in the end position [SSS, partially. MBES, partially SES, partially ROV – Video]
7. Recovery of the anchor, proceeding to new drop location
8. Final measurement of the anchor track by *VWFS Wega using* SES and SSS, or. MBES [the latter by *Guardian*]

The inspection envisaged in the measurement project plan of the final state of the anchor drag by Sediment Echo Sounder [VWFS Wega] proved unfeasible in practice. Instead, MBES measurement by Guardian or SSS measurement by VWFS Wega led to more informative results. Documentation of the MBES measurement and video recordings of the submersible robot by Guardian do not form part of this part-report.

All anchor drags were carried out against the prevailing tide direction thus in west-to-east direction or vice-versa. The reasons for this lay in the manoeuvrability of the offshore tug *Esvagt Connector* [every ship manoeuvres better „against the current“] and in the ROV operation on board the *Guardian.* In VTG there was the additional requirement to respect the traffic regulations. For this reason all anchor drags in VTG were effected from west to east on a falling tide.

In some of the drags the anchors were dragged twice, or in one case even three times, in relation to the drop position. This was due to the subjective impression of the tug’s skipper [„human factor“], that in the first drag the maximum pull force had not been exerted upon the anchor. In these instances it was decided after the current test to pull the anchor in again, in its existing position, without a new drop process. This affects Positions N2, N4, N5, N6 [two drags] and V1 [three drags]. This is accordingly noted in the illustrations and appendices.

With one exception [Position N4] all anchor drops were effected at the planned prescribed location. In the case of VTG the prescribed locations were optimized on the spot after evaluation of the base measurement [see 4.4] to the extent that the clay layer near the surface was also affected by the anchor drag. In the areas BSH North and BSH South the planned anchor drop positions were moved.

Execution of the anchor drags and the drop and final end position of the anchor was monitored from on board the *Guardian* via video recordings by a submersible robot and documented. On the offshore tug *Esvagt Connector* the drag forces were continuously monitored by a load cell.

In total anchor drags were effected in 17 of the 18 planned drop positions. Only in position 14 was no drag carried out. Explanation: *Esvagt Connector* informed the project manager [*Guardian*], that the previous drag in Position N3 had proved to be “too skewed” and they had probably encroached upon the area of Position N4 [although Appendix 3N shows that this opinion was somewhat over-pessimistic]. To avoid the risk of mixing up 2 anchor tracks, the project manager decided to leave out Position N4. However, as there were a total of 5 positions where the anchor was dragged twice or three times [see above] this should not be regarded as critical in evaluating the overall result of the investigation

4.3 Measurement work on *VWFS Wega*

The measurement work to be carried out by VWFS Wega during the anchor dragging tests consisted first of all in a base measurement of the part-areas [measurement boxes] by SSS and SES. The base measurement was agreed before the start of the anchor drags. After the anchor drags a highly illuminating measurement of the anchor tracks, also with SSS and SES, was carried out.

An originally planned „interim measurement“, i.e. measurement of the anchor track after the drag test with the anchor still in position by VWFS Wega was abandoned after the experience of the first drag. This interim measurement proved operationally very complicated and produced no significant extra information. As an alternative an MBES measurement was carried out by *Guardian* after the anchor drag before hoisting of the anchor.

4.4 Base measurement

In the three test areas BSH North, BSH South and VTG part-areas [= measurement boxes] were defined, in which the 6 anchor drop positions were planned [see Appendices 2N, 2S, 2V]. Before the start of the anchor dragging test a base measurement with SES and SSS was carried out by *VWFS Wega* [see Appendices N0, S0, V0] in each of these measurement boxes.

The base measurements were intended to enable any obstacles in the anchor drop area to be identified [SSS] and/or the substrate structures in the respective areas to be ascertained [SES]. The distance between profile lines for the base measurement was set at 100m.

SSS recording did not reveal obstacles in any of the planned anchor drop locations.

SES measurement made it possible at the planning stage of the test areas to confirm the anticipated seabed characteristics. Areas BSH North and BSH South are equally flat and display almost no morphological structures. The homogeneous composition of the seabed material can be confirmed from the SES readings in these two test areas. The fact that the material in test area BSH North is looser-lying than in test area BSH South is shown by the stronger signal reflections from the seabed in test area BSH North.

Because of the anticipated heterogeneous substrate structure the chosen area for base measurement in VTG was larger than in areas BSH North and BSH South. Here, SES measurement was intended to enlighten us concerning the “small folds of dense floor [clay/coarse clay] with a higher shear resistance reaching up until just under the surface“.

Such structures could in fact be identified from the SES readings [see Appendix V0]. Accordingly, the anchor drop positions in VTG could be planned anew on the basis of the SES measurement results [see Appendix 3V].

Fig 7 shows an example of an SES profile line from test area VTG in which sediment structures running at an angle to the seabed can be seen. These represent the “folds“ of ground with high shear resistance cited in the rationale for these investigations [see 1], which make cable-laying, according to Tennet, so difficult.

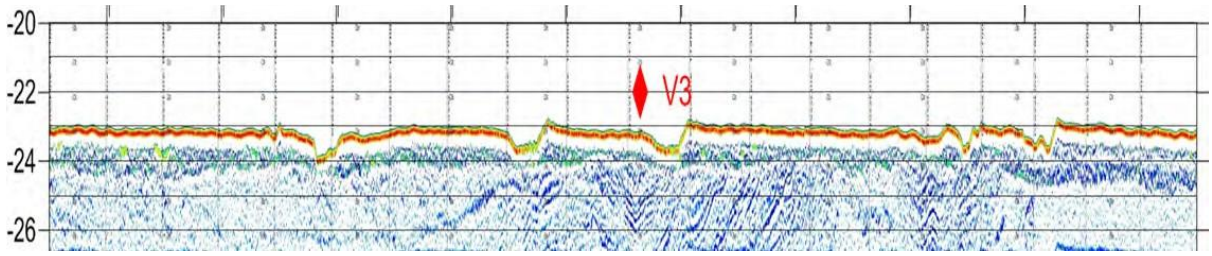

Plate 7: SES profile line with anchor drop position[s] marked [V3]

4.5 Anchor track measurement

In order to investigate the effect of the test anchors, in particular penetration into the seabed, various measurement systems [SES, SSS and MBES], as already shown, were used. Basically we should distinguish here between an area and a linear recording. The fan-type send/receive geometry enables area-based procedures such as MBES and SSS to record a broader strip of the seabed acoustically with one measuring cycle.

