Nord Stream AG

Offshore pipeline through the Baltic Sea

Memo 4.3A-9
Release of sediments from anchor operation

September 2008

RAMBØLL

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List of abbreviations and definitions

ρ	density of anchor
ρ_w	density of water
ρ_s	density of the soil grains
ρ_{soil}	bulk density of the sediment
w	Water content (Weight of water divided by weight of dry matter in percent)
f	Fraction of the kinetic energy converted to suspension of sediment
G	acceleration of gravity
H	distance above the seabed
m_a	mass of the anchor
m_{sus}	mass of sediment grains (without the water content)
U	downwards velocity of anchor
V	steel volume of anchor
V_{soil}	bulk volume of sediment

1. Introduction

1.1 The Nord Stream project

Nord Stream is a natural gas pipeline transmission system from Russia to Germany with connections to onshore transmission systems in these two countries. The system will consist of two almost parallel 48-inch steel pipelines and is to be built by Nord Stream AG. It will pass through the exclusive economic zones (EEZ) of five countries: Russia, Finland, Sweden, Denmark and Germany, and the territorial waters of Russia, Denmark and Germany. At full capacity, it will provide 55 billion cubic metres (bcm) of natural gas per year to Western European consumers. The European Union's institutions, recognizing the need to encourage the construction of new import routes, have designated Nord Stream a "project of European Interest" as part of the Trans-European Energy Networks (TEN-E).

The shareholders of Nord Stream AG are:

- OAO Gazprom
- Wintershall AG (a BASF subsidiary)
- E.ON Ruhrgas AG (an E.ON subsidiary)
- N.V. Nederlandse Gasunie

Nord Stream AG is based in Zug, Switzerland, with a branch office in Moscow, Russia. The company was established for the planning, construction and subsequent operation of the new offshore gas pipelines across the Baltic Sea.

1.2 Release of sediments from operation of anchors

This memo describes the possible suspension of sediment released in connection with operation of anchors.

During the operation of the lay barge used for approximately 75% of the first pipeline, anchors are used for propulsion and positioning of the lay barge. The anchors are moved consecutively by anchor-handling vessels to new positions, and during these operations some sediment may be released to the water column. For the rest of the pipeline and for the second pipeline dynamically positioning will be used, i.e. no anchors are used.

The sediment composition and seabed conditions vary along the pipeline. This memo will not deal with the different conditions throughout the alignment. The suspension of sediment in connection with the handling of anchors is estimated from analytical considerations to determine the order of magnitude of the suspension in a worst-case scenario.

2. Operation of anchors

2.1 Anchor configuration

The majority of the first pipeline will be laid by the lay barge Castoro Sei. During operation, Castoro Sei is positioned with 12 anchors, each of a weight of 25 tonnes, cf. /1/. The anchors are fastened to 12 anchor winches each with 3000m anchor wire of 76 mm diameter, /1/. The anchors are placed on the seabed on positions around the lay barge and are moved forward by tug boats during the operation of the lay barge. During movement of the anchors from one position to another the anchors and wires are lifted from the seabed to ensure manoeuvrability of the tug boats. Disturbance on the seabed from the anchors and the anchor wire is therefore limited. The distance between two positions of one anchor during operation of the lay barge is approximately 500 m. In one position the distance between two anchors next to each other is 200-1000 meters, depending on the water depth, cf. Figure 2.1.

