



# The Vessel M/S Estonia

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## Review of geotechnical investigations

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## Appendix

A Geotechnical site investigations of the wreck of M/S Estonia conducted previously.

# 1 Assignment

The Swedish Accident Investigation Authority (SHK) tasked the Swedish Geotechnical Institute (SGI) with conducting a review of the existing geotechnical investigations from the site of the wreck of M/S Estonia. The remit has also included considering possible geological explanations for the stated rotation of the vessel (change in position and list on the seabed) and the two holes that were observed in conjunction with investigations published in the autumn of 2020.

The aim of the report is to provide evidence ahead of forthcoming geotechnical site investigations.

The present report includes a summary of the results of geotechnical site investigations conducted previously. There is further investigation material in the case that SGI has not yet studied. This material may be of significance to the planning of the future site investigations and SGI requests that this material be sought out. A list of the material that should be sought out is presented in Appendix A. To conclude there is a discussion of various hypotheses relating to the rotation of the vessel and the two holes that have been observed. This discussion is based on the geological and geotechnical conditions at the location.

## 2 Summary of supporting documentation

The supporting documentation on which the investigation is based consists of procurement documents, reports, drawings and summarised descriptions of what occurred during the planning of the reinforcement and covering measures. In the present report, the documents below are referred to using [N] point NN with the intention of increasing the searchability of the cited documents.

- 1 Memo Protection of the Estonia. Historical description from a geotechnical standpoint. Drawn up by VBB VIAK, dated 20/10/1998, revised 10/03/1999
- 2 Summary of events over the period 1994–1996. Obtained by the Swedish Accident Investigation Authority on 31/03/2021 (Word document, file name: information från f.d anläggning VBB anläggning.docx)

The supporting documentation that forms the basis of the summary is extensive. A number of limitations and uncertainties linked to the supporting documentation have emerged during the work.

Raw data from site investigations and laboratory analyses have not been available when compiling the information. Accordingly, it has not been possible for SGI to make its own interpretation of geotechnical properties or conditions. The summary that has been produced is based on the evaluations and interpretations of the respective party. Nevertheless, the interpreted properties that are reported are deemed reasonable and have therefore not been called into question.

In some cases, especially in supporting documentation that has been produced in conjunction with the contracted works phase, it is not evident what status the supporting documentation has. There is a lack of documentation regarding the location and the accomplished reinforcement around the vessel. However there is documentation that probably completely or partly shows the measures that were undertaken as part of the covering works. This means that it has not been possible to map in detail the execution

and extent of the reinforcement measures that were implemented in 1996 ahead of the planned covering of Estonia.

### 3 Geological and geotechnical conditions

This chapter provides a summary of the topographical, geological and geotechnical conditions around the wreck. There is also a summary of the state of the vessel and the damage observed.

#### 3.1 Description of the area

M/S Estonia is located at a depth of 75 to 85 m on a slope that inclines in a north-westerly – south-westerly direction. The general inclination of the slope is approximately 1:6 to 1:8, with a difference in level between the foot and the crest of the slope of approximately 10 to 15 m. South of the vessel's bow (eastern end) is a slope in a north–south direction with an average inclination of 1:20 and a difference in level between the foot and the crest of the slope of approximately 6 to 8 m.

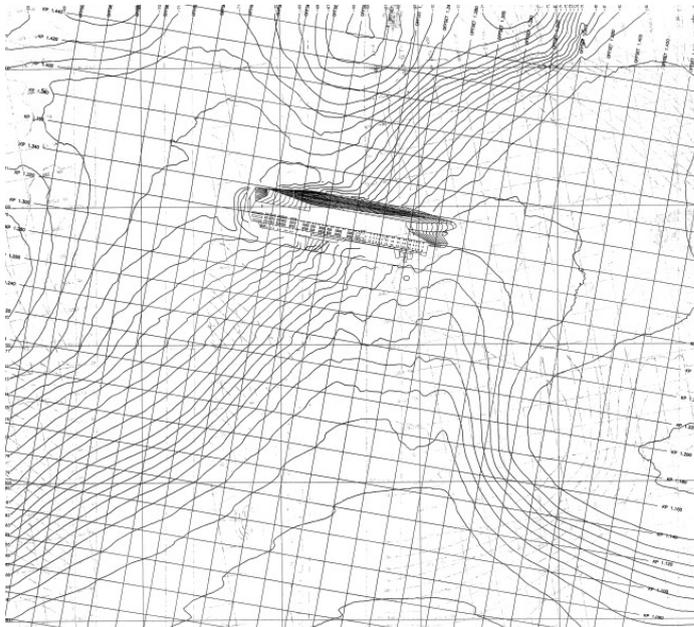


Figure 1. Bathymetry around the vessel (NMC, 1996).

The character of the area is dominated by furrows in an east–west direction, that are scoured in the clay. A lot of soft sediment that consists of stratified clay and silt was found in the furrows. The tender specifications for the reinforcement and covering works state: *‘There are no signs (of) objects or obstacles within the area investigated, aside from Estonia. The seabed is dominated by clay in low points, covered by a lot of soft sediment’* (Swedish Maritime Administration, 1995).

#### 3.2 Geotechnical conditions

The seabed around Estonia consists of a surface layer of extremely soft sediments with very soft clay beneath. Beneath the clay is solid glacial till. Figure 2 shows that the vessel is lying in a boundary zone between very soft post-glacial clay to the east and south of the vessel and a somewhat more solid glacial clay to the west and north of the vessel (but still very soft). Approximately 100 m north of the vessel, the surface of the seabed is stated as consisting of glacial till with rocky outcrops also having been observed in the immediate

surroundings (the red field in Figure 3). Figure 3 also indicates that stones and rocks are present on the surface of the seabed in the area immediately surrounding the vessel. The details in Figure 2 and Figure 3 should be considered an outline. The rocks and stones on the map should not be primarily interpreted as specifically determined positions of individual boulders and stones, rather as representing areas where these fractions are present on the surface of the seabed.

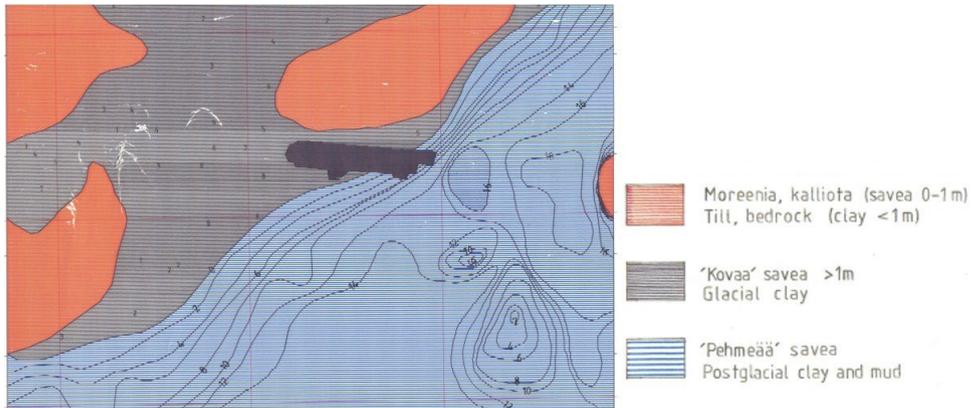


Figure 2. Soil type map with an outline of depth contour lines for post-glacial clay (Naval Research Institute, Finland, 1995).

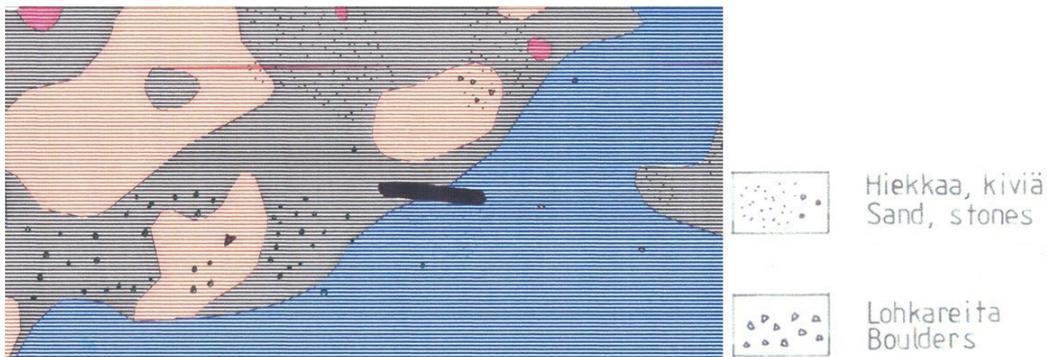


Figure 3. Soil type map indicating stones and rocks on the surface of the seabed (Naval Research Institute, Finland, 1995).

On the basis of geotechnical site investigations, the clay layer is estimated to vary in thickness between approximately 6 and 20 m. Figure 4 shows extracts from tender documents from the contractor Nordic Marine Contractors (NMC) (dated January 1996) in the form of a longitudinal section and cross-sections of the vessel, together with an interpreted soil layer sequence. The vessel is assumed to have some contact with the glacial till in its deeper part (NMC, 1996). The green line indicates the upper edge of the clay layer, which is a general representation of the previous surface of the seabed. Above the clay layer is a layer of fill material that was intended as a stabilisation measure ahead of the vessel being covered. The contracted works began on 19/04/1996. A government decision was made on 19/06/1996 to discontinue the covering of the vessel. The contractor ceased work on 27/07/1996.

The action proposal presented in the tender documents (Figure 4) were later adjusted, which means that both the interpreted geotechnical conditions and the planned

fill material volumes may have changed. It has not been possible to obtain the final action proposal from the supporting documentation.