However, on account of the hydro-acoustic limitations as a function of transmitting performance and wavelength, these systems are unable to penetrate the seabed in order to obtain Information on the composition of sediments or on obstacles in the upper floor level. The complex acoustic breakdown conditions would also prevent efficient Interpretation of signals running at an angle in the seabed. Systems using fan-type operation are thus only able to deliver Information re the surface structure of the seabed.

It was however an essential requirement in measuring the anchor tracks to detect the deepest recordable effect of the anchor in the seabed. This is not necessarily evident as an open surface structure, for example a digging, but may also be concealed by sediment in the seabed. The “deepest drop point of the anchor” can only be recorded by a procedure which is able to penetrate the seabed and detect layers and obstacles in the composition of sediments. For this purpose SES was used.

4.5.1 Sediment Echo Sounder [SES]

SES is a linear measurement system which sends and receives high-pulse-rate signals along a profile line [corresponding to the sailing direction of the ship]. Here, not only is the water depth recorded [meaning between surface and seabed] but also the sound reflections from the deeper layers of the seabed. In this way solidified sediment layers, disturbances in the sediment composition and also hidden obstacles can be charted. The concealed track of an anchor can thus be recorded as a “disturbance” in the composition of the sediment and identified.

The high level of energy required to penetrate the seabed can only be attained using low frequencies [< ca. 15 KHz, dependent on the seabed. These cannot however be bundled, which means that they can only be transmitted at a wide angle and thus deliver poor spatial resolution ["large footprint"].

In addition there are other acoustic effects [in short: spurious lobes and „ringing“] which seem to render the use of lower frequencies [penetrating the sea bed] unsuitable for small-scale, high-resolution shallow water applications [e.g. anchor-drag tracks]. The solution lies in so-called “parameter acoustics“, in which the differential frequency of two frequencies lying relatively close to one another produces a parameter signal of lower frequency.

In this way it is possible to produce a tight bundled low frequency acoustic signal with high spatial resolution, which is able to penetrate the upper sediments in the seabed and to chart these. The depth of penetration depends on many parameters. One could mention for example the water depth, the composition of the sediment, the thickness of the strata and the amount of gas or air in the seabed.

For the measurement of the anchor track a parametric shallow water Sediment Echo Sounder of type Innomar SES 200 Standard was used with the following essential features:

- Very small aperture angle of < +/- 2°
  I.e. only a small area sounded on the seabed [footprint], good horizontal resolution
- Short pulse length
  I.e. high vertical resolution of up to 6 cm [depending on the selected frequency and pulse length]
- High pulse rate -- at the prevailing water depths here ca. 16 to 22 pulses per second
- Selectable low [secondary] frequency used in steps between 4 and 15 KHz for these investigations:
  8 KHz [2 oscillations] for base measurement
  10 KHz [2 oscillations] for anchor track measurement
- Primary frequency ca. 100 KHz
- Active beam stabilisation

4.5.2 Side Scan Sonar

As mentioned in 4.5 the Side Scan Sonar [SSS] is an area-based procedure, which records the surface structures and textures of the seabed in a fan shape perpendicular to the ship's course. Exact depth information [as with MBES] cannot normally be ascertained from the readings of an SSS.

The SSS installed on *VWFS Wega* was used to portray the track produced by the anchor drag in the seabed. These readings then served as a basis for planning the SES measurement of the anchor track.

The Side Scan Sonar of Type Edgetech MPX 4300 used is permanently built into the measurement apparatus on *VWFS Wega*. For the investigations described here an ultrasound frequency of 410 KHz with a beam width of 75 m was installed.

4.6 Anchor track measurement procedure with SES and SSS, or MBES

On completion of the anchor drag in the anticipated drop position two parallel profile lines were sailed with SSS-recording along the presumed anchor track. As the imaging characteristics are usually most favourable in the centre of the sonar fans, the parallel profiles were offset in such a way that the anchor track was clearly displayed once in the port side sonar fan and once in the starboard side fan. The sonar images were processed on board *VWFS Wega* with the installed measurement system, so that the anchor drop position and the final location of the anchor after the anchor drag could be determined in line with co-ordinates. These points serve as a base line for the measurement of the anchor penetration depth using SES.

Measurement of the anchor track with SES then took place perpendicular to the direction of the anchor drag, with the profile gap as small as possible. Depending on the length of the anchor drag and the manoeuvring conditions [e.g. current] between 2 and 12 intersections of an anchor track occurred. Plate 8 shows schematically the combination of an SSS reading with the SES measurement.

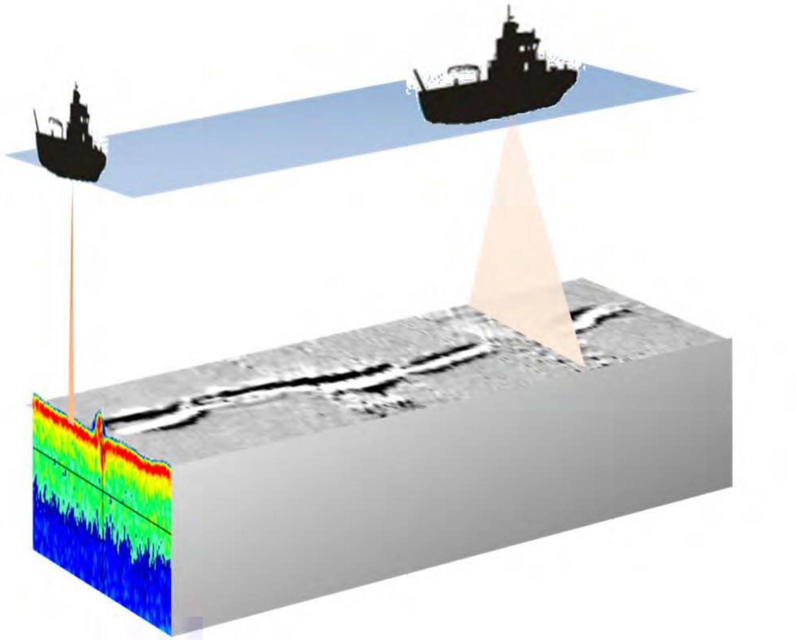

Plate 8: Schematic image of the combination of SES and SSS measurement

Measurement of the anchor tracks for several anchor drags was bundled, so that several anchor tracks could be travelled over with one profile line. Plate 9 shows the sonar reading of an anchor track with the drop position and end position of the drag [red diamond], as well as the SES profiles running perpendicular to the anchor track.