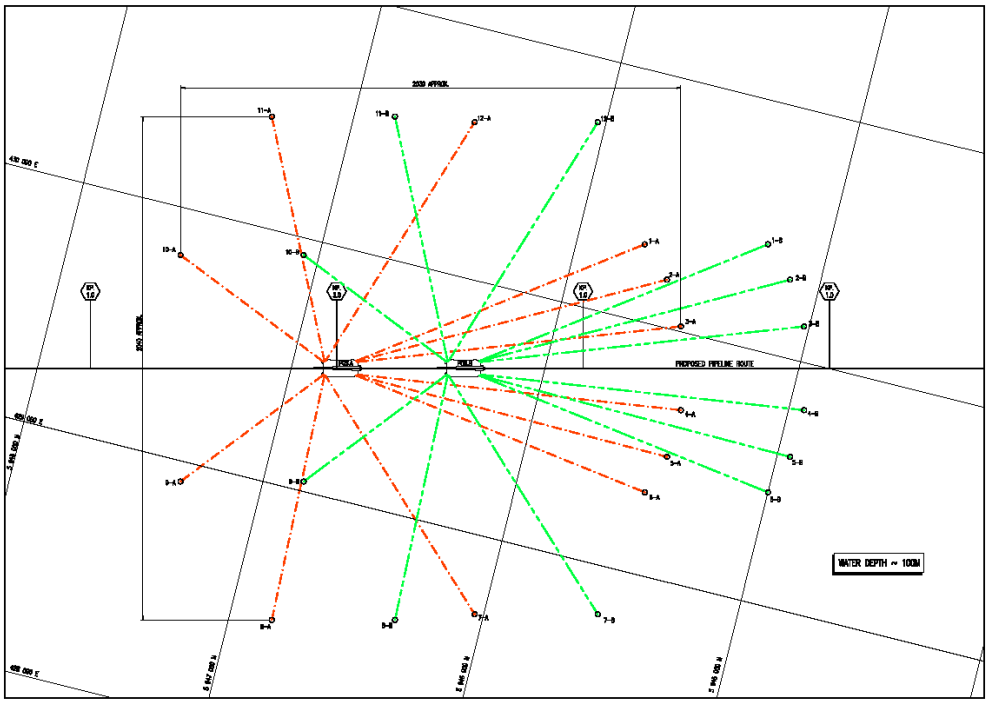

Figure 2.1: Anchor patterns at a water depth of 100 m

2.2 Process

During transport of the anchors from one position to another the anchors are lifted from the seabed, to avoid disturbances on the seabed from anchor and anchor wire, and it is expected that no or very little sediment will be released during transport of the anchors.

The processes which may create suspension of sediment are therefore when the anchors are laid down on the sea bed, when they are pulled up again and when the anchor wire is sweeping across the sea bed during movement of the lay barge.

In soft sediment it must be expected that the anchors might sink into the sediment when they hit the seabed. Therefore, when the anchor is pulled to give the desired holding capacity, no significant suspension of sediment to the water column is expected. When the anchor is pulled back again some sediment may stick to the anchor and may be suspended in the water column.

The anchor wire will typically rest on the seabed in a stretch of 100 to 150 m from the anchor, /2/. When the lay barge is moving forward the anchor wire will be sweeping across the seabed in a section of a circle as shown in the sketch in Figure 2.2. This may create some suspension of sediment even though the movement of the anchor wire is very slow.

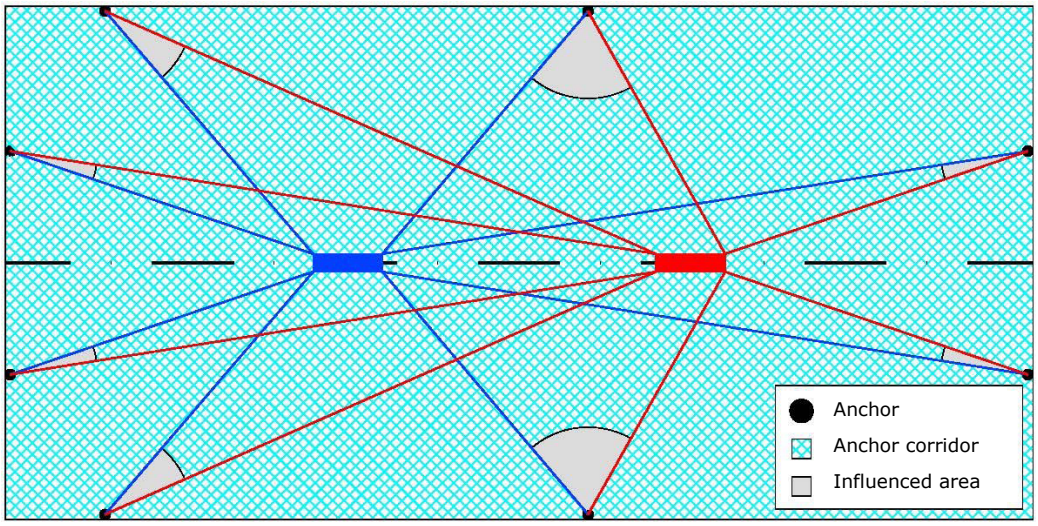

Figure 2.2: Areas influenced by the anchor wire (sweeping)