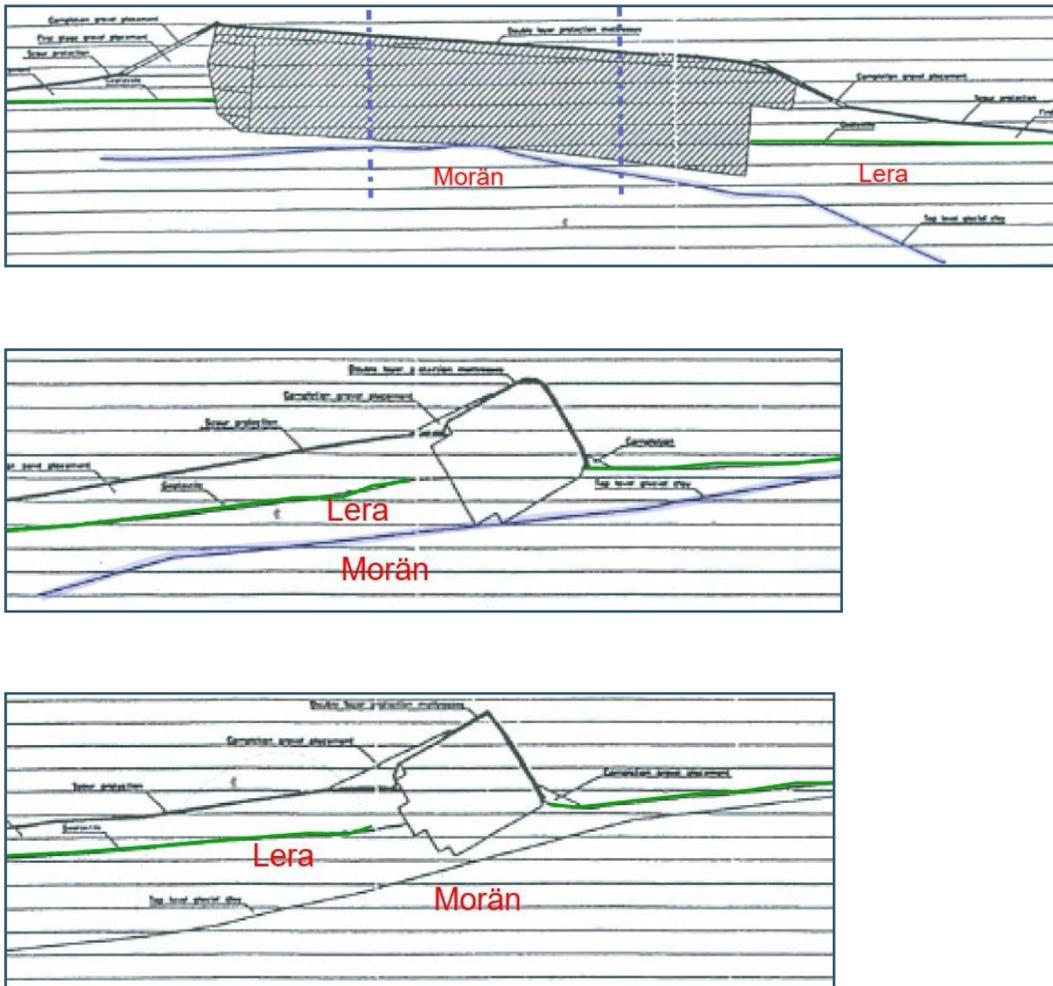


Figure 4. Top: longitudinal section through the centreline of the vessel. Middle: cross-section through the western part of the vessel. Bottom: cross-section through the eastern part of the vessel. Green line: upper edge of the clay layer. Vertical dashed line: approximate position of cross-section. The drawings refer to proposal to cover the vessel with concrete mattresses in tender documents from NMC (1995).

The thickness of the clay under and around the vessel has been interpreted by Delft Geotechnics (1996) and is shown in Figure 5. The thickness of the clay has been interpreted from the results of CPT soundings, which is a sounding method that is especially suitable for soft clays. The thickness of the clay is estimated to be a minimum of approximately 6 m at the north side of the vessel at its middle longitudinally. The thickness of the clay increases in a westerly and easterly direction to approximately 11 to 12 m at the stern and approximately 16 to 20 m at the bow. There is very stiff glacial till under the clay. Glacial till has been observed on the surface of the seabed approximately 100 m north of the vessel.

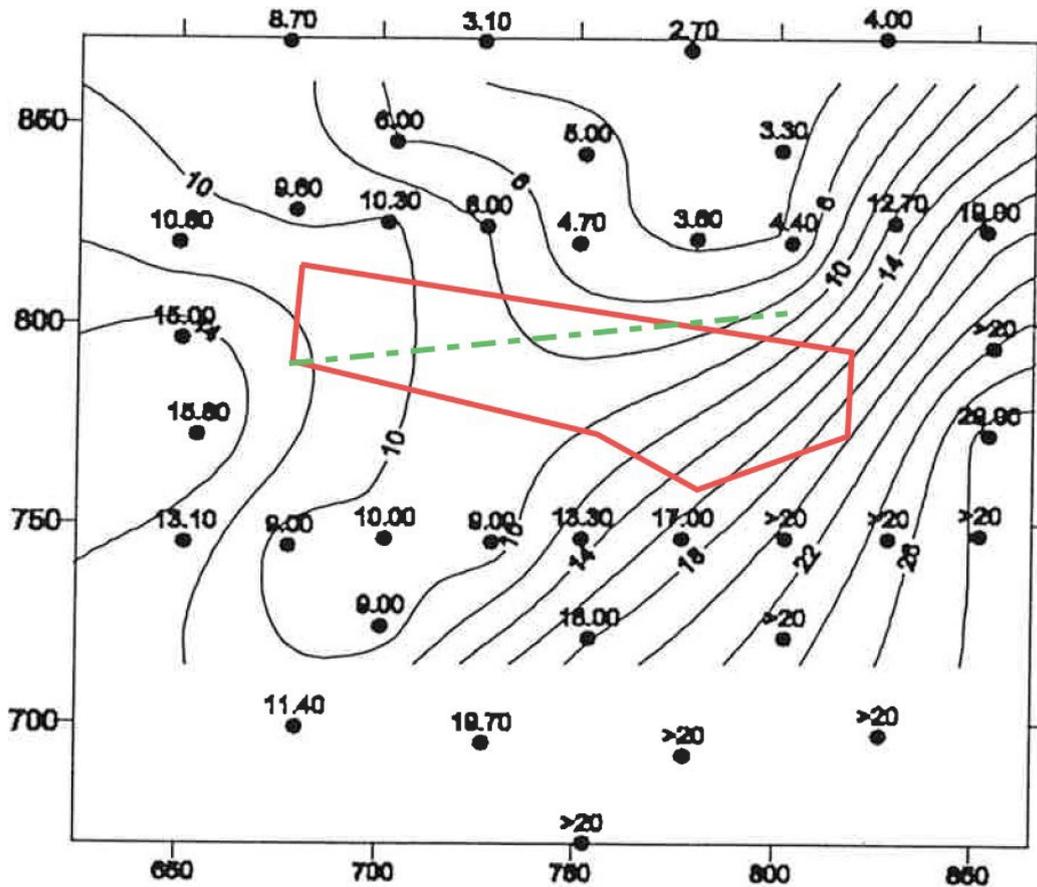


Figure 5. Interpreted clay thickness from geotechnical site investigations (CPT soundings) in boreholes and interpreted contour lines for clay thickness with equidistance of 2 m. Red line: the approximate position of the vessel. Green dashed line: interpreted boundary between glacial clay (to the north) and post-glacial clay (to the south). The figure is based on results from Delft Geotechnics (1996).

### 3.2.1 Shear strength of the clay

The undrained shear strength of the clay has been determined through evaluation of the results of the CPT soundings, vane shear tests using a hand-held vane tester in piston samples (torvane), fall cone tests, undrained triaxial tests and in-situ vane shear tests. On the basis of these results, the clay can be described as very soft, with extremely low shear strength. During the planning of the reinforcement and covering measures, separate shear strength profiles were adopted for the clay to the north and west of the vessel and for that to its south and east. These profiles are provided below:

North and west of the vessel (glacial clay):

$$z < 1.0 \text{ m} \quad c_u = 3.0 \text{ [kPa]}$$

$$z > 1.0 \text{ m} \quad c_u = 3.0 + 1.4 \cdot (z-1) \text{ [kPa]}$$

South and east of the vessel (post-glacial

$$\text{clay): } z < 0.75 \text{ m} \quad c_u = 0.75 \text{ [kPa]}$$

$$0.75 \text{ m} < z < 3 \text{ m} \quad c_u = 0.75 + 1.09 \cdot z \text{ [kPa]}$$

$$z > 3 \text{ m} \quad c_u = 3.2 + 1.35 \cdot (z-3) \text{ [kPa]}$$

where

$z$  = depth under the surface of  
the seabed

$c_u$  = undrained shear strength

At least four landslides have occurred to the east, west and south of the vessel. A general description of the slides is provided in section 3.4. The shear strength of the disturbed debris from the first landslide south of the vessel was assumed to be 0.75 kPa, i.e. the same shear strength as the top-most metre of the undisturbed clay. In the area where the seabed shows signs of heaving due to the landslide, the thickness of the top-most soft clay layer has been assumed to increase equivalent to the volume that has been moved to the southern part of the landslide area.