The time lapse between anchor drag and measurement of the anchor track was no longer than one day [see chronological procedure in Appendix 1].

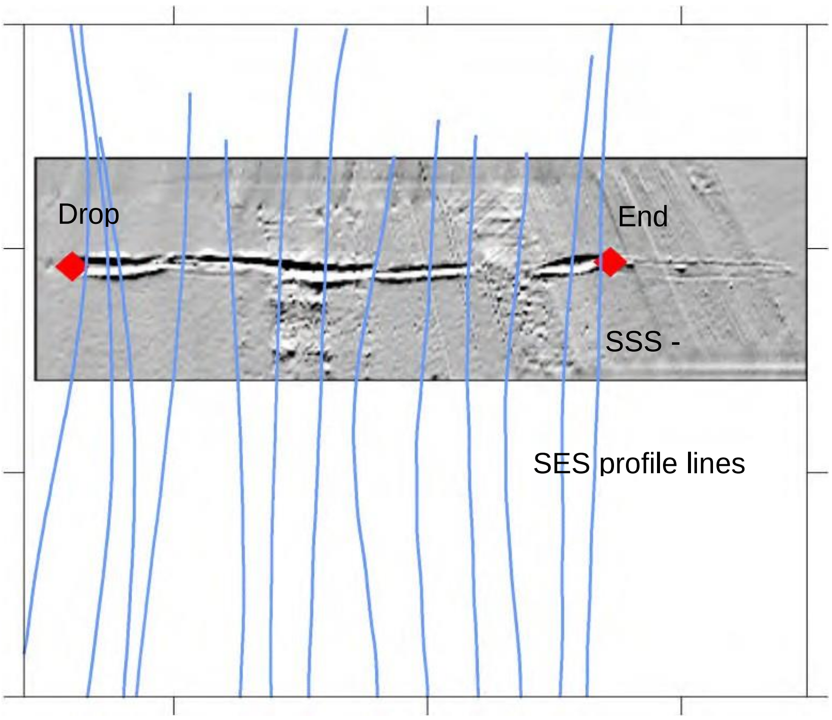

Plate 9: SES profile lines [blue] and SSS image of an anchor track measurement

5 Evaluation

Each anchor drag track was measured with 2 parallel SSS readings and several [2-12] intersections perpendicular to it, using SES. The SSS image was evaluated immediately on board *VWFS Wega*. For this purpose the sonar processing software SonarWiz [Chesapeak Technologies] was installed in the measurement apparatus. Processing essentially consists of correction and possibly combination [Mosaicking] of the sonar images. On the spot, the reading served to determine the anchor drop and end positions [Plate 9]. In a further step the sonar images were exported as geo-referenced TIF images [GeoTIF] and then served for depiction of the surface structure of the track produced by the dragged anchor on the seabed [2].

[2] Owing to technical problems exporting geo-referenced TIF images with the SonarWiz software, readings from the Guardian in a „shaded relief representation" also partly with MBES, were used for the images in this report [e.g. Appendix N1-6. S1-S6 and V1-V6]. The images show a representation very similar to the SSS readings. Owing to the software problems the images in the appendices mentioned did not match the quality of the real-time representation on board VWFS Wega during measurement.

The pattern of the surface structure is very similar in all anchor drags: a central "groove" [made by the anchor stock] and two lateral "walls" of sediment running left and right pushed up by the anchor blades [Plate 9]. As shown under 4.5 however, analysis of the surface structure does not permit a conclusion as to the maximum penetration depth of the anchor. The maximum penetration depth of the anchor is not normally due to the stock and thus in the central extended groove but due to the effect of the anchor blades, which lie buried under the aforementioned "Walls".

5.1 Processing the SES Data

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The maximum penetration of the anchor was recorded from the SES profiles running perpendicular to the anchor track. For evaluation, the evaluation software ISE delivered with the system used -- SES 2000 Standard [Innomar Technologie GmbH] was used. The SES profile runs were viewed and evaluated as a first step. In all profile runs the effect of the anchor on the seabed was identifiable.

Plate 10 shows an example of an SES profile which has intersected 2 anchor tracks. The ISE-Software offers two different Echogram representations. In the "AMP" representation the degree of amplitude of the demodulated reception signal [envelope] is illustrated in colour [Plate 10 below]. In the "1P" view positive changes in the amplitude of the demodulated reception signal [envelope gradient] is shown in colour. This view highlights impedance jumps and thus sediment layers [Plate 10 above]. The relatively small reflectors of the anchor tracks are more easily recognizable in the "AMP" view, therefore only this view has been selected for the evaluations below:

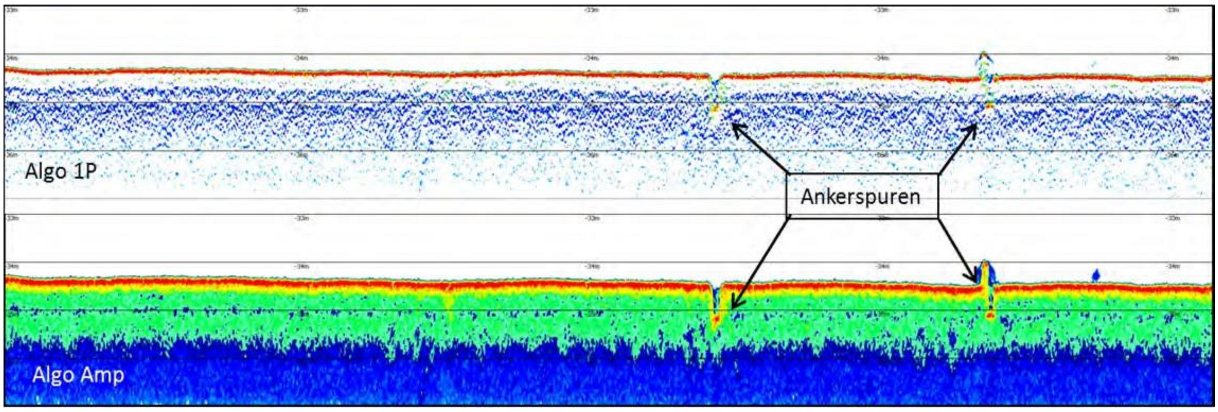

Plate 10: Illustration of an SES profile in the 1P Algo view [above] and in the Amp Algo view [below].

