CHAPTER 226

Half-Life Period of Sedimentation - Model Test on a Scale 1:1

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Abstract

In the framework of an extension plan for a large cargo handling berth, it is necessary for one alternative to build an artificial approach. The bottom of this dredged channel will lie approx. 6 m under the natural seabed level. The run of the axis is unfavourable since it is perpendicular to strong tidal currents which reach 2 m/s in the 705 cycles per year. In a model test, re-sedimentation for a volume of approx. 210,000 m^3 was observed indirectly in the standard procedure with repeated measurements by echo sounding as well as with a direct method using a sand-surface-meter combined with wind, tide, current and wave measurements.

History

The most important entrepot for energy in the Federal Republic of Germany is Wilhelmshaven. Its recent but nevertheless highly varied history began late - in 1853 - when a large Prussian naval port was established, the tradition of which continues up to the present time. In the year 1889, King William I of Prussia named the town after himself, i.e. Wilhelmshaven. Starting in 1957, the settlement of various oil companies and chemical concerns with their respective cargo handling installations including four large piers (Fig. 1) was influenced by the favourable natural conditions along the shore, especially water depth. Although no maintenance dredging had been carried out for a period of more than 10 years (1944 - 1957), a navigational depth of 11 m was still encountered. This can be attributed to the natural scouring force of the tidal current.

With the constantly increasing size of oil tankers, the navigation channel has been further deepened over several stages. The present target depth is between 18.5 and 20.0 m below chart datum so that fully laden tankers of 250,000 D.W.T. can put in at Wilhelmshaven under the right tidal conditions. The deep water region of

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Wilhelmshaven is located on the Jade which is a large arm of the sea on the coastline on the south side of the North Sea. The bay (555 km^2) has very little fresh water flow, so most of the deterministic and stochastic parts of the energy in the regime are transfered only from the North Sea into the Jade which differs from the situation in a typical river estuary.

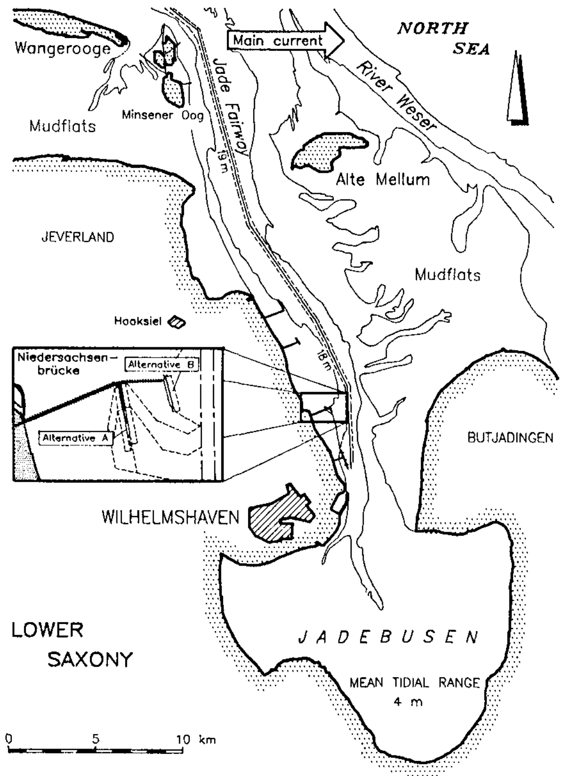

Figure 1. The Jade with the fairway and four cargo handling berths

Situation and Methods

The regular semi-diurnal tidal range of close to 4 m reaches its maximum all along the German coast. During one tide, approx. 1 billion cubic meters of salt water move into and out of the Jade, 705 times a year. As a rough estimate, approx. 6 million cubic meters of solid material is carried into the regime during this period. This process in combination with the artificial water depth in the fairway is the reason for recurrent dredging activities of up to 10 million cubit meters per year. In the framework of a current extension plan for a large cargo handling berth (called

"Niedersachsenbrücke") on the inner part of the Jade, there are two alternatives. For one alternative it is necessary to build an artificial approach between the berth and the navigation channel (see Fig. 1). The bottom of this dredged channel with a length of approx. 1 km will lie 6 - 7 m below the natural seabed level (12 - 13 m). The run of the axis is unfavourable since it is perpendicular to strong tidal currents which reach 2 m/s and have a high suspension load.

In view of this background, the simple but also substantial question for a cost-benefit calculation is the amount of maintenance dredging that will be needed to equal the sedimentation rate for a defined span of time in such an underwater depression. Also, because of the increasing importance of environmental aspects concerning the disposal of the material, a most critical point in design is the estimation of quantity in maintenance dredging which can be summarized in the question: *How many m³ should be expected per year?*
Since we intuitively feel that the quantity of maintenance dredging will be related to the channel geometry, a prediction of this maintenance dredging will be necessary in order to complete the evaluation of particular alternatives. On the other hand, the prediction of such sedimentation is an extremely complex problem in itself and the classical sediment transport formulas will not be sufficient for predicting the bottom changes in a marine approach channel. In the example (Fig. 2), the deepening from 9.8 to 11.3 m is the reason for an increased shoaling rate of more than 200 %. However, a few untested methodologies for predicting channel shoaling do exist (SPM/I 1984, Galvin 1983, Bijker, Massie 1986).

