Nord Stream AG

Offshore pipeline through the Baltic Sea

Memo 4.3A-4
Spreading of sediments during pipeline layout

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List of abbreviations and definitions

θ	shields parameter
ρ	density
A	area
d	grain size
g	gravity
h	distance above the seabed
k_N	bottom roughness
P	pressure
Q	flow
r	bending radius of pipeline
R	radius of pipe
s	relative density
u	flow velocity
U_f	friction velocity
v	velocity
v_{LB}	velocity of lay barge
v_p	vertical velocity of pipeline during layout
V	volume
x	horizontal distance
z	distance above the seabed

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 Spreading of sediments during pipeline installation

This memo describes the possible suspension of sediment released in connection with pipeline installation directly on the seabed.

During the pipeline installation process, sediments from the seabed may be suspended due to the following processes:

- The current generated in front of the pipeline when it falls through the water column near the seabed may eventually bring sediment into suspension
- The pressure from the pipeline when it hits the bottom may create an upwards movement of sediment.

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 during the layout process is estimated from analytical considerations to determine the order of magnitude of the suspension for a worst-case scenario.

2. Summary

The vertical velocity of the pipe is estimated under the assumption that the pipeline is describing a sector of a circle in the water column during the pipeline installation process. The velocity is asymptotically reaching zero at the seabed and is seen to be less than 1 mm/s within the lower metre, when the lay barge operates in calm water (no waves). In waves, vertical movement of the lay barge may cause the vertical velocity of the pipe to be up to 60 times higher, but velocity in the last metre above the seabed is still below 5 cm/s. This is, however, very conservative because it is based on the assumption that the laybarge follows the excursions of the waves directly.

Erosion below the pipe during pipeline installation is estimated for the worst case of sediment-grain size and vertical velocity of the pipeline of 5 cm/s and 0.1 cm/s. Erosion only occurs in the case of 5 cm/s vertical velocity of the pipe and only when the pipe is less than 5 cm from the seabed. This does not cause suspension of sediments to the water column.

The upwards flow through the seabed generated by the pressure from the pipe during layout has been estimated both for the case where the pipeline stays on the seabed and the case where the pipeline sinks into the seabed. In both cases the suspension of sediment is evaluated to be small.

3. Vertical velocity of the pipeline during installation

3.1 Average layout velocity

The vertical velocity of the pipeline when it falls though the water column during the layout process is of importance for estimating the possible suspension of sediment. The vertical velocity of the pipeline is not constant through the water column and may also change in different areas of the Baltic Sea because of bottom conditions and water depth.

Therefore, it is only the order of magnitude of the maximum velocities that is estimated in the following.

The pipeline will be installed by the S-lay method. To estimate the order of magnitude of the vertical velocity of the pipeline, the lower part of the pipeline in the water column is assumed to describe a sector of a circle during the pipeline installation process. The circle is assumed to have a radius according to the minimum bending radius of the pipeline.

Under these assumptions, the vertical velocity of the pipeline at different depths in the water column can, from purely trigonometric considerations, be described by:

$$v(z) = v_{LB}\sqrt{1-\left(\frac{r-z}{r}\right)^2}$$

where v_{LB} is the horizontal velocity of the lay barge along the pipe route, z is the distance from the lowest point to the seabed and r is the bending radius of the pipeline.

Approximate sizes of the parameters giving the maximum vertical velocity are shown below.

Velocity of the lay barge, v_{LB} (km/day)	3
Minimum bending radius of the pipeline, r (m)	3,000