$$\begin{aligned} z < 0.75 + z_{\text{slide}} \text{ m} & \quad c_u = 0.75 \text{ [kPa]} \\ 0.75 + z_{\text{slide}} \text{ m} < z < 3 + z_{\text{slide}} \text{ m} & \quad c_u = 0.75 + 1.09 \cdot z \text{ [kPa]} \\ z > 3 + z_{\text{slide}} \text{ m} & \quad c_u = 3.2 + 1.35 \cdot (z - 3) \text{ [kPa]} \end{aligned}$$

### 3.2.2 Other soil parameters

General parameters for glacial clay to the north of the vessel:

- Bulk density =  $1.4 \leq \gamma_w \leq 1.7$  tonnes/m<sup>3</sup>
- Water content =  $50 \leq W_N \leq 110$  %
- Plastic limit =  $20 \leq W_P \leq 40$  %
- Liquid limit =  $40 \leq W_L \leq 95$  %
- Elastic modulus,  $E_{u,50} = 100 \cdot \sigma'_{vo}$

General parameters for post-glacial clay to the south of the vessel:

- Bulk density =  $1.25 \leq \gamma_w \leq 1.5$  tonne/m<sup>3</sup>
- Water content =  $80 \leq W_N \leq 180$  %
- Plastic limit =  $40 \leq W_P \leq 50$  %
- Liquid limit =  $100 \leq W_L \leq 140$  %
- Elastic modulus,  $E_{u,50} = 100 \cdot \sigma'_{vo}$

For clay north and south of the vessel, the compression properties at a depth of more than 3 m were assumed to be:

- Compression index,  $C_c = 1.2$
- Initial void ratio,  $e_0 = 3.0$
- Coefficient of consolidation,  $c_v = 4 \cdot 10^{-8}$  m<sup>2</sup>/s

## 3.3 Reinforcement measures

On 15/12/1994 the Swedish Government decided that the vessel would be covered. After opening the tendering process on 20/09/1995, a contract was signed with the contractor Nordic Marine Contractors (NMC) on 11/01/1996. The tender document describes a proposed solution consisting of the vessel being covered with two layers of concrete mattresses in the bow and stern, a covering consisting of light fill overlaid by fill of blast stone. Concrete mattresses are normally used for protection against erosion and

consisted in the proposal of prefabricated wire-linked concrete blocks. In order to ensure the stability of the vessel (and that the vessel was covered), it was proposed that embankments of sand be constructed in order to increase stability to the east, west and south of the vessel.

The embankments would be built on top of a strong geotextile, see Figure 6. The seabed would also be reinforced using ‘forced penetration strings’, which are described as stone embankments acting as dividers made of string fill of blast stone (25–150 mm). The geotextile was intended to be anchored between the fill and the clay in the northern part of the area in order to then enable tensile forces from the southern area to be transferred to the northern area where the clay is somewhat stiffer.

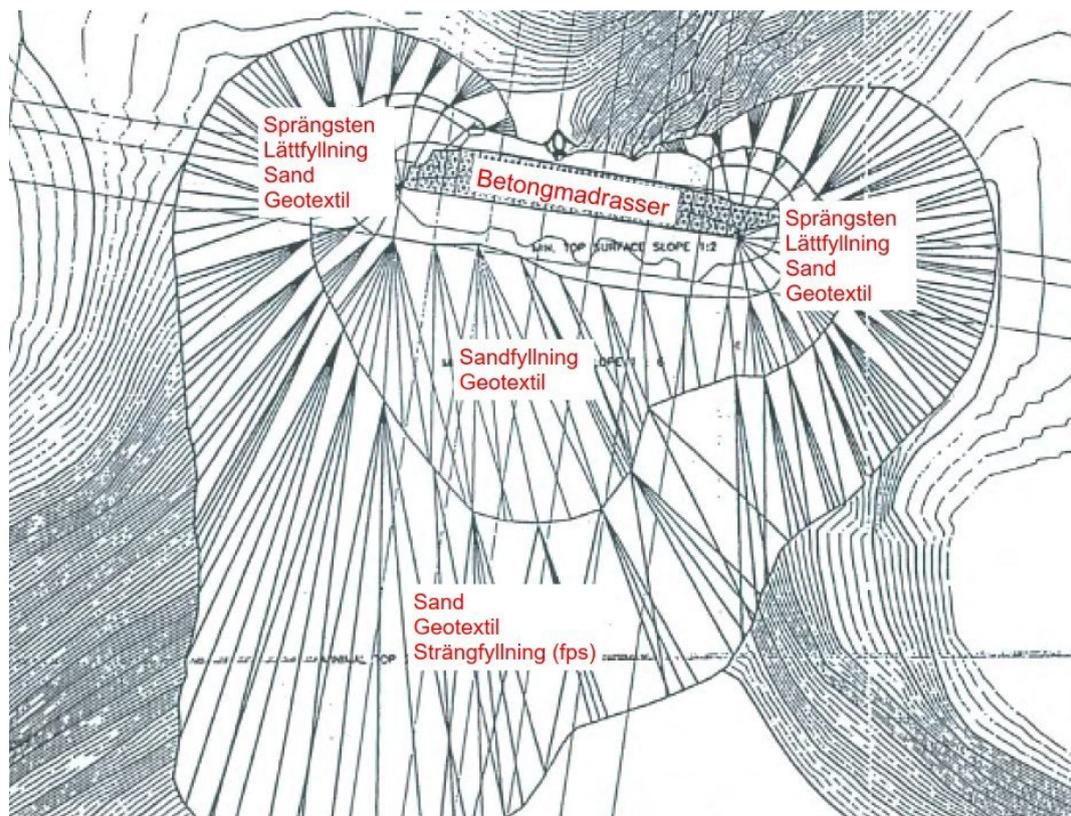


Figure 6. Tender document drawn up by NMC (1995). Proposed solution for covering and stabilisation measures.

On 19/06/1996, the Government decided to discontinue the process of covering Estonia no later than when the embankments with any reinforcements had been completed ([1] point 38).

The covering process was discontinued on 27/07/1996. Figure 7 shows a description of the estimated measures that were probably completed around the vessel. The reliability of this description is uncertain as the status of the drawing is unknown.

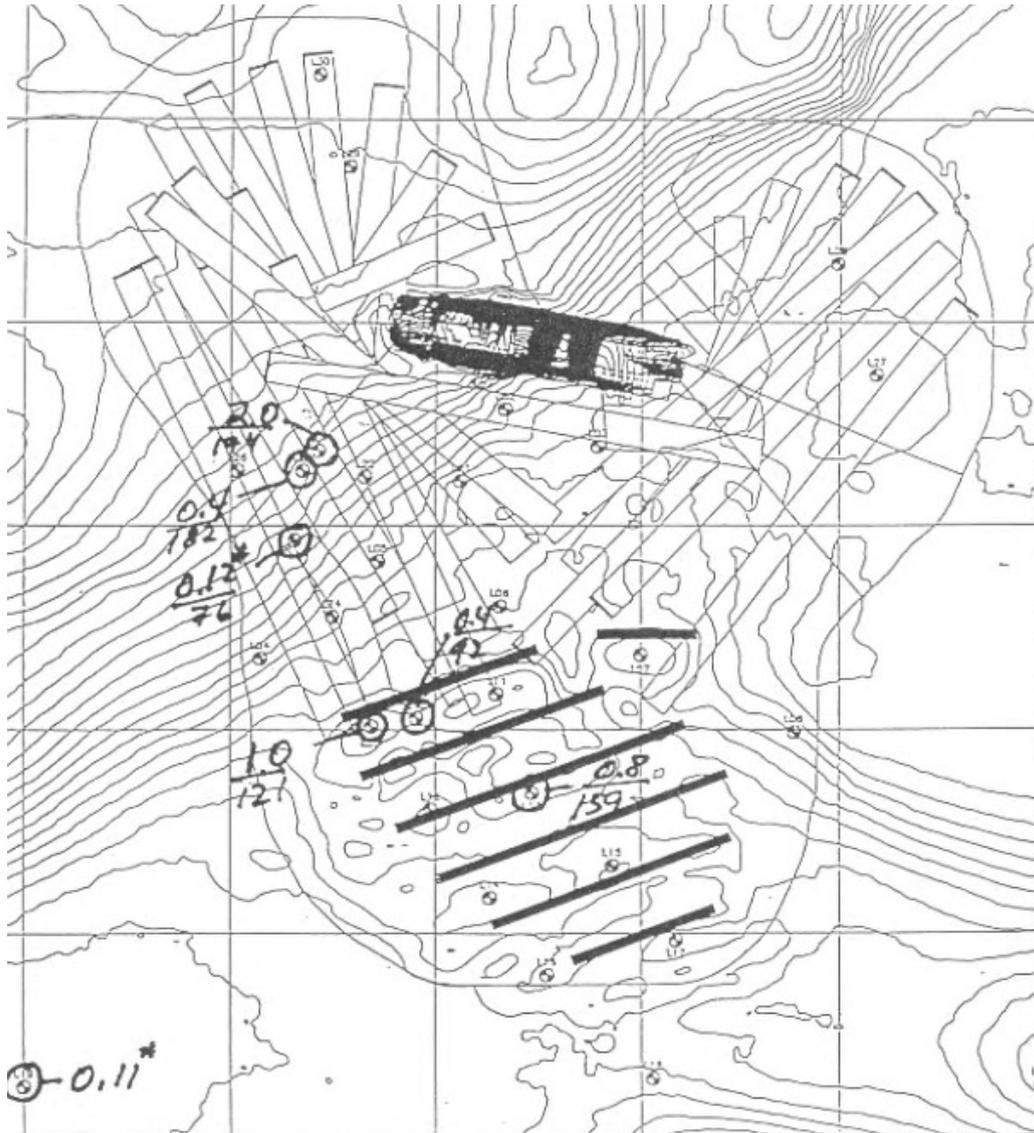


Figure 7. 'Seabed soil samples, Locations', Delft Geotechnics (19/09/1996). Dark, broad lines=forced penetration strings, rectangular=geotextile, circular=sampling points. Notes: evaluated shear strength (value above line), water content (value below line).