Glossary: anchor tracks

In short, these were as follows:

a. Filtering of the position data [palpable errors and position jumps]
b. Interpolation of the position data on the „ping“ time-points [exact synchronisation of echo-sounder and position data]
c. Digitisation of the water depth [seabed survey]
d. Use of a threshold filter
e. Reduction of water column noise
f. Tide adjustments [only relevant for base measurements in the test areas]

The raw SES data, cleaned as above, were thus ready for analysis of the anchor penetration depth.

5.2 Analysis anchor penetration depths

The aim of the analysis of the SES Data was to establish the „deepest effect of the anchor on the seabed“. This was based on the premise that an anchor dragged over or in the seabed causes an alteration to the seabed locally by loosening, compression or displacement of sediments. This local alteration to the originally homogeneous composition of the seabed is then detected via a jump in amplitude in the acoustic signal and can be digitized as a depth value.

As a reference horizon for this depth value the level of the “undisturbed seabed“ was established, i.e. the level of the seabed BEFORE the anchor drag at the same point. The level of the undisturbed seabed was here determined by a follow-up digitization of the assumed seabed profile without the effect of the anchor, while the undisturbed floor horizon either side of the anchor track was calculated via linear Interpolation on the anchor track.

This provides the following definition of the anchor penetration depth:

Anchor penetration depth was defined as the vertical distance from the point with the deepest discernible effect in the seabed to the seabed level considered “undisturbed“ at the same point PRIOR to the anchor drag.

Plate 11, a to d, explains the procedure for evaluation using ISE Software:

a. Digitisation of the water depth [border between water and seabed], automatic algorithm in ISE. → black line in Plate 11a;
b. Identification of the anchor tracks [N1 / N2 in Plate 11a]
c. Manual digitisation of the assumed profile of the “undisturbed seabed“ in the area of the anchor tracks [pink line in Plate 11b]
d. Discarding the original digitization [Step a.] → the assumed level of the undisturbed seabed runs through the anchor tracks [Plate 11c]. [error in original here?]
e. Digitisation of the deepest discernible effect of the anchor in the seabed [N1 and N2 in Plate 11d]
f. Calculation of the vertical distance between the level of the undisturbed seabed [Plate 11c] and the point of deepest discernible effect [Plate 11d] = anchor penetration depth. The result is calculated with the help of the Targetpicker Toolbox in the ISE-Software.

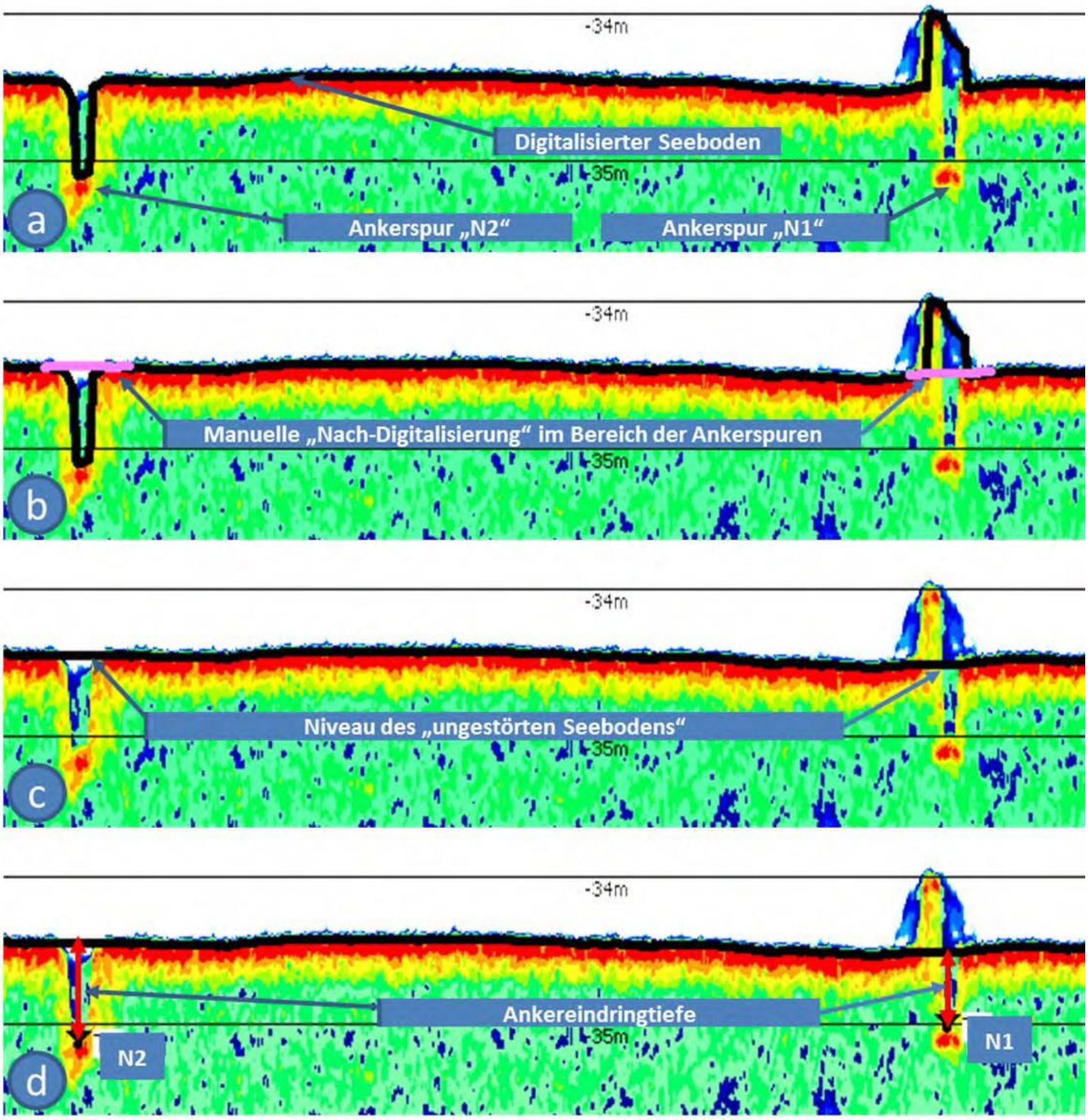

Plate 11: Obtaining the anchor penetration depth from SES profiles

Glossary Digitised seabed Anchor track Manual “post-digitisation” in the anchor track areas Level of the undisturbed seabed Anchor penetration depths