3. Suspension of sediment

The suspension of sediment is in the following quantified under the assumption of a soft seabed dominated by sediments in the clay/silt fractions and organic material, which is regarded as the worst case in relation to sediment suspension. In case of hard seabed and sand sediments the suspension in relation to anchor operation is assumed to be negligible. The mechanical impact is assumed to be too small to create suspension on a hard seabed and in case of coarse sand sediments, the settling velocity of the sediment is so large that the grains not will be suspended for a longer time period.

3.1 Release of sediment from anchor lay-down

The size of the suspension of bottom material can be estimated by anticipating that the kinetic energy of the anchor when it hits the seabed is transferred to potential energy of suspended sediment, as it requires a certain amount of potential energy to raise the sediment into the water column due to its higher density compared with the density of water. The energy loss from shear stress and friction between the water and the grains as well as the cohesion between the grains is taken into account by a factor, *f*, of the kinetic energy which is converted to suspension of sediment.

The vertical velocity of the anchors when they fall to the seabed is of importance when estimating the kinetic energy that is responsible for possible suspension of sediment.

The anchors are released from the anchor handling vessels and controlled laid down on the seabed. The vertical velocity of the anchors is limited by the speed of the anchor winches and is estimated to be well below 1 m/s when hitting the seabed. A conservative value of 1 m/s is used for estimating the kinetic energy of the anchors.

The mass of sediment which is suspended in the water column can be calculated from:

$$m_{sus} = \frac{\frac{1}{2} m_a U^2 f}{gh\left(1 - \frac{\rho_w}{\rho_s}\right)}$$

where m_{sus} is the mass of sediment grains (without the water content), m_a is the mass of the anchor, U is the downwards velocity of the anchor, g is gravity, h is the height to which the sediment is raised in the water column, f is the fraction of the kinetic energy converted to suspension of sediment, ρ_w is the density of water and ρ_s is the density of the soil grains.

An energy transformation process where kinetic energy of one subject is transferred to another subject has normally a low efficiency because a lot of the energy dissi-

pates and produces heat. Furthermore there is a loss of energy because of the resistance when the sediment grains moves upwards in the water column and because of the cohesion between the grains when they are released from the seabed. It is therefore assumed that less than 20% of the kinetic energy of the anchor is transferred to potential energy of suspended sediment grains. The upper limit of 20% might even be a very conservative estimate and it is more likely that 1% to 10% of the energy is transferred to suspended sediment. The suspended sediment is assumed to be distributed evenly in the lower 10 meters of the water column on basis of the quite large weight of the anchor. This means that the mass centre point of the suspended sediment is 5 m above the seabed. The assumed values of the input parameters are shown in table 3.1.

m_a (tonnes)	U (m/s)	H (m)	f (-)
25	1	5	1% - 20%

Table 3.1: Release of sediment from anchor lay down

f (-)	Mass (dry weight) of suspended sediment, m_{sus} (kg)
1%	4
10 %	40
20%	80

Table 3.2: Estimated release of sediment from anchor lay down

3.2 Release of sediment when taking up the anchor

When pulling up the anchor from the seabed it is assumed that the anchor is taken up along the same path as it is pulled down into the sediment, i.e. the entire soil volume covering the anchor is not taken up in the water column when taking up the anchor. However, some sediment may stick to the anchor or is simply withdrawn when the anchor is taken up and may therefore be suspended in the water column. It is not straight forward to estimate how much sediment which in this way is taken up and released to the water column, but from a geometrical point of view the area on the anchor blades, where the sediment can stick, is approximately 20 m^2. Assuming that half of this area is covered with sediment, i.e. 10 m^2, the mass of sediment which is raised up in the water column can be estimated using different thicknesses of sediment sticking to the anchor.