### 3.4 Landslides that have occurred

At least four landslides have been documented in the area surrounding the vessel ([1] point 10 and 49). The first landslide occurred south of the vessel and is thought to have occurred in conjunction with the vessel hitting the seabed. Two landslides with an area of approximately 800 m<sup>2</sup> each occurred while the sand fill was being laid in the eastern and western parts of the fill area. The fourth landslide, which had a larger area, occurred shortly afterwards in the area south of the vessel.

The level of the seabed, evaluated from bathymetric surveys performed in 2006 (Traficom), is shown in Figure 8. The surveys are reasonably consistent with the reinforcement measures that are presented in the drawing by Delft Geotechnics (1996), see Figure 9. The positions of the forced penetration strings presented in the drawing are consistent with the

long, thin embankments running in an east-west direction that are visible in the hill shading approximately 200 to 400 m south of the vessel.

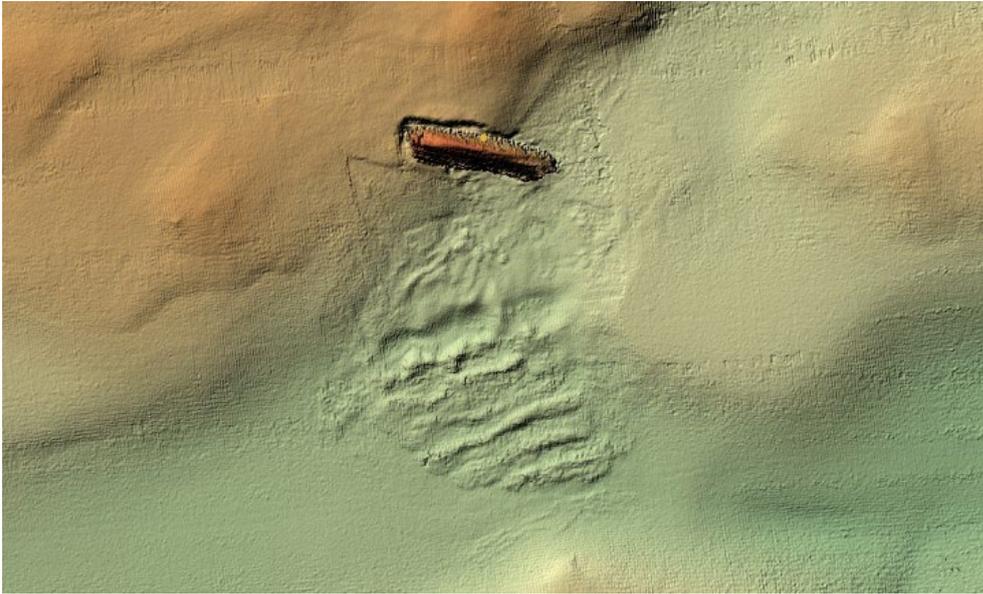


Figure 8. Seabed topography evaluated from bathymetric survey (Traficom, 2006).

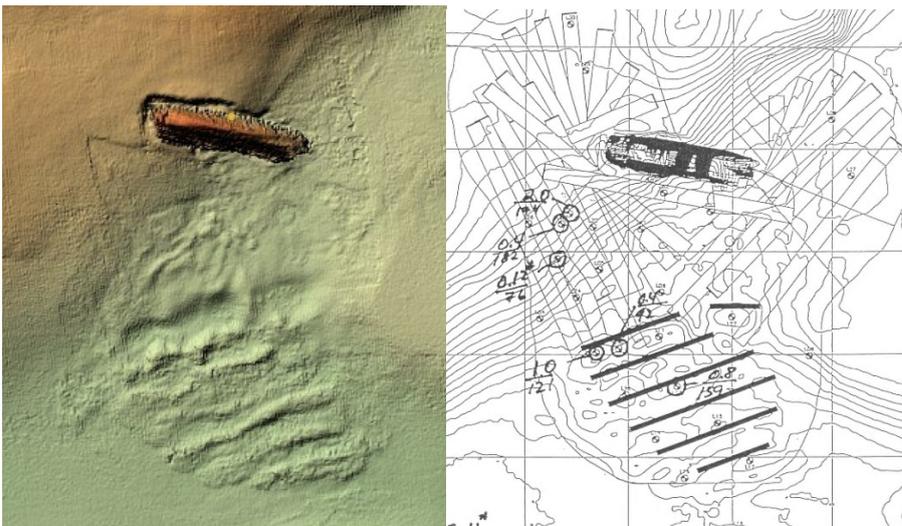


Figure 9. Comparison between reported completed reinforcement measures (1996) and seabed topography (2006).

### 3.5 State of the vessel

The position of the vessel on the seabed is N59°22.9', E21°41' with a starboard list of approximately 120°, with the stem pointing east (Joint Accident Investigation Commission of Estonia, Finland and Sweden, 1998). The angle of the list is stated in [2] point 29 to have been obtained from calculations performed using depth soundings from a remotely operated vehicle (ROV). Figure 10 and Figure 11 show the results of bathymetric surveys from 1996 (NMC and Jepsens-ACZ). The reported sections show that, on the basis of this data, the angle of the list is approximately 114 to 115°.

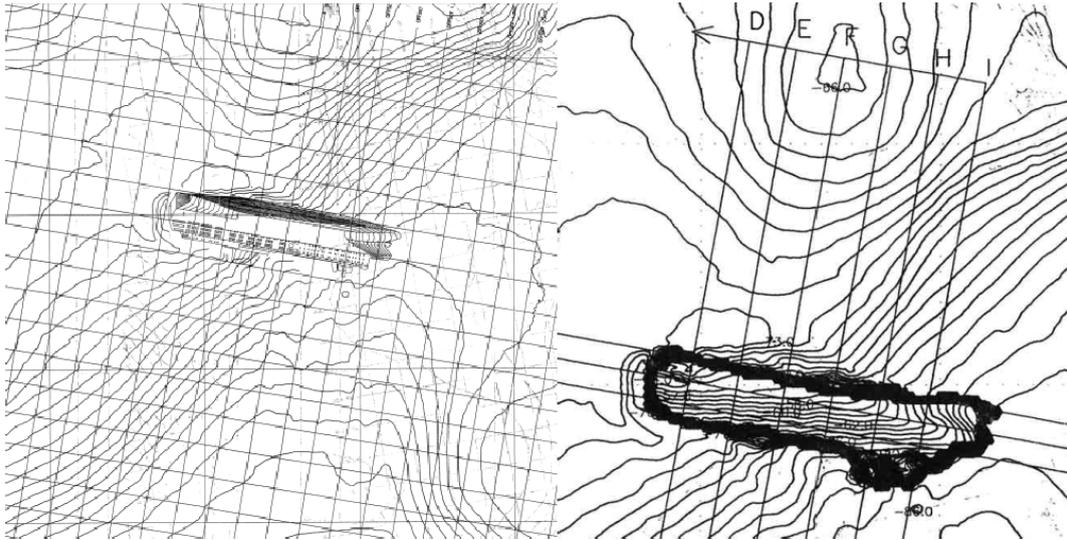


Figure 10. Seabed contour lines evaluated from bathymetric surveys around the vessel. Left: NMC (1996). Right: Jebsens-ACZ (1996).

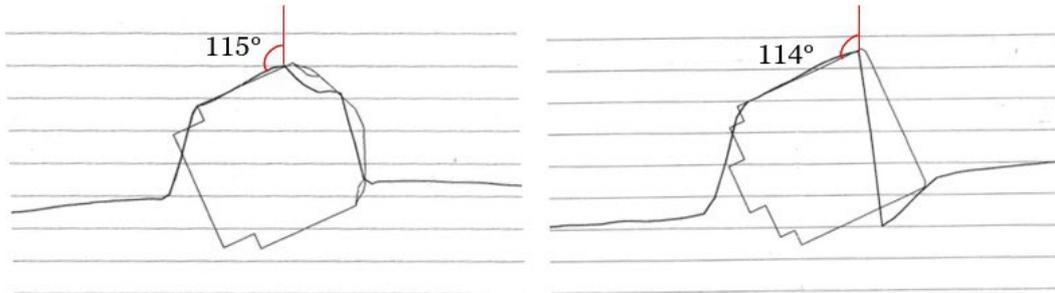


Figure 11 Interpreted angle of the vessel's list based on the results of bathymetric surveys. Based on Jebsens-ACZ (1996). Left: section D-D. Right: section G-G. The positions of sections is shown in Figure 10.

### 3.6 Holes in the vessel

In 2020, a group of Estonian experts was given access to video material from an ROV that filmed the vessel's hull. Parts of this video material were published on 28 September in a documentary by Discovery+. A written opinion by the group of experts (Tabri et al., 2020) states that a hole (Hole 1), with a width of c. 1 m and a height of c. 4 m has been observed by the fender close to the waterline. A clear inward dent in the sheet metal with a depth of c. 1.2 m has been observed around the hole. A second hole (Hole 2) was also observed along the fender on the starboard side, further aft. The sheet metal around Hole 2 has been torn up, most probably along a longitudinal weld. No local buckling was observed in the area surrounding the hole.

Approximate positions and geometries of the holes are shown in Figure 12 and Figure 13.