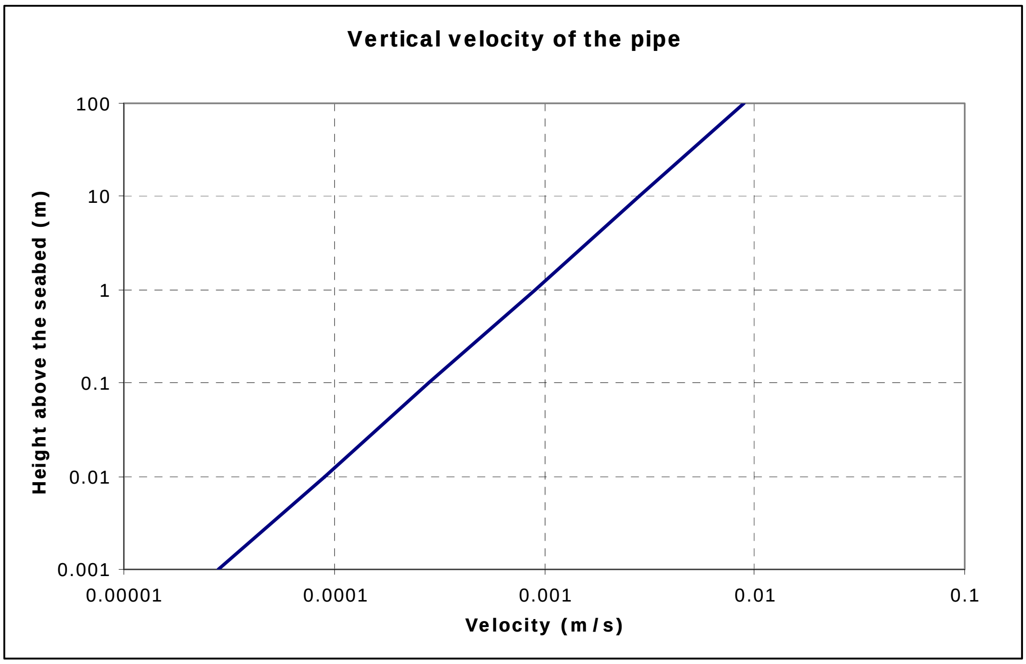


Figure 3.1: Vertical velocity of the pipeline in the water column during pipeline layout

The calculated velocities are shown in Figure 3.1. The velocity is asymptotically reaching zero at the seabed and is seen to be less than 1 cm/s in the major part of water column. Based on the above assumption the vertical velocity of the pipe is less than 0.9 mm/s within the lower 1 m.

3.2 Vertical movement of the lay barge

The calculated vertical laying velocity of the pipeline is seen to be rather small. However, when laying the pipeline the lay barge moves up and down because of waves. This vertical movement of the barge may increase the velocity of the pipeline near the seabed.

The movement will be highly irregular, so in the following analysis only a single downwards movement is examined to estimate the order of magnitude of the velocity near the bottom. Using the assumption that the pipeline describes a section of a circle in the water column, the movement can be described by the same equation as the mean velocity described above.

A lay barge of the size suitable for the project will probably be able to operate in conditions with a significant wave height up to 3 m with a period of approximately 10 seconds /4/. The vertical movement of the lay barge during the pipeline installation operation is therefore in the following estimated to an order of magnitude of 3 m per approximately 5 seconds (assuming linear waves). This is, however, a very conservative estimate, because the laybarge far from follows the excursions from the waves. From the above description of the velocity of the pipeline following the velocity of a moving circle (a wheel) during pipe-laying, a single vertical downwards excursion of 3 m at the surface at a depth of 100 m gives a horizontal movement of the touchdown point of 12 m. This means that a point 1 cm above the seabed will move down to the seabed during the wave period, assuming the seabed is horizontal. By the assumption that this will take in the order of five seconds, the horizontal average pipeline installation velocity is 2.4 m/s (compared to the vessel speed of 3 km/day = 0.04 m/s). This means that the horizontal velocity of the pipeline due to wave-induced up-and-down movement of the lay barge is up to an order of 60 times the mean velocity due to horizontal vessel speed. In the lower 1 m of the water column we can therefore expect vertical velocities of the pipeline of up to 5 cm/s. However, the average velocity at the point where the pipeline theoretically will touch the seabed after one excursion will be only 0.1 cm/s.