It is of critical importance in the manual digitisation of the level of the “undisturbed seabed“[Step c.] and of the „deepest point of effect“ [Step e.], always to carry out manual digitisation at the same signal amplitude point. The norm here in hydrographic measurement is a value of ca. 20-30% of the rising edge. Plate 12 illustrates the relationships and shows manual digitisation a. of the seabed and b. of the deepest point of effect on the rising edge of amplitude. The difference between both points then provides the anchor penetration depth

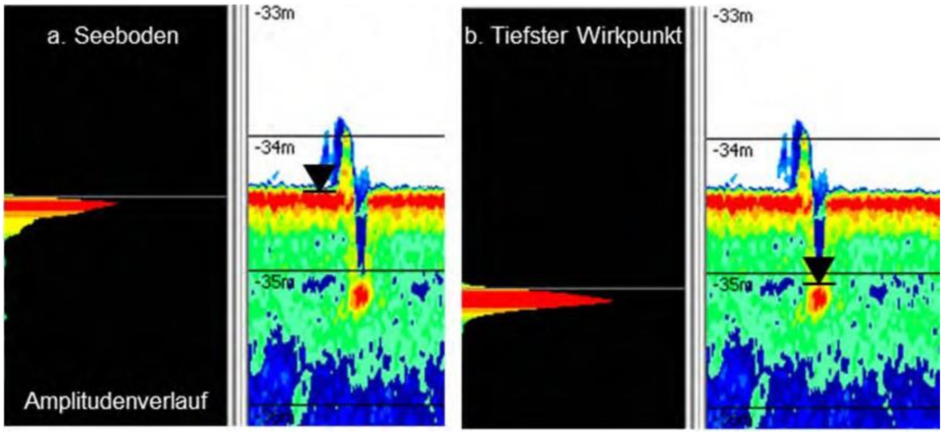

Plate 12: Digitisation of SES signal amplitudes

Glossary: Seabed Deepest point of effect Amplitude progression

All anchor tracks detected are evaluated in the manner illustrated, The fact that the surface readings for the anchor tracks were available from the SSS measurement as supplementary information, and that identification of the anchor effect in the seabed was possible with certainty means that the selected procedure can be considered robust and reliable.

5.2.1 Treatment of errors

In evaluating uncertainty in establishing the anchor penetration depth there are basically two sources of error to consider:

a. inaccuracies or individual variations in digitisation [„human factor"]…:
   i. of the undisturbed seabed
   ii. of the „deepest point of effect"

   Establishing the „deepest point of effect" and the level line of the „undisturbed seabed" is manual in the ISE evaluation program. Repeat tests and tests with different operatives have shown that [an error in?] digitisation in the Algo-AMP representation [Plate 12] of around. ± 2-3 cm is possible.

b. Errors due to altered sound velocity in the sediment

   As using the echo sounder [as with an SES] is in principle a time-lapse measurement the speed of the ultrasound signals must be known in order to determine depths. The speed of sound through water can be determined using appropriate sensors. However if the signal penetrates the seabed, there is a variable sound speed which depends on the characteristics of the sediments. The anchor penetration depth is determined as a difference between a signal from the seabed surface to a point [deepest point of effect] which may, at least partially, be covered by sediments. Here the sound velocity is not exactly known and counts as an error in determining the difference.

The water depth [seabed - surface] is ascertained by the speed of sound through the water. In the test area this is around 1470 m/s. The speed of sound in the sediment cannot be measured exactly, but can be estimated at 1500 [lightly compacted] to 1600 m/s [more firmly compacted]. Depths with an under-estimated sound velocity involve, for the above purposes, a depth error in the region of 2 – 8 %. With maximum anchor penetration depths of < 1m the error arising is maximum ca. 8 cm. As the sound velocity in the sediment is always higher that in the water, the measured [anchor penetration] depths in the sediment are perceived as too small. Note: the deduced error of 8 cm is a maximum value at 1 metre anchor penetration depth and with an anchor track completely covered by compacted sand. The actual parameters were however in the main clearly more favourable. Bearing in mind that the matter under investigation has safety consequences this maximum value for evaluating errors is applied below:

Thus in the overall error evaluation there is a maximum uncertainty of ca. 11 cm in determining the anchor penetration depth.

Note that in obtaining the actual anchor penetration depths these 11cm must be added to the measured anchor penetration depths. This produces a "theoretical" anchor penetration depth [erring on the safe side] i.e. the actual anchor penetration depth will most probably never have exceeded the “theoretical” anchor penetration depth.

6 Results

A detailed individual illustration of all anchor-dragging tests can be found in the appendices which follow:

Test area	Appendix number = anchor drop position
BSH North	N1 – N6 [without N4]
BSH South	S1 – S6
VTG	V1 – V6

These appendices more or less constitute the core evaluation of the anchor-dragging tests. With regard to the anchor penetration depth, the essential parameters of each of the 17 dragging tests evaluated are documented.