Figure 12. Approximate positions of observed Hole 1 (red cross) and Hole 2 (orange line) (Tabri et al., 2020)



Figure 13. Animation with geometries and position of Hole 1 (Discovery+)

A video survey of the vessel was also conducted during a previous site investigation that took place between the end of 1995 and beginning of 1996. The holes described above were not detected during this survey as it was conducted on another part of the vessel. The video survey was conducted along three lines along the length of the vessel (east–westerly). Line 1 was along the centreline of the vessel, lines 2 and 3 ran parallel to the centreline 5 m and 10 m, respectively, to the south. However, the holes in question are north of the centreline. It is also stated that the camera views were not very clear due to the distance from the vessel and the turbidity of the water at the time of the survey (NMC, 1996).

### 3.7 Contact between the vessel and rocks or glacial till

Figure 5 shows that the interpreted thickness of the clay under the vessel varies between approximately 6 and 20 m.

When planning the covering and reinforcement works, it was presumed, as a conservative assumption, that the vessel was not in contact with the glacial till and was instead floating in the soft clay. However, as early as the tendering phase, VBB VIAK (the Swedish Maritime Administration’s geotechnical client support) stated that *‘the ship must be in contact with the glacial till in order to remain in the position in which she is lying’* ([2] point 34), but no site investigations were conducted during this phase in order to confirm whether this was the case.

During NMC’s (the contractor) subsequent planning of the reinforcement and covering measures, the issue of contact between the vessel and the underlying glacial till layer was discussed from the perspective of stability. However, this report is absent from the

supporting documentation we have studied thus far, so the extent of the contact area between the vessel and the glacial till is unknown. Furthermore, it is unclear whether the vessel is deformed in these contact areas.

In June 1997, VBB VIAK (the client's geotechnical support) requested that a complementary seismic survey be performed in order to investigate the contact between the vessel and the glacial till. *'Because of the necessity of contact with glacial till for stability of the Estonia and the effect of an unfavourable location of the contact area we request that verification is made of the contact with glacial till, the area of contact and the position of the contact area. The verification can be done with a detailed seismic survey with minimized uncertainty in position and depth'* ([1] point 76).

During a subsequent meeting, NMC stated that it was impossible to determine with absolute certainty the level of the surface of the glacial till, especially under the vessel. The seismic survey was conducted over the period 08/09/1997 to 10/09/1997 by the Netherlands Institute of Applied Geoscience TNO for NMC.

VBB VIAK reviewed the report and shared NMC's conclusion that the vessel is in contact with the glacial till: *'Based on what is described in the report containing the supplementary information in the fax (16/12/1997), VBB finds that the proposed design is deemed possible taking into account the stability provided by the contact there is between Estonia and the glacial till'* ([1] point 81).

VBB VIAK requested that the accuracy of the seismic surveys should be assessed. However, it is not possible to determine whether this has been done.

## **4 Recommendations for planned site investigations**

It has emerged from the supporting documentation studied thus far that there are additional results from previous site investigations that may be of value to the planning of the forthcoming site investigations. SGI therefore proposes that this material be sought out for the purpose of providing further clarification of the prevailing conditions at the site. It is recommended that all the documents listed in Appendix A, and the associated raw digital data, be sought out. All raw data should be compiled in digital form so that it can be presented clearly and used for comparison with the results of future site investigations. This refers to:

- Bathymetry
  - Seabed topography
  - The initial position of the vessel (x, y and z coordinates) and inclination
- Borehole coordinates
- Sounding results
- Laboratory results
- Seismic survey results
- Detailed description of the reinforcement works completed:
  - Forced penetration strings
  - Geotextile
  - Fill

It is recommended that an assessment of the accuracy of the previous information that the vessel's initial list was 120° be checked. SGI has been unable to deduce with what accuracy the inclination has been stated from the supporting documentation obtained. It

is important to the continued investigation to clarify whether 120° represents a rough estimate or if this should be regarded as a verified value.

#### **4.1 Site-conditions**

On the basis of results from the investigations conducted previously, it is expected that the following conditions apply at the site.

Safety from landslides can be expected to be very low in the area surrounding the vessel. At least four landslides have occurred in conjunction with the sinking of the vessel and the implementation of the covering and reinforcement measures. All forms of disturbance of the clay, erosive activity, local dredging and/or application of loads etc. can lead to additional landslides. This means that there is an increased risk associated with entering the area surrounding the vessel before the slope stability conditions have been clarified. In the event of a landslide, it is not possible to rule out the movement of the entire vessel. If the forthcoming site investigations involve people being present in the area surrounding the vessel, or activities being conducted that may affect the slope stability conditions, these works need to be preceded by a risk assessment.

According to Figure 7, the surface of the seabed to the east, west and south of the vessel is largely covered by geotextile. According to documents from NMC dated 26/01/1996, the geotextile is made of a woven polyester fibre with a tensile strength of 500 kN/m. This is due to its intended load transfer function. The geotextile is equipped with interwoven loops that allow it to be reinforced, when necessary, with reinforcing bars of the same type used in concrete. However, the supporting documentation does not indicate whether reinforcing bars have been used.

The presence of the geotextile may cause problems when performing any seabed sampling or soundings and may potentially affect the results of seismic measurements. Supplementary information about which type of geotextile was finally chosen, whether reinforcement took place and where it has been laid should be sought out.

When the covering and reinforcement measures were discontinued, the construction of forced penetration strings and geotextile had been under way for approximately three months and filling with sand for approximately six weeks. The length of the forced penetrations strings is shown in Figure 8 and Figure 9. It has not been possible from the material studied so far to see in which areas fillings with sand have taken place. The sand fills can also be expected to have moved due to the landslides.

Given the fillings that has been conducted and the landslides that have occurred, it may, to the south of the vessel, be difficult to obtain geotechnical site investigation results that are representative of the area in terms of sampling, soundings and vane shear tests.

The area to the south of Estonia consists of sediments containing gas. During the initial geotechnical site investigations by Rockwater in 1994, the pore gas caused acoustic blanking during the seismic surveys (Swedish Maritime Administration, 1995).

## 4.2 Site investigation methods

The extent and selection of site investigation methods is dependent on which questions the investigation aims to answer. If the primary aim is to assess whether the two holes observed in the vessel have geological causes, the recommendation is to clear up the following uncertainties:

- The presence of rocks in the clay and/or glacial till under and around the vessel of such a size that they may have caused the observed damage to the vessel
- The extent of the vessel's contact with glacial till and the thickness of the clay layer under other parts of the vessel
- Detailed surface scanning of the entire vessel in order to gain a complete picture of deformation and damage

Bathymetric surveys should be conducted as such information can be used in order to evaluate any movements of the vessel in the vertical and horizontal planes and any rotation.

Measurement results can also be used to evaluate difference in settlements under and around the vessel by comparing results from past and new measurements. A survey of any movements of the vessel between 1994 and 2021 is important in order to get a clear picture of any contact points between the vessel and more solid soil layers (glacial till) and thus also give an indication of whether the load of the vessel has been mainly transferred to the clay or the glacial till. This requires raw data from measurements from the period 1994 to 1996 that can be compared with new measurements. This information can be used to enable an assessment of whether the movements may have caused the damage to the vessel.

It is recommended that the current inclination of the vessel be measured for comparison with previous measurements from the investigation and planning period between 1994 and 1997.

Finally, it is recommended that the contract for procurement of geotechnical site investigations ensures that the client, the Swedish Accident Investigation Authority, will get the ownership of the raw data from the site investigations, not just a report on the final product such as a geotechnical investigation report and/or a geotechnical memo etc. It is proposed that the raw data be stored together as part of the investigation so that they can be used in the event that new questions arise in the future about the conditions around the vessel that need to be investigated.

## 4.3 Sampling and laboratory analyses

If the causes in section 4.1 are dealt with and it is possible to obtain piston samples of a satisfactory quality, laboratory analyses can be conducted in order to, for example, evaluate changes in the shear strength and compression properties of the soft clay layer.

When taking piston samples, specific emphasis should be placed on handling and transport of samples, and on laboratory analyses being conducted a short time after the samples were taken in order to increase the chances of obtaining good quality results. Taking into account the properties of the clay, laboratories should be used that have documented experience of tests on very soft seabed sediments and clay.

#### **4.4 Analyses**

Information about the soil layer sequence of the seabed, the undrained shear strength of the clay and the topography of the seabed can be used to calculate the stability of the slope where the vessel is lying. Calculating the *stability of the vessel* requires information about the thickness of the clay layer under the vessel and its contact with the glacial till, as well as knowledge about the contact area between the vessel and the soil. Information about the soil layer sequence and the compression properties of the clay can enable rough estimates of future settlements to be made. Slope stability calculation and settlement calculations are, however, associated with a large number of uncertainties such as the quality of the results from the samples, how representative the samples are of the area as a whole, the properties of the soil under the vessel, the contact areas between the vessel and the clay, variations in soil layer sequence etc.

Slope stability calculations and settlement calculations are of less significance to assessing the causes of the holes observed in the vessel. If piston sampling and advanced laboratory experiments are implemented, it is proposed that the purpose of the results be made clear, i.e. what questions the investigation is intended to answer. This is so as to set reasonable expectations of what is possible to achieve through the results of geotechnical investigations. Existing supporting documentation indicates that the clay has a very low shear strength and is very compressible. Taking into account the historical landslides, it has already been demonstrated that the slope stability in the area is very low. Any supplementary sampling and laboratory testing, if the quality of the samples is satisfactory, will probably confirm the previous results. At the same time, there will probably still be uncertainties, e.g. with regard to the contact area between the vessel and the clay and how representative the samples are of the area.