It is assumed that it is primarily in the areas dominated by soft clay, where the sediment will stick to the anchors and is suspended to the water column. From /3/ the water content, w, in the upper part of the seabed in the areas dominated by clay is estimated to approximately 90%. The dry density of the soil grains are estimated to 2650 kg/m^3. In Table 3.3 the resulting release of sediment is shown.

Thickness (mm)	Mass (dry weight) of suspended sediment, m_{sus} (kg)
1	8

5	39
10	78

Table 3.3: Release of sediment when taking up the anchors.

3.3 Release of sediment from sweeping

The anchor wire will typically rest on the seabed in a stretch of 100 to 150 m from the anchor, /2/. When the lay barge is moving forward the anchor wire will be sweeping across the seabed in a section of a circle.

From Figure 2.1 the angle between the lines of the anchor wire when the lay barge has moved from position A to position B and the anchor is in position A is determined. The results are shown in Table 3.4.

Anchor number, cf. figure 2.1	***Angle (degrees)***
10 and 9	15°
11 and 8	24°
12 and 7	26°
1 and 6	12°
2 and 5	9°
3 and 4	5°

Table 3.4: Angles

The average angle is approximately 15°. Assuming the anchor wire is lying on the seabed in a stretch of 125 m, this gives an average area on the sea bed per anchor wire of 2080 m2 which is influenced during a sweep from position A to position B.

Taking the dimension of the anchor wire into consideration, i.e. a diameter of 7.5 cm /1/, the upper 5 - 10 cm of the seabed material is expected to be pushed/influenced by the anchor wire if the seabed is soft. The chain moves very slow across the seabed, and the motion of the impacted seabed material is also slowly. Therefore most of the material will only be moved just over the top of the chain and the opposing gravity force which will keep the material near the bottom. However, a small part of the fine fractions of the sediment may be lifted higher up in the water column and may therefore be suspended for a longer time period. Defining the suspended sediment as sediment lifted more than a few centimetres up in the water column, it is expected that less than 1% of the sediment impacted by the anchor chains will be suspended in the water column. In Table 3.6 the calculated release of sediment is shown for different fractions of the impacted sediment assumed to be suspended.

Influenced area **(m^2)**	***Water content, w***	***Density of sediment grains, ρ_s*** **(kg/m^3)**
2080	90%	2650

Table 3.5: Presumptions

Suspension per m² **(mm)**	***Mass of sediment (dry weight), m_{sus}*** **(kg)**
0.25	400
0.5	800
1	1600

Table 3.6: Release of sediment from sweeping

Given a total width of the anchor corridor of 2040 m, the number of anchors of 12 and the distance between positions A and B of 500 m, the total influenced area can be determined to approximately 2% of the anchor corridor.

The total release of sediment from sweeping is calculated to 10 - 38 tonnes/km in areas with soft sediment in the anchor corridor giving the largest release of the processes analysed.

3.4 Suspension height during anchor sweeping

The vertical distribution of suspended sediment and the suspension height is in the following estimated for the sweeping process. The suspension height is defined as the maximum height where a concentration above 1 mg/l is found.

Equilibrium concentration profiles for suspended sediment can be established for sandy sea beds,
/4/,
/5/. Also empirical concentration profiles for suspension over mud beds can be found, /6/. However, these profiles are developed to describe the concentration of suspended sediment in conditions where the motion from currents and waves in it self is able to bring the sediment in suspension and give rice to sediment transport. This means that the profiles describe suspended sediment in areas with a continuous source of sediment to the water column governed by the turbulence created by current and waves.

The situation where the anchor chain brings sediment in suspension is different in the way that the source of sediment can be seen as a point source in time. The anchor chain will only cause suspension at the moment where it passes a given place.

To determine the vertical distribution of suspended sediment a dynamical approach, rather than the equilibrium approach, has to be made.

The turbulent diffusivity is an important parameter to establish when determining the concentration profile. Three processes have to be considered when determining the turbulent diffusivity of the sediment:

- The impact on current and turbulence from the anchor chain it self
- Turbulence created by the natural current

- Turbulence created by waves

Under waves the suspended sediment is confined to the relatively thin (few mm or cm) wave boundary layer,
/4/. Therefore, waves do not contribute significantly to bring the suspended sediment higher up in the water column.