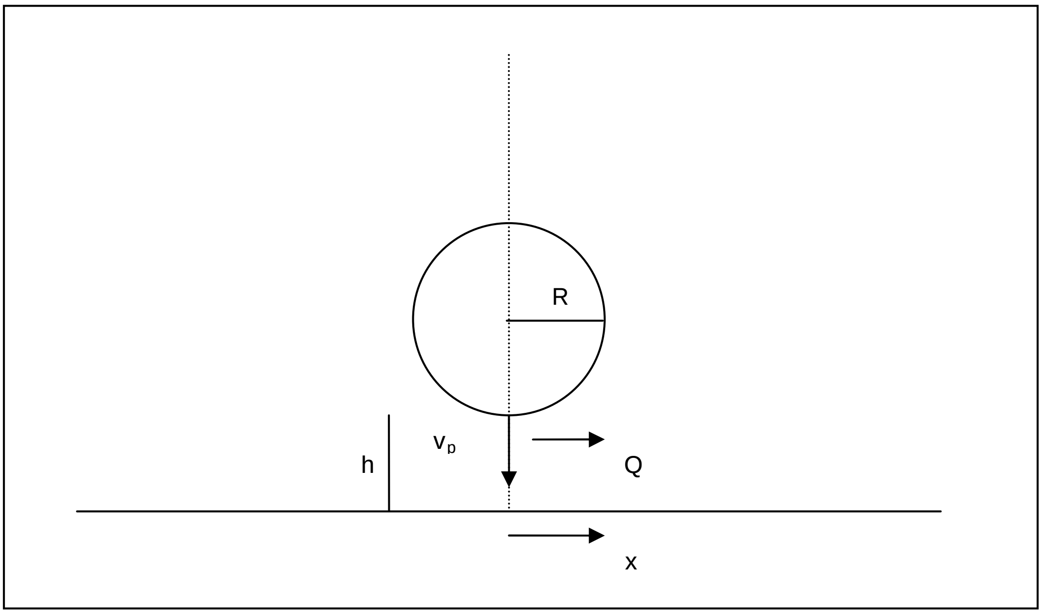
4. Suspension of sediment

4.1 Erosion during layout

When the pipeline is moving down through the water column it replaces a corresponding volume of water, creating a current in front of the pipe. When approaching the seabed the velocity of this current increases because the area where the water has to escape decreases towards zero.

The bottom conditions and the grain sizes of the sediment vary at different areas of the alignment of the pipeline. Therefore the analysis is not site-specific regarding sediment-grain size but the worst-case scenario is analysed.

In the following, a 1 m section of the pipeline is considered as it falls through the water column. Near the bottom, the section of the pipeline is approximately horizontal, meaning that the section can be described in a two-dimensional cross-section perpendicular to the length of the pipeline.



An approximation to the flow velocity can be reached by calculating the mean velocity of the displaced water volume flowing out in the area below the pipe. The volume of water that has to escape below the pipe per time unit is zero below the centre of the pipeline and increases towards the edges of the pipe, with an equal flow on each side of the centreline. Anticipating a constant downwards velocity of the pipe, the flow as a function of the distance from the centreline is given by:

$$Q = v_p x$$

where Q is the flow capacity per unit length, v_p is the velocity of the pipeline and x is the distance from the centreline. The area the flow has to escape through is both a function of the distance from the centreline and the distance from the centre of the pipe to the seabed, the latter of which changes over time. The area is given by:

$$A = h + R\left(1 - \sqrt{1 - \left(\frac{x}{R}\right)^2}\right)$$

where A is the area, h is the distance between the pipeline and the seabed and R is the radius of the pipeline. The mean velocity of the current below the pipeline when it is near the seabed can now be found from:

$$v = \frac{v_p x}{h + R\left(1 - \sqrt{1 - \left(\frac{x}{R}\right)^2}\right)}$$

In Figure 4.1 and Figure 4.2 the horizontal flow velocity below the pipeline in different distances of the pipeline from the seabed is shown for a constant vertical pipeline velocity of 5 cm/s and 0.1 cm/s.