### **5 Discussion concerning rotation of the vessel and the cause of holes in the vessel**

The main disclosures in the opinion from the group of Estonian experts (Tabri et al., 2020) are two observations in the video material from 2020: two holes in the starboard side of the vessel close to the fender and that the vessel has rotated since 1997 from a list of 120° to a list of 132° on the starboard side.

The following discussion uses the group of experts' hypotheses in respect of rotation of the vessel and cause of the holes in the vessel as a starting point, taking into consideration the summary of geotechnical conditions reported in chapter 3.

The discussion is based on the following simplified assumptions: the frame of the vessel is assumed to be rigid (with infinitely stiffness) and the vessel is viewed in accordance with foundation theory, as a foundation with an inclined base. Further evaluation of the plausibility of various hypotheses requires interdisciplinary discussion in which it is proposed that expertise from shipbuilding, materials technology, geology and geotechnical engineering be represented.

The aim of the discussion is to demonstrate the importance of requiring accurate geotechnical data in order to allow geological causes of the holes to be confirmed or ruled out.

## 5.1 Rotation of the vessel

Figure 14 is taken from the opinion by the group of Estonian experts. On the left is shown the vertical position of the vessel before she sank, in the middle is the position given for the vessel on the seabed between 1994 and 1997, and on the right is the position given for the vessel in 2020.

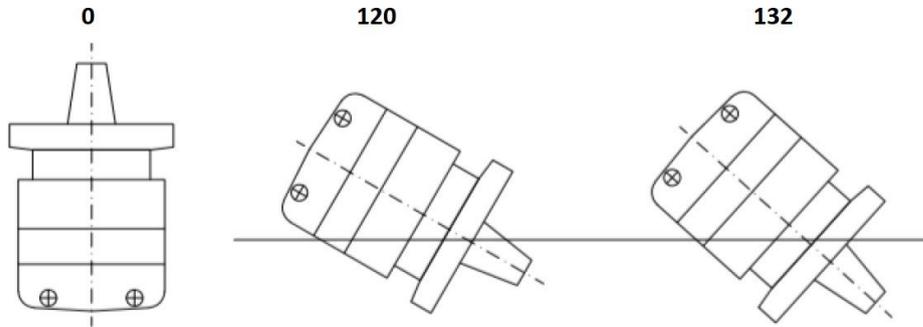


Figure 14 Illustration of the change in the position of the vessel through clockwise rotation, described as a heaving of the starboard side (Tabri et al., 2020).

Given the orientation of the vessel in an east – westerly direction, the rotation has, in that case, occurred in a southerly direction, see Figure 15.

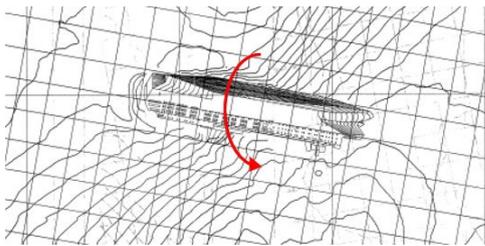


Figure 15. The vessel's stated rotation towards the south (based on NMC, 1996).

Figure 14 indicates that the starboard side has been elevated to some extent above the seabed, which made it possible to inspect parts that were previously covered by soil. Verification that the soil layer's coverage of the starboard side has changed requires high-resolution measurement data of the position of the vessel on the seabed relative to the surface of the seabed between the years 1994 and 1997 and measurement of the vessel's current position.

Figure 16 shows the position of the vessel's centre of gravity in profile and cross-section. Along the vessel's vertical axis (in the centreline), the centre of gravity is located c. 11 m above the bottom edge of the vessel and is located c. 62 m from the stern in the vessel's longitudinal axis (Smit Tak, 1995).

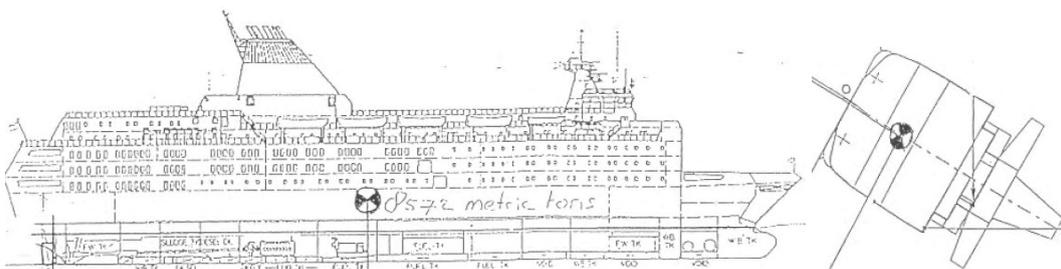


Figure 16. Position of the vessel's centre of gravity (black-white circle) (Smit Tak, 1995).

In conjunction with the planning of the reinforcement and covering measures, the assessment was made that the vessel is in contact with the glacial till at the deepest part of the vessel, which is the upper deck on the starboard side, see Figure 17.

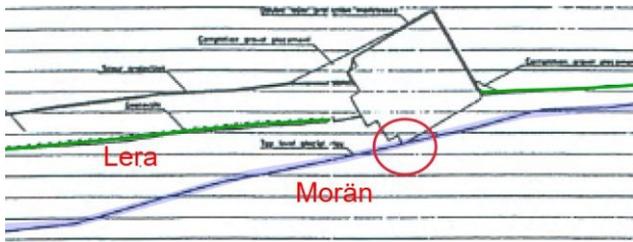


Figure 17. Interpreted area of contact between the vessel and glacial till (NMC, 1995).

If the position of the vessel's centre of gravity is assumed to be the same after its sinking as before, and that the vessel is a rigid construction, it is possible to formulate a hypothesis for the expected rotation. Taking into account the interpreted contact point between the glacial till and the vessel, and the position of the vessel's centre of gravity, the vessel can be expected to rotate towards the north, which equates to anticlockwise rotation in Figure 18 on the left. However, the vessel is reported to have rotated towards the south, which is clockwise rotation as shown in Figure 18 on the right.

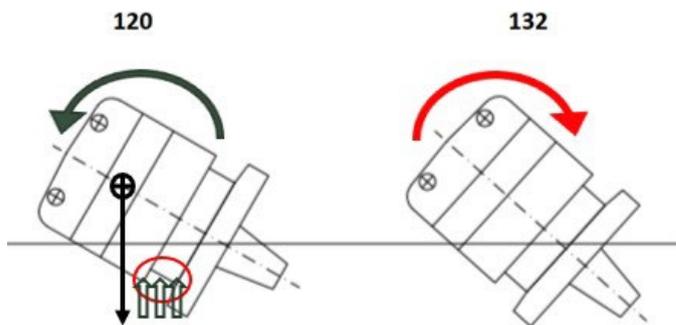


Figure 18. Left: expected direction of rotation taking into account the position of the vessel's centre of gravity and the interpreted contact area with glacial till. Right: the vessel's reported direction of rotation (figure based on Tabri et al., 2020).

An alternative scenario may be that the vessel is in contact with the glacial till at a lower deck on the starboard side (farther north) as shown on the left side of Figure 19. If the glacial till layer is close to the surface of the seabed or exposed along the northern side of the vessel, there may be a contact area north of the centre of gravity. If the vessel is not in simultaneous contact with the glacial till south of the centre of gravity, a rotation can arise as a result of settlements on the south side. In which case, settlements occur over a longer period of time and is caused by the effect of the load of the vessel on the clay layer. The vessel can then be expected to rotate around the southern end of the area of glacial till and, over time, make any damage north of the rotation point visible as shown on the right side of Figure 19.

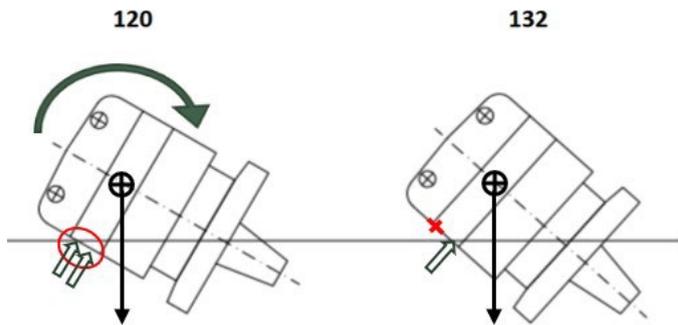


Figure 19. Alternative scenario in which the area of contact between the glacial till and the vessel is north of the centre of gravity. The red cross represents the approximate location of Hole 1 (figure based on Tabri et al., 2020).

However, an initial assumption is that it is more likely that the vessel is in contact with the glacial till at its deepest part, south of the centre of gravity. This theory is supported by the fact that at least four slides have occurred south of the vessel, but never under the vessel. If a substantial portion of the vessel's weight had been placed on the very soft clay layer, landslides would probably have occurred.

If the vessel is in contact with the glacial till on both sides of the centre of gravity, it can be expected to be stable and not show any rotation.

One further alternative scenario is that, at some point during the period 1996 to 2020, the vessel has moved from its position and slid down the sloping layer of glacial till. If the glacial till layer under the vessel has a varying inclination, the vessel may have rotated in conjunction with the slide, see example in Figure 20.