Under currents the suspended sediment can be diffused up in the water column due to the turbulent motion. Under natural sediment transport conditions with combined waves and currents the sediment is suspended within the wave boundary layer and diffused further up into the flow by the turbulence associated with the current,
/4/.

The anchor chain is assumed only to influence the current profile in a narrow area near the seabed, because it is a limited water volume it will move during the short pass of the anchor chain. As for the combined wave and current motion it is assumed that sediment is suspended within the boundary layer created by the anchor chain and diffused further up into the flow by the turbulence associated with the current.

The area of influence from the anchor chain is estimated to 2.5 times the diameter, i.e. the lower 25 cm of the water column. It is assumed that the sediment suspended during the sweep instantly is distributed in the lower 25 cm of the water column due to the turbulence created in the lower 25 cm by the chain it self.

In the equilibrium approach the balance between settling of sand grains and upwards diffusion due to the turbulent water motions is under currents governed by the equation,
/4/:

$$w_s C = -K_s \frac{dC}{dz}$$

Where K_s is the eddy diffusivity of the sediment, C is the concentration and w_s is the settling velocity of the grains or aggregates.

There are different assumptions of the size and distribution of the eddy diffusivity of the sediment, but a general acknowledged equation is the diffusivity parobolically varying with depth,
/5/:

$$K_s = \kappa u_* z \left(1 - \frac{z}{h}\right)$$

Where u_* is the friction velocity and κ is von Karman's constant. The friction velocity can be determined from the median grain size of the sediment, d_{50} and the velocity U(z) at z meters above the seabed from,
/4/:

$$u_* = 0.121\left(\frac{d_{50}}{z}\right)^{1/7} U(z)$$

In mud beds the sediment can not be seen directly as grains because of the cohesion. However, it can be assumed that the anchor chain will mechanically split the cohesive mud into aggregates of larger size than the original clay-size particles with a density lower than soil material itself, as described in /7/. In /7/ the settling velocity of the aggregates has furthermore been estimated. To establish a concentration profile, the suspended mud is in the following assumed to be in the form of aggregates following the physical behaviour of grains with the settling velocity found in /7/.

The dynamical approach is based on the same physical description of the processes as in the equilibrium approach. Considering a 1 x 1 m water column following the mean water motion by the current the concentration of sediment is influenced by the two processes balancing in the equilibrium approach, i.e. settling of grains and upwards diffusion due to the turbulent water motions, and furthermore horizontal dispersion. If neglecting the horizontal dispersion the concentration of suspended sediment as function of time and height above the seabed is governed by the equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(K_s \frac{\partial C}{\partial z}\right) - w_s \frac{\partial C}{\partial z}$$

The above equation has been solved numerically using a finite difference scheme with an equidistant grid (spacing 0.25 m between grid points). The input parameters are shown in the table below. The calculation represents an area of very soft seabed (mud) on 70 m of depth.

Typical velocities from the lower 1 meter of the water column representing calm, normal and rough conditions has been found from the hydraulic model, /7/.

Median grain diameter, d_{50}	0.004 mm
K	0,4
Water depth, h	70 m
Current velocity 1 m above the seabed, calm conditions	0.005 m/s
Current velocity 1 m above the seabed, normal conditions	0.02 m/s
Current velocity 1 m above the sea-	0.15 m/s

bed, rough conditions	
Settling velocity of aggregates, w_s	0.11 mm/s
Initial concentration in the lower 25 cm of the water column	10.6 kg/ m^3

Table 3.7: Parameter values used in the calculations

The initial concentration has been found by assuming that the suspension of 0.001 m^3 of sediment is distributed in the lower 25 cm of the water column giving a concentration of 10.6 kg/m^3 using a density of 2650 kg/ m^3 of the seabed material.

The horizontal dispersion which not has been taken into account in the above equation will decrease the concentration compared to what is calculated. Furthermore horizontal dispersion is usually larger than the vertical dispersion and therefore the calculated concentrations represent the maximum interval of concentrations that is possible.