Plate 13 shows a reduced-scale explanatory example of position V1

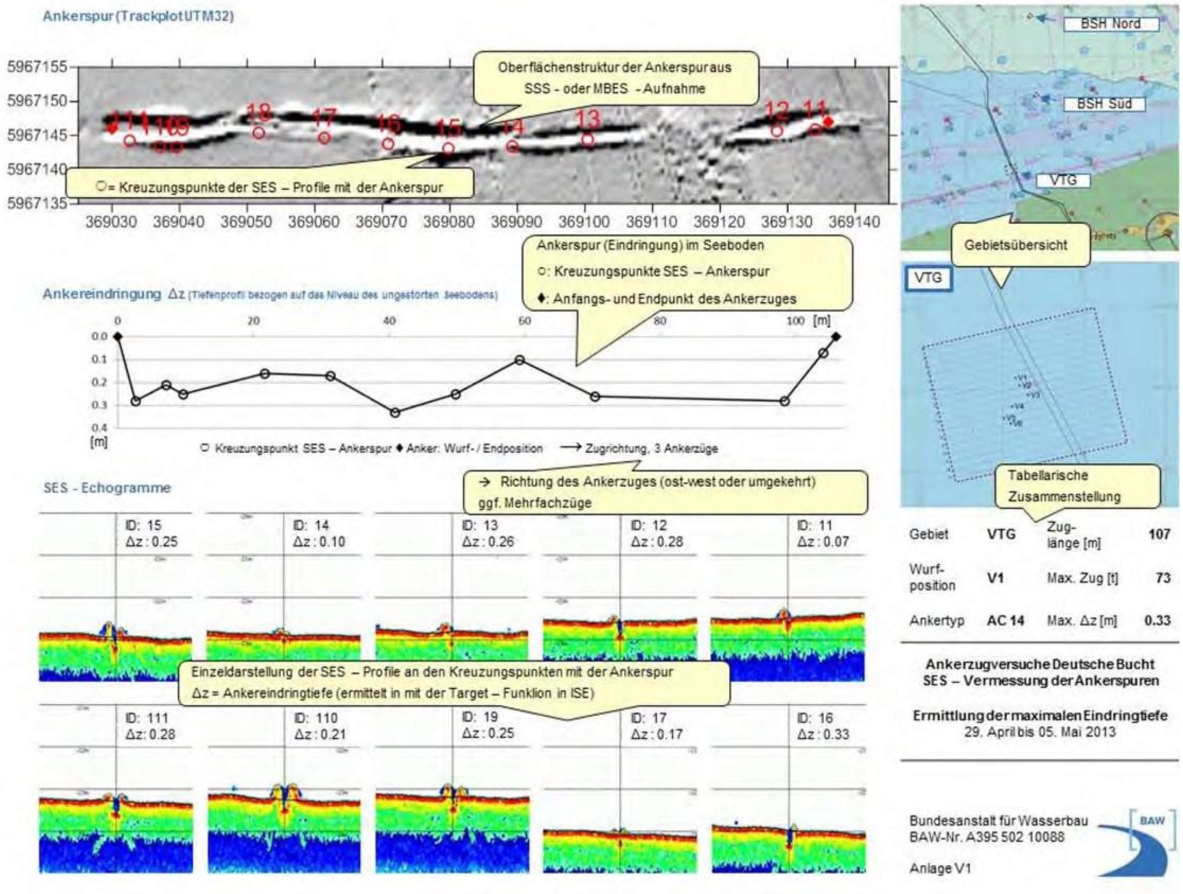

Plate 13: Explanation of appendices N1-6, S1-6 and V1-6

Glossary Plate 13	
Oberflächenstruktur des Ankerspur aus SSS oder MBES Aufnahmen	*Surface structure of the anchor track from SSS or MBES readings*
Kreuzungspunkte der SES Profile mit der Ankerspur	*Intersection points of the SES profiles with the anchor track*
Ankereindringung - Tiefenprofile bezogen auf das Niveau des ungestörten Seebodens	*Anchor penetration depth profiles relative to the level of the undisturbed seabed*
Ankerspur - Eindringung im Seeboden	*Anchor track - penetration in the seabed*
Kreuzungspunkte SES - Ankerspur	*SES - anchor track intersection points*
Anfangs- und Endpunkt des Ankerzuges	*Start and end point of the anchor drag*
Kreuzungpunkt SES - Ankerspur	*SES - anchor track intersection point*
Anker Wurf-/End-position	*Anchor drop / end position*
Zugrichtung Ankerzüge	*Drag direction Anchor drags*
Richtung des Ankerzuges [ost-west oder umgekehrt]	*Direction of the anchor drag [east-west or vice-versa]*
Ggf mehrfachzüge	*Multiple drags in certain cases*
Einzeldarstellung des SES Profil an den Kreuzungspunten mit der Ankerspur	*Individual representation of the SES profile at the intersection points wirh the anchor track*
Ankereindringtiefe [ermittelt mit der Target- funktion in ISE]	*Anchor penetration depths [obtained using the target function in ISE]*

Gebietsübersicht	Area overview
Tabelarische Zusammenstellung	Summary table
Gebiet	Area
Zuglänge	Drag length
Wurfposition	Drop position
Max.Zug	Max. Drag
Ankertyp	Anchor type
Ankerzugversuche Deutsche Bucht SES - Vermessung der Ankerspuren	Anchor tests in German Bight SES measurement of the anchor tracks
Ermittlung der maximalen Eindringtiefe	Obtaining the maximium penetration depth

The co-ordination of the test areas, the anchor drop positions and the start and end points of the anchor drags evaluated are documented in Appendices 2N, 2S, 2V [list of co-ordinates and area overview]

.

Plate 14 to Plate 16 [also Appendices 4N, 4S, 4V] show the track of the anchor in the seabed via the individual images of the anchor drags [Appendix S1-6, N1-N6 and V1-V6] for each of the three test areas again summarized. Here „0“ always marks the start point of the anchor drag [black diamond] and the second black diamond the end of the drag. The circles mark the intersection points with the SES profile, at which an anchor penetration depth was recorded. Connecting these two points then produces the anchor track in the seabed, the start and end point being „by default“ set to „0“ , i.e. the anchor lies on the seabed at the start and end of the drag.