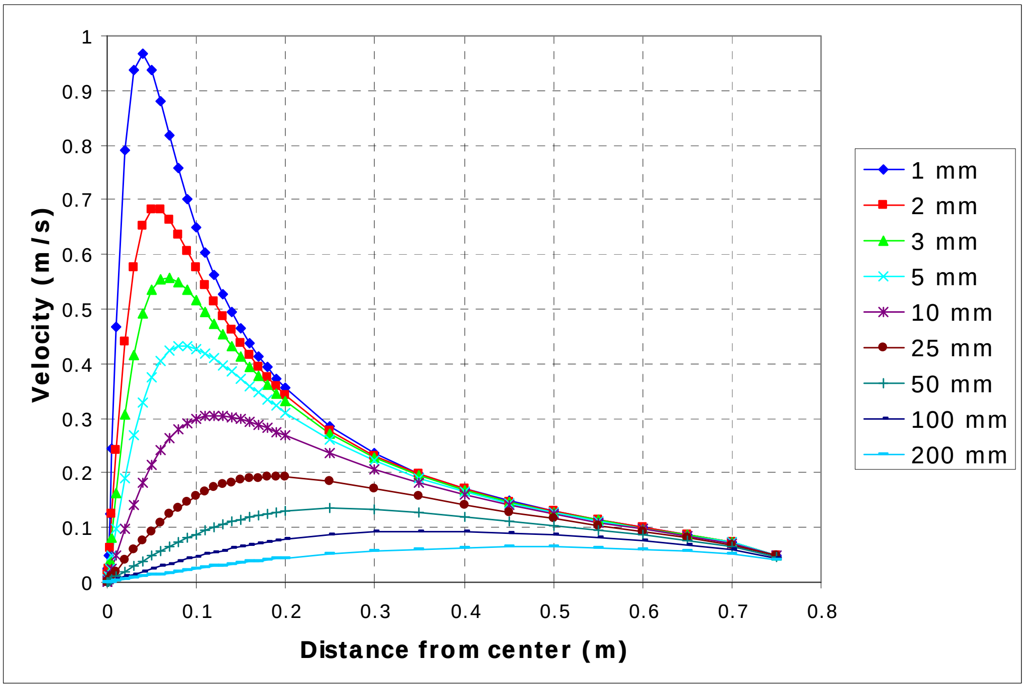


Figure 4.1: Horizontal flow velocity below the pipeline for a vertical pipeline velocity of 5 cm/s. This is valid for the lay barge under rough conditions.

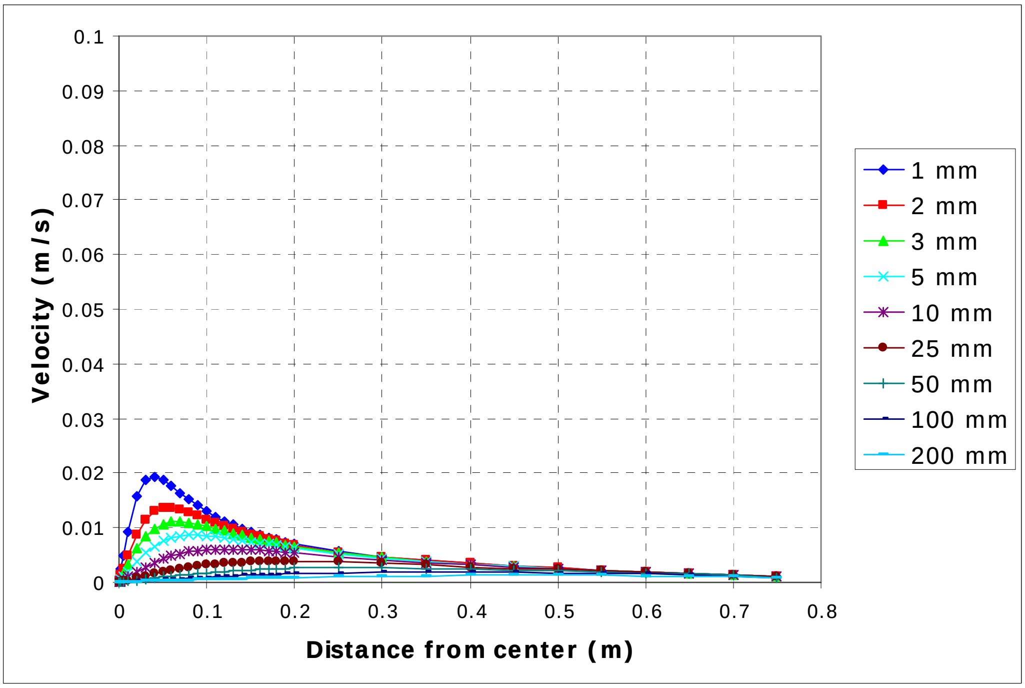


Figure 4.2: Horizontal flow velocity below the pipeline for a vertical pipeline velocity of 0.1 cm/s. This is valid for the lay barge under calm conditions.

The flow velocity must be related to a criterion for movement of the seabed particles. The critical Shields parameter defines the limit where the particles will start to move and has been found experimentally for a large number of different values of bottom shear stress, particle density and grain size. The critical Shields parameter for non-cohesive sediment is defined by, /1/:

$$\theta_c = \frac{U_{fc}^2}{(s-1)gd}$$

where θ_c is the critical Shields parameter, U_{fc} is the critical friction velocity, s is the relative density, g is the acceleration of gravity and d is the grain size. If the Shields parameter and thereby the friction velocity is larger than the critical parameter then the particles will start to move.