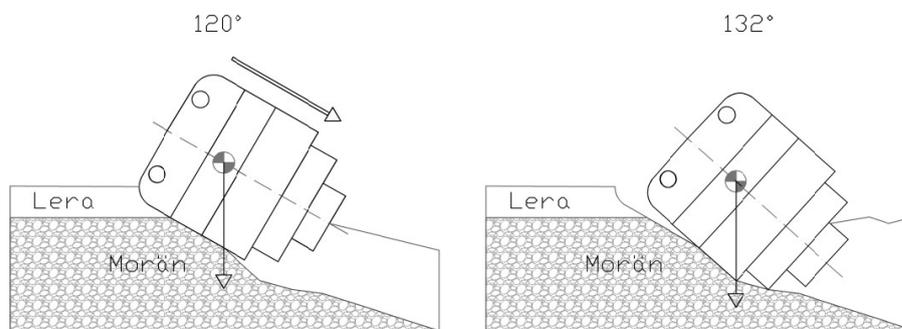


Figure 20 Schematic drawing of the hypothesis that the rotation was caused by sliding. Geometries of the glacial till and clay layers are shown schematically and are not consistent with actual conditions.

From the bathymetric measurements by Traficom (2006), it is possible to discern a depression or 'trench' to the north and west of the vessel, see Figure 21. Currents normally arise along the edges of sunken vessels. If the soil consists of material that is sensitive to erosion, an eroded depression arises in the surface of the seabed. However, the deep trench around Estonia may also have been caused by the vessel having moved in a south-westerly direction, which is the expected direction if movement were to occur.

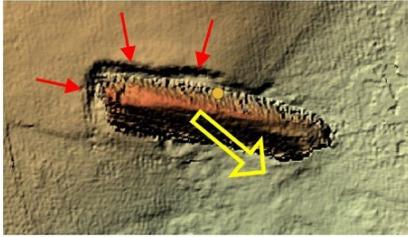


Figure 21 Depression around the vessel (red arrows) and expected direction of movement of the vessel (yellow arrow), based on Traficom (2006).

If the vessel is assumed not to be in contact with the glacial till and is floating in the soft clay, rotation to the south can arise as settlements occurred over time. This is because the thickness of the clay increases towards the south. In this case, however, there is no explanation for the cause of Hole 1.

In the discussion above, the vessel is assumed to have a rigid construction. If the vessel has a low/insufficient structural load-bearing capacity, high concentrations of load can cause structural breaks and potentially create an apparent rotation of the body of the vessel. However, this alternative hypothesis is not discussed in the present report.

## 5.2 Cause of holes in the vessel

Based on the supporting documentation obtained, it is not possible to either confirm or deny the existence of the holes during the period 1994 to 1997 as there is no documentation of the vessel being examined north of the centreline. Nor is it possible to assess whether the holes have arisen as the vessel hit the seabed. In the following discussion, it is assumed that the holes have arisen after the vessel reached its static equilibrium position in conjunction with the sinking.

The opinion from the group of Estonian experts gives geological causes as a possible explanation for the two holes observed, i.e. that the vessel has come into contact with rocks on the seabed. The vessel is resting in very soft sediments. If the holes were to have geological causes, an uneven distribution of the contact pressure between the vessel and the soil is required, with high local concentrations of stress. The clay on the seabed reduces the risk of high concentrations of stress by enabling the contact pressure to be more evenly distributed between the vessel and the soil. Uneven contact pressure arises if there are points where contact is made with an uneven and rigid/solid material. Accordingly, the vessel needs to be, or to have been, in contact with rocks and/or a local point/peak of glacial till.

The group of Estonian experts state that very little of the seabed was possible to observe in the video material (2020) but that the seabed appears to be relatively hard and solid without obvious larger rocks. However, Figure 3 does show the presence of rocks on the surface of the seabed within a larger area surrounding the vessel, primarily to the south-west of the vessel. When laying the forced penetration strings south of the vessel, the blast stones sank into the seabed sediments themselves until they reached a deeper, more stiff clay layer ([1] point 27). This sinking can also be expected to have occurred in the case of rocks that have been deposited on the seabed. In order for rocks to stick out, these need to be sitting on top of more stiff layers of soil. This may explain why the rocks in Figure 3 are primarily documented within the more solid glacial clay to the north and east of the vessel.

No detailed description is provided about the distance between the vessel and the interpreted solid seabed. These details are inconsistent with the assessments of the character of the seabed made during the period between 1994 and 1997 by, among others, VBB, NMC, Delft Geotechnics, NGI and independent experts. A summary of these assessments is provided in sections 3.1 and 3.2. Observations of a ‘hard and solid’ seabed might potentially refer to areas reinforced with geotextile and sand fill, or with forced penetration strings.

Furthermore, the opinion states: ‘*Ship mass (12 000 ton) significantly exceeds the force required for the opening (500–1000 ton). Thus, an uneven surface under the ship side could introduce concentrated forces that could lead to penetration damage*’ (Tabri et al., 2020). In the opinion, the position of the vessel is compared with the original seabed topography and the position of Hole 1, see Figure 22.

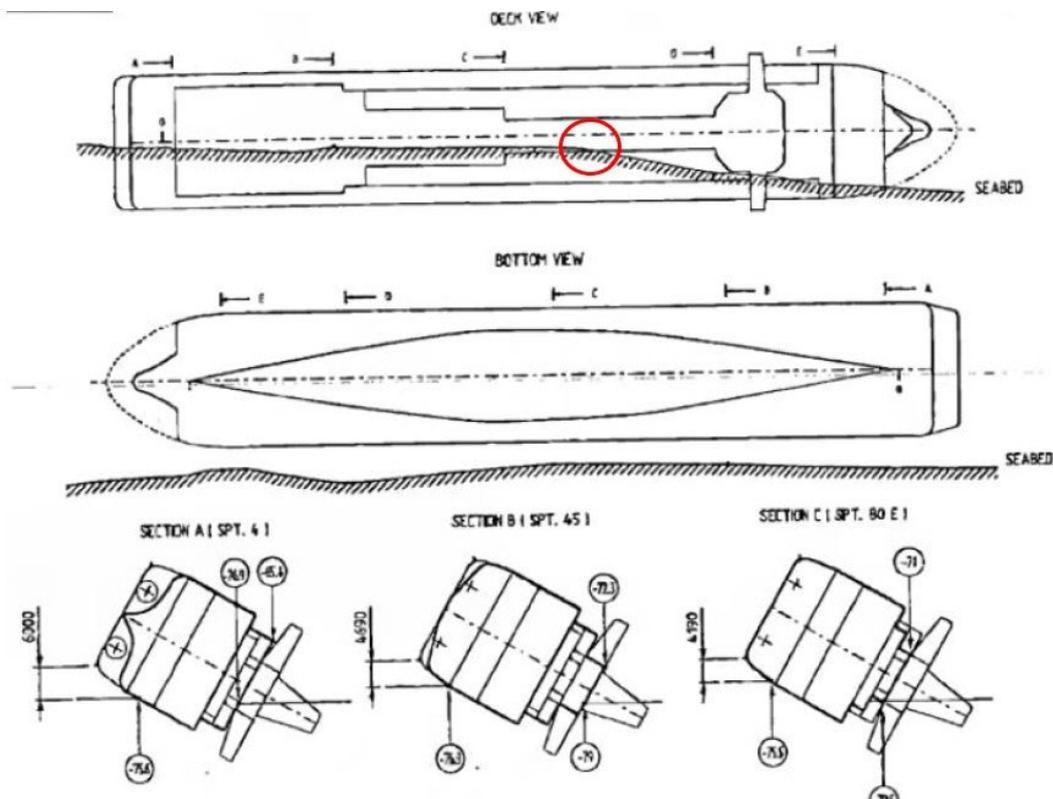


Figure 22. Schematic showing the position of the vessel on the seabed in relation to the original seabed surface according to documentation from 1994. The red circle marks the approximate position of Hole 1, which is said to coincide with the crest of a slope on the surface of the seabed (Tabri et al., 2020).

The comparison refers to the total mass of the vessel and the size of the force required to act on the point at which the hole has arisen. According to the estimate above, this is equivalent to 4.5–9 % of the weight of the vessel above the water (total steel weight: 10,920 tonnes [Smit Tak, 1995]). Another starting point is evaluation of the contact pressure that can arise between the vessel and the earth. For Hole 1 and the dent to arise on the vessel, increased local contact pressure needs to be applied to the soil layer without the soil breaking up. A force of 500–1000 tonnes distributed evenly over an area of 4.1 m<sup>2</sup> results in a contact pressure of c. 1–3 GPa.

However, contact pressure of such a size cannot arise in the clay since the clay would be expected to reach failure from a contact pressure equivalent to a few per cent of

what is required in order to cause the hole. The presence of rocks on the surface of the seabed alone does not therefore provide a complete explanation of the occurrence of Hole 1 as there must also be contact between rocks and more solid soil layers at a greater soil depth, e.g. glacial till. The preceding chapter contains proposed site investigations for the purpose of assessing whether the holes observed in the vessel may have geological causes.

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## **Appendix A - Geotechnical site investigations of the wreck of M/S Estonia conducted previously**

The geotechnical supporting documentation referred to in [sic] is set out below:

- 1 Memo Protection of the Estonia. Historical description from a geotechnical standpoint. Drawn up by VBB VIAK, dated 20/10/1998, revised 10/03/1999
- 2 Summary of events over the period 1994–1996. Obtained by the Swedish Accident Investigation Authority on 31/03/2021 (Word document, file name: information från f.d anläggning VBB anläggning.docx)

It is recommended that the complete underlying data for these documents be sought out, including the report regarding borehole coordinates, sounding results, laboratory results, seismic surveys, bathymetric surveys and measurements of the position of the vessel at different times. All raw data from the aforementioned results should be asked for and obtained. It is recommended that this data be sought from the Swedish Maritime Administration, Rockwater A/S, VBB VIAK (now Sweco), NMC or any of the company's contracted consultants or subcontractors.