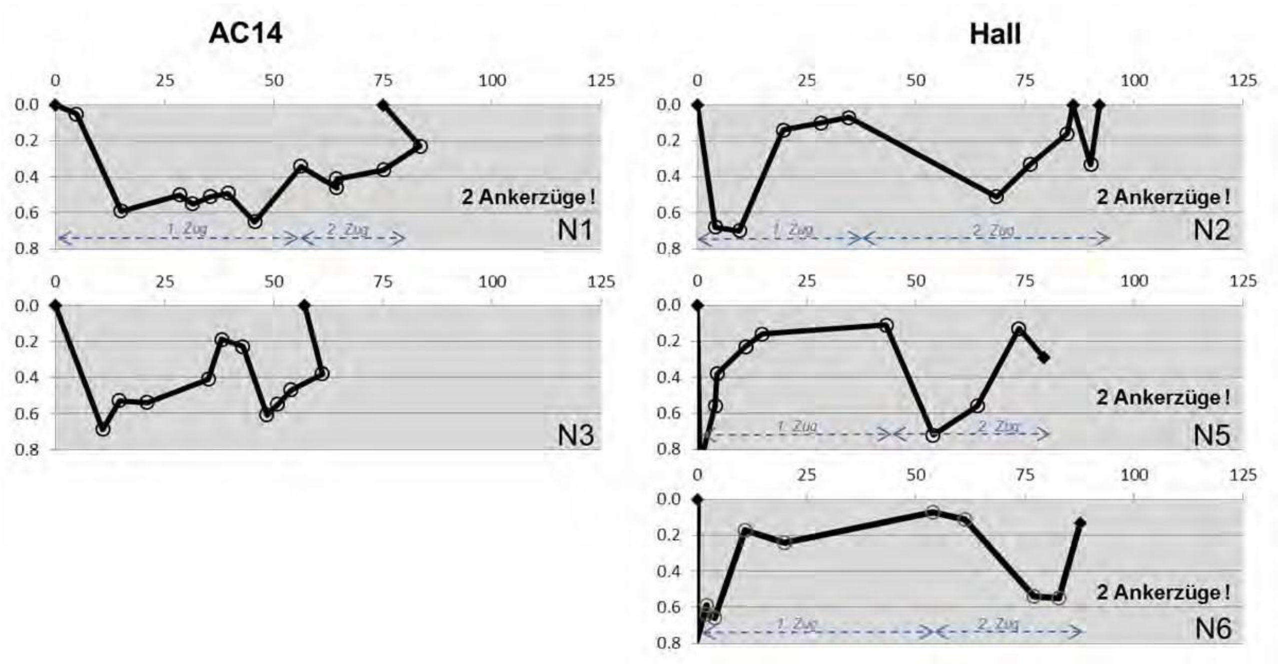

Plate 14: Summary of all anchor tracks [depth profiles] in test area BSH North.