For a horizontal sand bed the critical Shields parameter is found to be nearly constant in the order of 0.05, /1/. However, for cohesive sediments the critical Shields parameter is found to be much larger than this, /2/, and therefore there is a minimum value of the critical friction velocity which is found for a grain size around 0.2 mm (corresponding to fine sand), /2/:

$$U_{fc} = \sqrt{\theta_c (s-1) g d} = 1.3 cm/s$$

In /2/ some empirical values of critical friction velocity from natural rivers are given for different sediments. For sandy clay a value of 1.9 cm/s is given and for mud (colloidal), 3.5 cm/s.

To relate the average current velocity to the friction velocity a velocity profile has to be estimated. An exact velocity profile for the unsteady flow considered is not trivial to derive, but an approximation can be found using the velocity profile for steady turbulent boundary layers:

$$\frac{u}{U_f} = 2.5 \times \ln\left(\frac{z}{k_N / 30}\right)$$

where u is the velocity at the level z above the seabed, U_f is the friction velocity at the seabed and k_N is the bottom roughness, which is of the size of the mean grain diameter. From the velocity profile the velocity at a distance of $2k_N$ is seen to be

$$u = 10 \times U_f$$

The velocity will increase further away from the seabed, but because of the very narrow flow area below the pipeline, when the maximum flow velocities are reached, the above relation will be used between the mean flow velocity and the friction velocity in the following.

For fine sand the mean velocity that will start erosion of the seabed is on basis of the above analysis 13 cm/s.

An empirically derived value for the minimum velocity, where erosion of the seabed starts, can be found in /5/ and /6/ to 10 cm/s.

Compared to the calculated flow velocities below the pipeline it is seen that in rough conditions having a fall velocity of the pipeline of 5 cm/s there will be erosion when the centre of the pipeline is between 0 and 5 cm from the seabed in the area approximately 40 cm on each side of the centreline of the pipeline, using 13 cm/s as the critical velocity. Using a critical velocity of 10 cm/s there will be erosion when the centre of the pipeline is between 0 and 8 cm from the seabed in the area approximately 55 cm on each side of the centreline of the pipeline. Having a fall velocity of the pipeline of 0.1 cm/s there will be no erosion, even using the lowest value of the critical velocity.

Because of the narrow space between the pipeline and the seabed, the transported sediment must mainly be carried as bed-load transport and deposited in the area still below the pipeline where the friction velocity at the seabed decreases. The deposition will of course create larger flow velocities in the deposition areas which will expand the area in which the sediment transport occurs, especially if the pipeline moves up and down during the layout process. However, the sediment transport will still only occur where there is narrow space between the seabed and the bottom of the pipeline. So even if the movement of the pipeline due to waves creates turbulence that will suspend a small fraction of the transported sediment, it can only be within some centimetres of the seabed and will therefore be deposited in the close vicinity of the pipeline.

4.2 Upwards flow generated from increased pore pressure

When the pipeline hits the seabed, the weight of the pipeline will be transferred to the seabed sediment. Anticipating that the pipeline will not sink into the seabed material, the sediment will be compressed according to the elastic characteristics of the sediment, increasing the pore pressure of the sediment. The increased pore pressure will release a small amount of pore water, generating a flow of pore water in the seabed material directed upwards to the water column. This flow may cause some of the sediment at the seabed to be suspended in the water column.

To analyse the process a model for the flow in the seabed material using a conceptual groundwater model has been set up. In the model a two-dimensional section perpendicular to the pipeline is considered. An area of 15 m on each side of the pipeline and 10 m in depth is described in a 1 x 1 m grid. At the seabed a constant pressure is used as boundary. The other boundaries are considered impermeable.

The increased pressure on the seabed is calculated by considering a 1 m section of the pipeline. The volume of this section is 1.77 m3, giving a total weight of the section of 2,900 kg assuming a pipeline density of 1,800 kg/m3, which is a conservative estimate of the density from maximum wall thickness. The pressure from the pipe can be found from:

$$P = \frac{V(\rho_p - \rho_w)g}{A}$$

where P is the pressure, V is the volume, ρ_p is the density of the pipeline, ρ_w is the density of water, g is gravity and A is the area at which the pipeline influences the pressure at the seabed.

The area at which the pipeline increases the pressure at the seabed is set equal to the half-cell size of the model, i.e., 0.5 m, but is used for calculating the pressure in the entire column below the pipeline.