The area of the disturbance of the anchor chain is of the order size of 100 meters. When the water column in consideration has been transported 100 m by the mean current, and therefore every point where sediment is released has travelled to a point outside the impacted area, it can be expected that the horizontal dispersion has lowered the concentrations considerably. Therefore the calculations have been done only within the period where the mean current moves the sediment particles a distance of 100 meters.

The concentration profile containing the highest level above the seabed where 1 mg/l is found is shown in the figure below, under the different conditions.

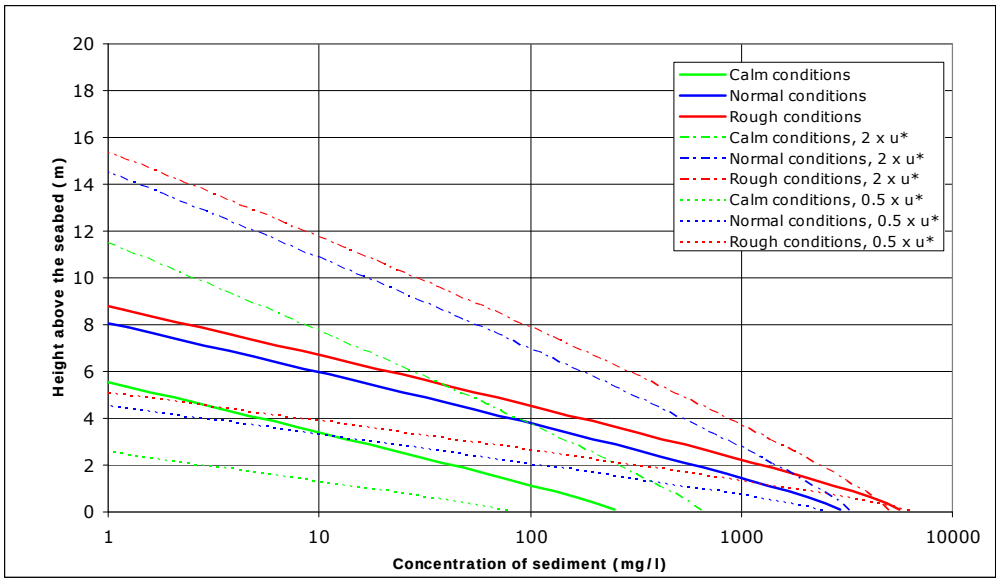

Figure 3.1: Concentration of sediment

The sensitivity of the friction velocity has been evaluated by making the calculations with the double and the half of the estimated value.

It can be seen that for normal to rough conditions a representative suspension height of 8-9 meters are found, and a total interval from approximately 2 – 15 meters considering the sensitivity of the suspension height on the friction velocity.

It is concluded that a suspension height of 10 meters is representative for the suspension from sweeping.

4. Conclusion

In areas with soft fine grained sediment anchor operations may create suspension of sediment and the possible size of the suspension has been estimated.

When the anchor is dumped at a new position and when it is taken up again the estimate of the size of the release of sediment to the water column is of the order of 10 - 160 kg in total. The release of sediment from the sweeping process is estimated to 400 - 1600 kg. From this evaluation the sweeping process will give a release of sediment of more than 10 times the release from the other processes together and is therefore seen to be the most important process in connection with suspension of sediment.

The total release of sediment in connection with sweeping is calculated to approximately 10 – 38 tonnes/km of the pipeline in areas with soft sediment.

It is estimated that the suspended sediment is distributed within the lower 10 meters of the water column.

Assuming the release of sediment is distributed instantaneously in the lower 10 m of the water column in the anchor corridor the average sediment concentration is approx. 0.5 - 2 mg/l. As the releasing process is dynamic and some of the sediment released first will be settled before new sediment is released the actual concentrations will be lower than this.

Assuming that the sediment is deposited in the same area, i.e. no further spreading, the sedimentation in the anchor corridor is 0.005 kg/m^2. This corresponds to 0.005 mm/m^2 assuming that the porosity of the settled sediment is 60%.

5. References

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/6/ Whitehouse et al.: Dynamics of estuarine muds, HR Wallingford, 2000.

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