**I)** An initial geotechnical and bathymetric site investigation was conducted by Rockwater A/S and Smit Tak at the end of November/beginning of December 1994 on behalf of the Swedish Maritime Administration. The site investigations encompassed:

- Bathymetric survey (echo sounding)
- Geological mapping of an area of 4 km<sup>2</sup>
- Sampling of seabed sediment with vibra core

Results are reported in the document *Condition Survey of the Vessel Estonia, Survey Report*, Rockwater A/S (undated but drawn up in December 1994, 62 pages, 2 drawings).

**II)** A more detailed geotechnical site investigation was conducted by Rockwater A/S over the period 21/05/1995 to 30/05/1995. The investigations encompassed:

- Bathymetric survey (echo sounding of an area of 500x500 m<sup>2</sup>)
- Measurement of temperature/conductivity from the surface of the water at 37 points
- CPT sounding at 37 points
- Borehole sampling at 11 points, the majority to a depth of 10 m under the seabed
- Gravity core sampling at 4 points to a depth of c. 2.5 m
- Box core sampling at 2 points to a depth of 0.5 m
- Laboratory tests encompassed determination of:
  - Density
  - Moisture content
  - Atterberg limits
  - Undrained shear strength
    - Dry vane
    - Fall cone
    - Triaxial tests (unconsolidated undrained, UU, and CIU)
  - Organic content
  - Particle density
  - Particle size distribution

Soundings and sampling was conducted no closer than c. 10 m from the vessel.

The results are reported in the document *Estonia – Seabed Investigation*, Rockwater A/S, 11/07/1995 (2 folders). Based on linear interpolation between the sounding points on either side of the vessel, VBB VIAK makes the assessment that the vessel may be in contact with the underlying solid glacial till. However, the accuracy of the measurements is not deemed to be sufficient in order to confirm contact with the glacial till or the size of this contact.

**III)** A complementary geotechnical site investigation was conducted by NMC between 29/12/1995 and 03/01/1996. The investigations encompassed:

- Bathymetric survey (echo sounding of an area of 500x500 m<sup>2</sup>)
- Video survey of the vessel
- Geotechnical investigations
  - Large core sampling (Ø220 mm)
  - Vane shear tests
    - In removed soil samples
    - In situ
  - Organic content
  - Atterberg limits
  - Triaxial tests (CAUC, test specimen Ø66 mm, 150 mm high)
- Test filling (forced penetration strings)

Results are reported in the document *Engineering field report on complementary investigations*. Drawn up by NMC, dated 26/01/1996.

Figure 23 shows coordinates for the complementary boreholes conducted by NMC.

Figure 24 shows an overview of of all the boreholes conducted thus far.

<u>Large diameter sampler</u>			<u>Seabed vane tests</u>		
NMC-SA-1	N 6 582 657	E 538 733	NMC-VT-1	N 6 582 673	E 538 749
NMC-SA-1A	N 6 582 669	E 538 746	NMC-VT-2	N 6 582 747	E 538 676
NMC-SA-2	N 6 582 731	E 538 658	NMC-VT-3	N 6 582 743	E 538 778
NMC-SA-3	cancelled		NMC-VT-4	N 6 582 550	E 538 650
NMC-SA-4	N 6 582 549	E 538 680	NMC-VT-5	N 6 582 650	E 538 650
NMC-SA-5	N 6 582 630	E 538 635	NMC-VT-6	cancelled	
NMC-SA-6	cancelled		NMC-VT-7	N 6 582 700	E 538 850
NMC-SA-7	N 6 582 679	E 538 829	NMC-VT-8	N 6 582 800	E 538 875
NMC-SA-8	N 6 582 809	E 538 897	NMC-VT-9	N 6 582 825	E 538 625
NMC-SA-9	N 6 582 837	E 538 646			

Figure 23. Coordinates complementary bore holes conducted by NMC.

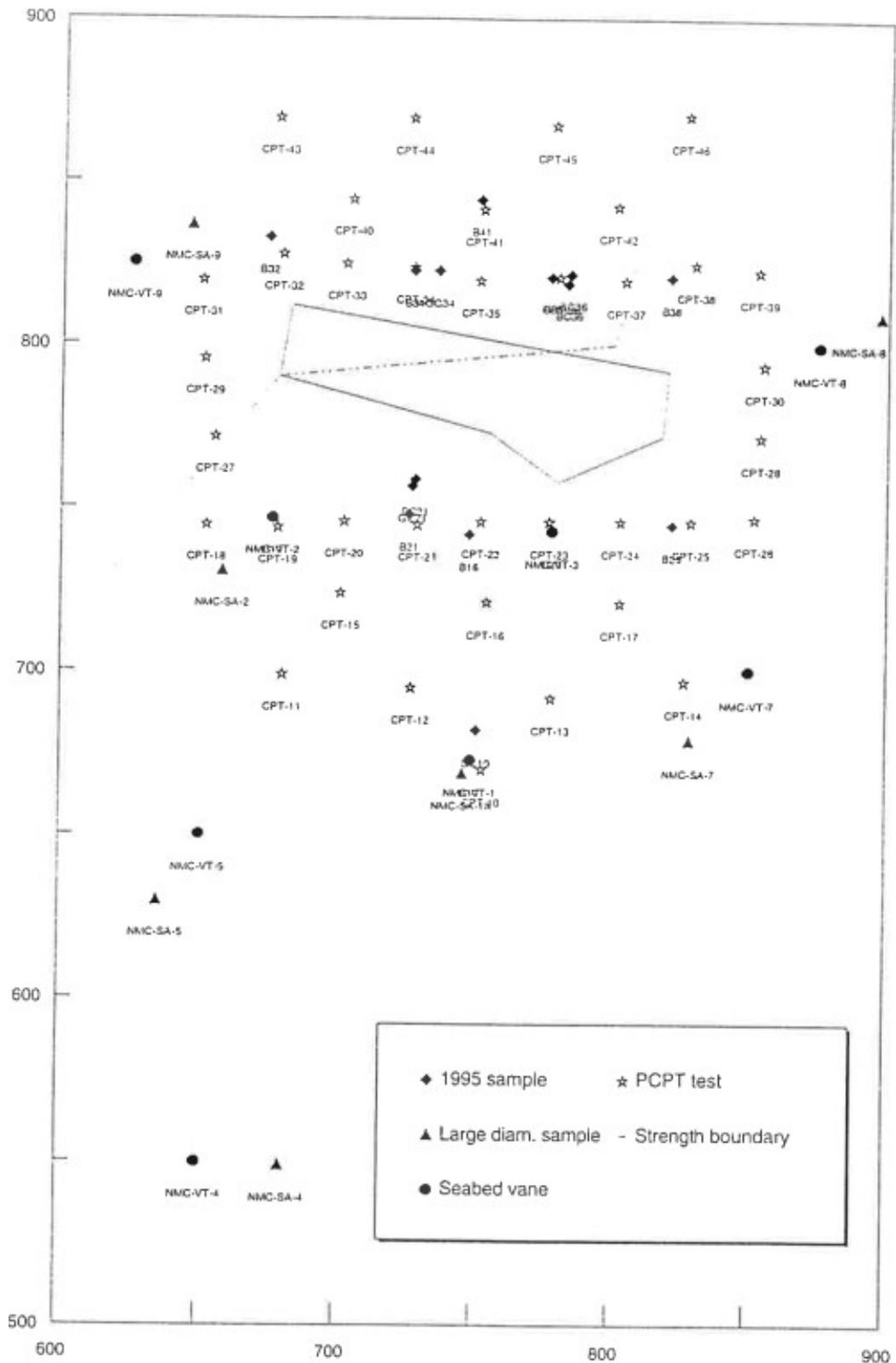


Figure 24. 'Layout of all site investigations', position of M/S Estonia drawn in outline. Drawn up by Delft Geotechnics, dated 29/02/1996.

- IV) Delft Geotechnics conducted supplementary laboratory tests encompassing CRS tests on samples and water absorption tests on light fill. The results are reported in the document *Additional Soil Investigation. Ver 02*. Drawn up by Delft Geotechnics, dated 20/03/1996 (30 pages+39 appendices).
- V) NMC conducts a supplementary seismic survey over the period 08/09/1997 to 10/09/1997. The results of the supplementary seismic survey are reported in the document *Investigation Report on Contact with Glacial Till. Rev. 01*. Drawn up by NMC, dated 31/10/1997 (16 pages+appendix).
- VI) In [2] point 40 it is stated that the works that were contracted out also ended up including the installation of transponders on critical parts of M/S Estonia in order to measure movements:

*'... The works that were contracted out also ended up including transponders that were placed on critical parts of M/S Estonia. These transponders allowed movements to be measured with significantly greater accuracy. All measurements that I was able to see showed no evident movements of M/S Estonia. Measurements probably also after the seabed slide, but I am not able to confirm this with certainty.'*

SGI has not been able to determine in which document/documents the measurement data from the movement transponders is reported, but recommends that these are sought out, preferably with the associated raw data.

During the planned site investigations, the positions of these transponders should be measured again in order to evaluate the size of movements over the period 1997–2021.

#### **List of geotechnical site investigations**

- I Condition Survey of the Vessel Estonia, Survey Report, Rockwater A/S (undated but drawn up in December 1994)
- II Estonia – Seabed Investigation, Rockwater A/S, 11/07/1995
- III Engineering field report on complementary investigations. Drawn up by NMC, dated 26/01/1996
- IV Additional Soil Investigation. Ver 02. Drawn up by Delft Geotechnics, dated 20/03/1996
- V Investigation Report on Contact with Glacial Till. Rev. 01. Drawn up by NMC, dated 31/10/1997
- VI Measurement data movement transponders



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