This gives an increased pressure below the pipe of approximately 200 hPa corresponding to a 2 m water column. The pressure increase is assumed to be transferred to the pore pressure even though some of the pressure will be absorbed as tension between the sediment grains. The pressure is assumed to be transferred to the pore water instantaneously.

As a worst-case scenario, hydraulic parameters for a highly permeable sand aquifer are used as input parameters for the model, cf. Table 4.1.

Parameter	Value
Hydraulic conductivity	1 x 10^{-3} m/s
Storage coefficient	5 x 10^{-5}

Table 4.1: Hydraulic parameters

The size of the suspension of bottom material can be estimated by anticipating that the kinetic energy of the sediment flow 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. This approach assumes that it is non-cohesive seabed material and that there is no energy loss from shear stress and friction between the water and the grains.

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

$$m_{sus} = \frac{\frac{1}{2} m_w v^2}{gh\left(1 - \frac{\rho_w}{\rho_s}\right)}$$

where m_{sus} is the mass of sediment grains (without the water content), m_w is the total mass of flowing water, v is the velocity of the pore water, g is gravity, h is the height to which the sediment is raised in the water column, ρ_w is the density of water and ρ_s is the density of the sediment grains.

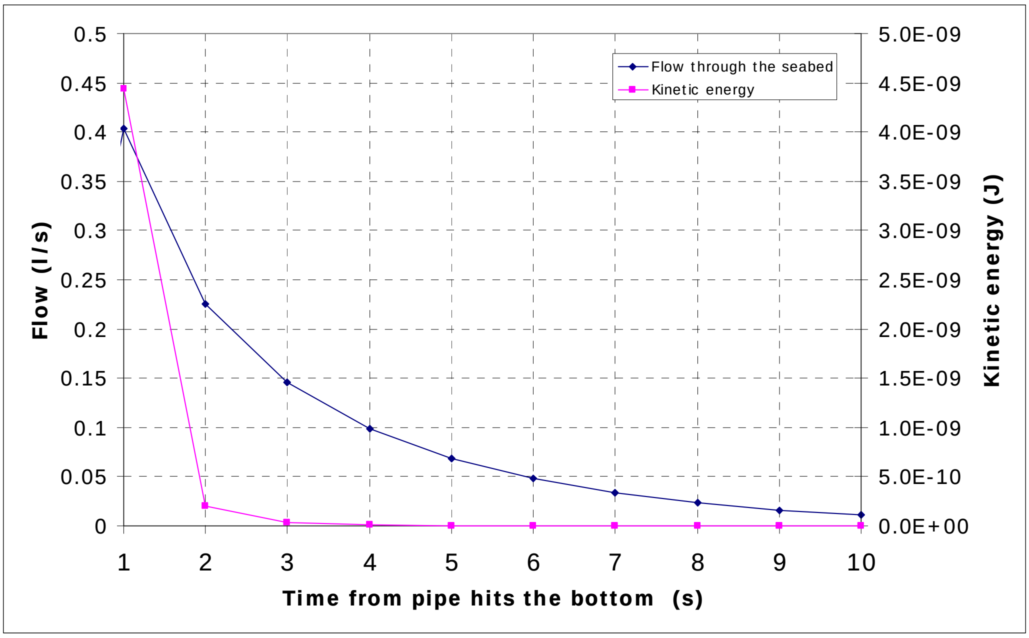


Figure 4.3: Flow and kinetic energy

By applying increased pressure in the column below the pipeline the flow through the seabed has been calculated dynamically by the groundwater model. The corresponding kinetic energy of the water flowing though the seabed has been calculated on basis of the flow results.

The calculated flow through the seabed and the corresponding kinetic energy is shown in Figure 4.3. The total water volume released from the seabed is calculated to be approximately 1 litre per metre of the pipeline, and the kinetic energy of the flow is calculated to be 4.7 x 10^{-9} J per metre.

Table 4.2 shows the mass of sediment that can be suspended at different levels above the seabed.It is assumed that the sediment is distributed uniformly over the depth.

Height of suspension (cm)	Mass of suspended sediment (mg) – sand
1	< 1
10	<< 1
100	<< 1

Table 4.2: Calculated suspension of sediment per metre of pipeline

From Table 4.2 it is seen that the suspension of sediment from this process is negligible.