Glossary Anchor drags

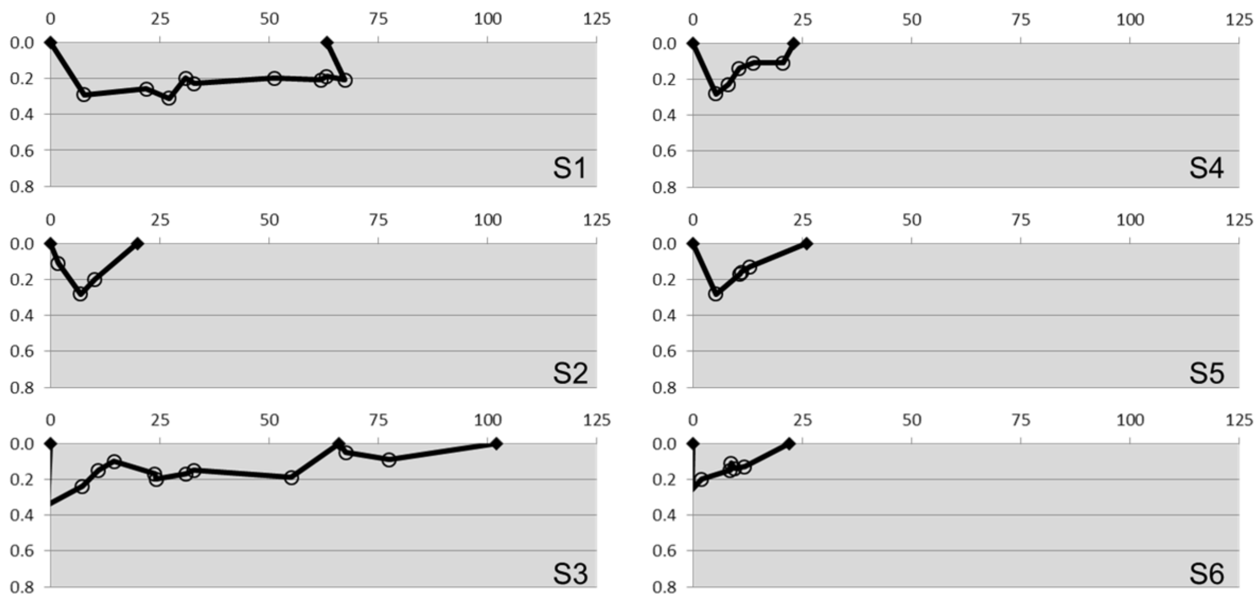

Plate 15: Summary of all anchor tracks [depth profile] in test area BSH South

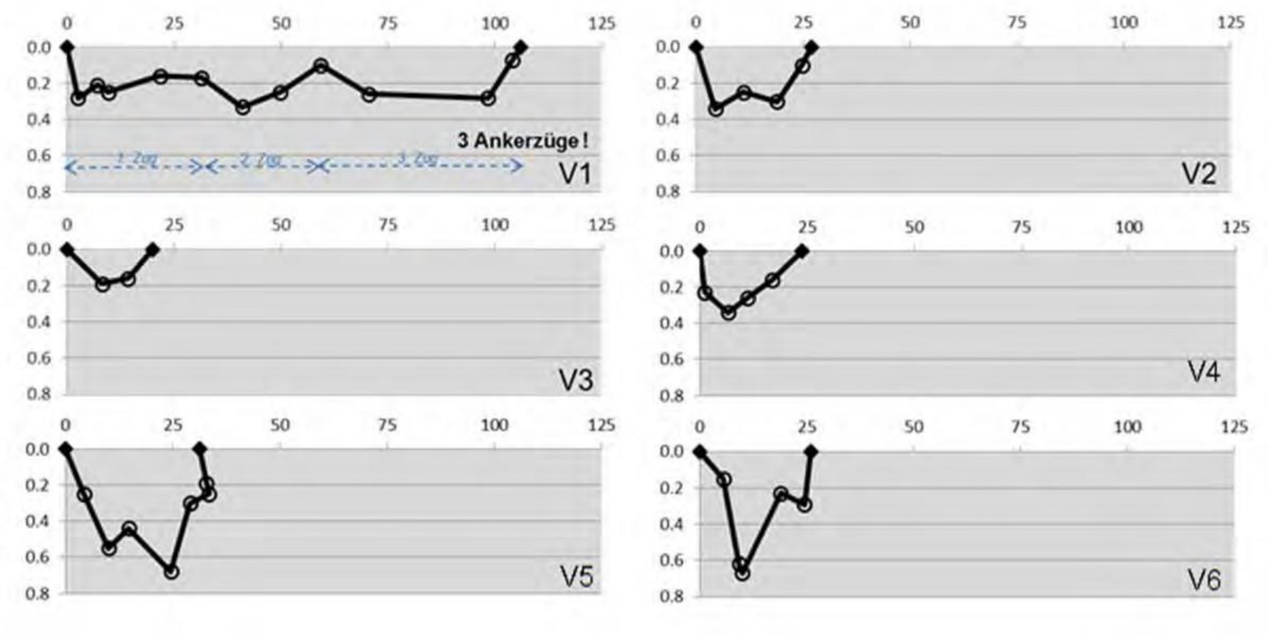

Plate 16: Summary of all anchor tracks [depth profile] in test area VTG

The length of anchor drag, expressed as the difference between drop point of the anchor identified in the sonar image and the end point of the anchor drag, is represented in the three test areas differently. Firstly one must consider those anchor drags where the anchor was dragged twice [N1, N2, N5,and N6] or three times [V1] for reasons explained at 4.2, separately.

The length of the individual drags cannot be exactly determined here from the SES readings, but can only be estimated from the image of the anchor track [Plate 14 - Plate 16, or Appendices 4N, 4S, 4V] [marked in blue]. If we now consider the drag tracks [taking multiple drags into account, see above.] we see a different image for the two anchors under consideration: the anchor drags with the Hall anchor produce, in each of the 3 tests per test area, a very similar drag image, both in the penetration depth and in the length of the anchor drags. Thus in the anchor drags with the Hall anchor in the test areas with more firmly layered sediments [BSH South and VTG] the breakout criterion was already reached after 25m [drag-force > 80 t or anchor break-out], [see measurement project plan]. In the test area BSH North, using the Hall anchor, 2 drag tests were carried out in all three drop positions. Here the anchor track in the seabed seems very similar.

The drag lengths of the anchor tracks of the HHP AC14 anchor are not quite so similar as those of the Hall anchor, especially in test area BSH South. Here the drag length varies from 25 to 100 m. In test area VTG, 3 drags were necessary in Position V1 3 [total length 100m] in order to complete the anchor drag leaving the crew of the *Esvagt Connector* satisfied that a valid test had taken place [max. drag force achieved].

Regarding the anchor penetration depth to be tested, however, all anchor dragging tests evaluated delivered an unambiguous result.

This result is summarised in figures in Table 4 to Table 6 for the three test areas. Alongside the anchor penetration depth [Max. Δ z] the other parameters, drag length [see above] and maximum drag are listed.
.
The maximum drag is based here on the readings of the of the load cell of the *Esvagt Connector.*

Position	Anchor type	Drag length	Max Drag	Max. Δ z	Remarks
		[m]	[t]	[m]	
N1	AC14	67 [52+12]	62	0.65	2 anchor drags
N2	Hall	92 [35+57]	64	0.70	2 anchor drags
N3	AC14	57	82	0.69	
N5	Hall	87 [45+42]	58	0.88	2 anchor drags
N6	Hall	92 [55+37]	65	0.78	2 anchor drags

Table 4: Parameters of anchor drags carried out in test area BSH North

Position	Anchor type	Drag length	Max Drag	Max. Δ z	Remarks
		[m]	[t]	[m]	
S1	AC14	63	86	0.33	
S2	AC14	20	**95**	0.28	
S3	AC14	**102**	64	**0.34**	
S4	Hall	23	76	0.28	
S5	Hall	27	72	0.28	
S6	Hall	22	80	0.26	

Table 5: Parameters of anchor drags carried out in test area BSH South

Position	Anchor type	Drag length	Max Drag	Max. Δ z	Remarks
		[m]	[t]	[m]	
V1	AC14	107 [30+30+47]	73	0.33	3 anchor drags
V2	Hall	27	75	0.34	
V3	AC14	20	78	0.19	
V4	Hall	24	79	0.26	
V5	AC14	31	80	0.67	
V6	Hall	26	80	0.67	

Table 6: Parameters of anchor drags carried out in test area VTG

The maximum measured penetration depth seen in all drag tests carried out is for the Hall anchor, with 0.88 m at Position N5 in area BSH North. In test area VTG, relevant for the authorisation process sought, the maximum measured penetration depth was 0.68 m with the HHP AC14 Anchor. If we take into account the uncertainty factor - resulting from the error evaluation [5.2.1] - of 0.11m, and if this added to the measured values, the test results presented can be summarized as follows:

In none of the anchor drags carried out was an anchor penetration depth of more than 1 metre observed using the method envisaged In the shipping lane area this value is actually barely 0.8 metres.

7 *Discussion and the way ahead*

The scope, precise forward planning and disciplined execution of the tests mean that the measurement data obtained make an important contribution to the evaluation of possible anchor penetration depths and to the interactive effect on the seabed in the area observed. Such intensive and detailed field tests are unprecedented and make a further, scientific evaluation of the results possible. The aim of this report however was firstly to investigate and document the maximum observable depth of effect of the anchor in the seabed with the help of high-resolution SES measurement of the anchor track.

The quality of the measurement results obtained should be considered very good. The following elements justifyte this:

- Professional working environment aboard *VWFS Wega;*
- A crew, and especially captain, specialising in small-scale test and measurement tasks;
- Use of a range equipment very well suited to the problem being investigated. In particular the performance of the Sediment Echo Sounder SES2000 Standard entirely fulfilled expectations;.
- Good integration of the overall hydrographic measurement system, i.e. SSS, SES, the ship's movement and positioning sensors and the associated software;.

On the basis of these good measurement results, and with the evaluation techniques mentioned, especially the SES evaluation software ISE, it was possible to achieve reliable detection and determination of the anchor tracks in the seabed. The results achieved are thus to be considered robust and reliable.

Over and above the question of anchor penetration depth which was the subject of this report, the scope of the tests offers a good basis for further scientific analysis and evaluation. We should strive for such an application in co-operation with the participants or other institutions.

Bundesanstalt für Wasserbau Hamburg, August 2013

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