4.3 Upwards flow generated in soft sediments

The example above assumes the seabed sediment is so firm that the pipeline will not sink into the seabed. However, in some parts of the Baltic Sea the upper metres of the seabed sediment are dominated by very soft clay with limited carrying capacity and water content above the liquid limit, /3/. In these areas the physical behaviour of the sediment will be more like a viscous substance and the pipeline may sink into the seabed, displacing the sediment, which will flow to the sides and upwards as the pipe sinks down.

The pipeline would probably sink into the seabed very slowly because the viscosity of the seabed material must be assumed to be decades above the viscosity of water.

To quantify the maximum possible suspension caused by the process, a simple model assuming that the pipeline creates a flow of sediment with the same velocity as the pipeline when it sinks into the seabed is used.

The size of the suspension of bottom material can be estimated by anticipating that the kinetic energy of the sediment flow is transferred to potential energy of suspended sediment, as described in the section above. Because the sediment will mainly flow horizontally it is only a part of the kinetic energy that is directed upwards and is able to create a suspension of sediment. In the following, 10% of the kinetic energy is assumed to create suspension of sediment.

A situation where the pipeline hits the seabed with a high velocity, i.e. in a situation with wave-induced vertical movement of the pipeline, is considered. By using the concept described in Section 3 to evaluate the movement of the pipeline, the section of the pipeline that is influenced by the movement can be estimated. During one excursion, the touchdown point will move 12 m in front of and 12 m behind the average location of the touchdown point. In all, a section of 24 m is influenced. With an average movement of the lay barge of 3 km/day, the time a point on the seabed is influenced by the wave-induced movement can be estimated to 24/3000 days = 11 min. During this time the pipeline will hit the seabed approximately 70 times by assuming a wave period of 10 seconds.

The above description of pipeline installation assumes that the pipeline at rest is lying on the seabed during the wave-induced movement and the touchdown point moves forwards and backwards. In the following example, a situation where the pipeline is able to sink some distance into the seabed is considered. This means compared with the above that the actual depth at which the pipeline is at rest is slightly greater than the water depth. A 1 m section of the pipeline is considered in the following. Assuming that the resistance in the seabed material is no larger than in the water, the pipeline will move up and down in the sediment during the time period when the section is influenced by the wave-induced movement.

The largest volume of sediment that can be moved each time the pipeline moves down is estimated by anticipating that the pipeline sinks into the seabed with the highest velocity, i.e. 5 cm/s, during the time of the excursion. Using a wave period of

10 seconds the downwards movement will last for approximately five seconds (assuming linear waves), giving a 25 cm downwards excursion. With a pipeline volume of 1.77 m3/m, the average volume of sediment displaced during one excursion is 0.24 m3/m.

Assuming that the sediment will have the same velocity as the pipeline, the kinetic energy of the sediment can be estimated.

The kinetic energy of the moving sediment in one excursion is by the above assumptions 0.27 J at a 1 m section of the pipeline.

Based on this, the total released kinetic energy during 70 excursions is 19 J, giving the resulting possible suspension of sediment using the assumption of 10% used for suspension as shown in Table 4.3 for different levels above the seabed within which the sediment is distributed, assuming a uniform concentration profile.

Height of suspension (cm)	Mass of suspended sediment (kg) – soft clay
1	60
10	6
100	0.6

Table 4.3: Calculated suspension of sediment per metre of pipeline

The amount of suspension in sediment is seen to be much greater than in a situation where the seabed is rigid. However, it is still small amounts of sediment that would be suspended, and only at the vicinity of the seabed. From the above calculation, it can be seen that, with the made assumptions, the suspension over a 1 km stretch can be up to 600 kg 1 m above the seabed, 6,000 kg 10 cm above the seabed and 60,000 kg 1 cm above the seabed. However, for suspension heights just 1 – 10 cm above the seabed the movement of sediment can be seen as a mudflow near the seabed rather than suspended sediment in the water column.

5. Conclusion

The pipeline is laid from a barge with a low horizontal speed, giving an even lower vertical velocity of the pipeline that decreases towards zero at the seabed. Only very small amounts of sediment have been found to be suspended during pipeline installation directly on the seabed for worst-case scenarios. The suspension has been calculated without taking friction into account, which will further reduce the possible suspension of sediment during pipeline layout. It can be concluded that suspension caused by pipeline installation is negligible in the case of firm sediment. In the case of very soft clay sediments where the pipeline is able to sink down, some small suspension of sediment near the bottom can be expected. However, compared with suspension during trenching and rock-dumping, this is negligible.

6. References

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