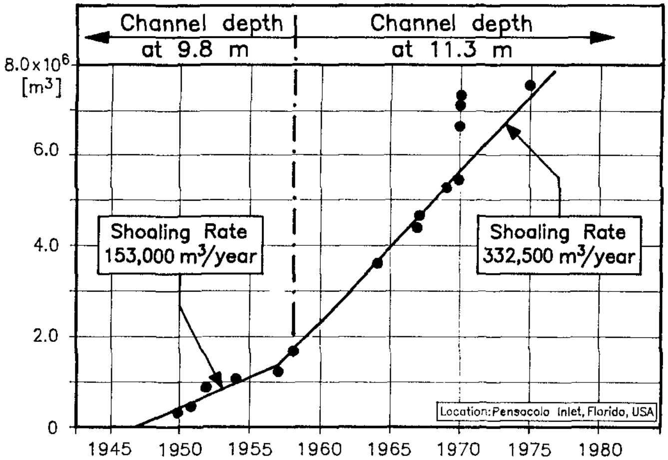

Figure 2. Mass dredging curve (from CERC, 1984)

The quality of powerful numerical models for such sophisticated questions are at a research level and far from adequate for forecasting engineering practice. The condition is much the same for simple models, for example, combining suspension

load and sink velocity. To meet the requirements, valid data on the physical processes in the specific area sill be needed as input for calibration and checkup.
For the assessment of the different alternatives, the potential of sedimentation in the area is important. For the evaluation of these values, different methods are used (Basinski, 1989):

- Contained water samples
- Pumping samples in vertical profiles
- Turbidity profiles
- Stationary traps on the bottom
- Sand gauges (Sand-Surface-Meter)
- **In-situ model test on a scale 1:1**

One important result during regular tides was the quantity of sediment in suspension which was measured at approx. 15 t per hour and unit meter or about 100,000 t in the channel during the flood and ebb tide current. The local flow and wavefield has a rather high influence on this transport capacity.

Results of the Model Test in a Scale 1 : 1

In the framework of the investigation, a model test was set up at this stage since there was an independent requirement for a volume of approx. 210,000 m^3 of sand on land. After checking the physical parameters of the sandy soil (d_{50} = 0.25 mm and d_{60}/d_{10} = 2.3), a large underwater depression was dredged in the center of the designed approach with a maximum depth of approx. 22 m below chart datum (Fig. 3).

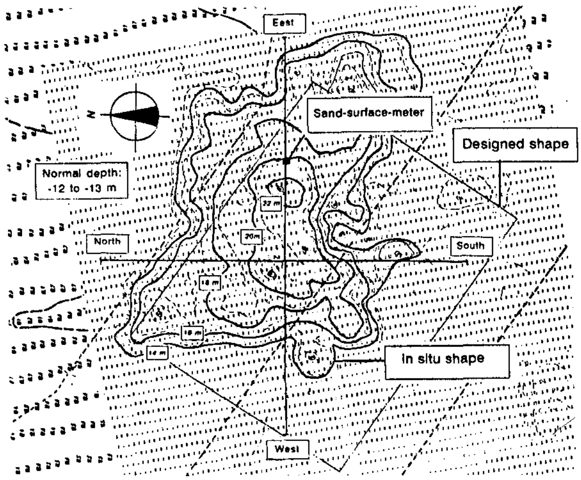

Figure 3. Test dredging - in situ shape in the initial stage

Subsequently, re-sedimentation was observed indirectly by the standard procedure with repeated measuring by echo sounding as well as with a direct method using a so-called Sand-Surface-Meter (SSM) in the deep center area of the dredged structure over a two month period (Manzenrieder, Witte 1986, Erlingsson 1990). Re-sedimentation and/or rearrangement within the structure started already during the dredging activities. The results of repeated precise echo sounding give information on the development in quantity over a period of one year. In table 1, all numerical values are listed.

Table 1: Re-sedimentation in an artificial depression
([a] Days after the end of dredging)

Sounding No.	Sounding Date	Duration of Sedimentaion[a]	Max. Depth	Artificial Volume
0	31.01.1991	-	13,0 m	0 %
1	09.02.1991	2	22,5 m	100 %
2	12.02.1991	5	22,3 m	98 %
3	21.02.1991	14	22,0 m	95 %
4	05.03.1991	26	21,8 m	93 %
5	04.04.1991	56	20,9 m	83 %
6	03.05.1991	85	20,2 m	76 %
7	05.06.1991	118	19,2 m	65 %
8	10.07.1991	153	18,2 m	55 %
9	11.09.1991	216	17,8 m	51 %
10*	13.11.1991	279	17,8 m	51 %
11*	16.01.1992	343	16,9 m	41 %

* Uncertainty in the echo sounding execution

In Fig. 4, the development of the bottom shape which was taken by echo sounding is given up to sounding No. 9. The right-angled axis is shown in Fig. 3. The tidal currents cross the depression in the North-South direction with velocities up to 2 m/s. In Fig. 5, the remaining value at the end of the dredging period is assigned to time. The analysis of the information from the soundings indicate an average sedimentation rate of 2.4 cm per day.

To get more detailed information on the processes in the dredged structure, a Sand-Surface-Meter (SSM) was installed in the center area of the depression. Modern instruments such as this were used in addition to the classical areal sounding method which of course only give continuous data on the relative bottom position for a single point but during all sea conditions (Manzenrieder, Snippe 1991). The necessity for this instrument is shown in Fig. 6.

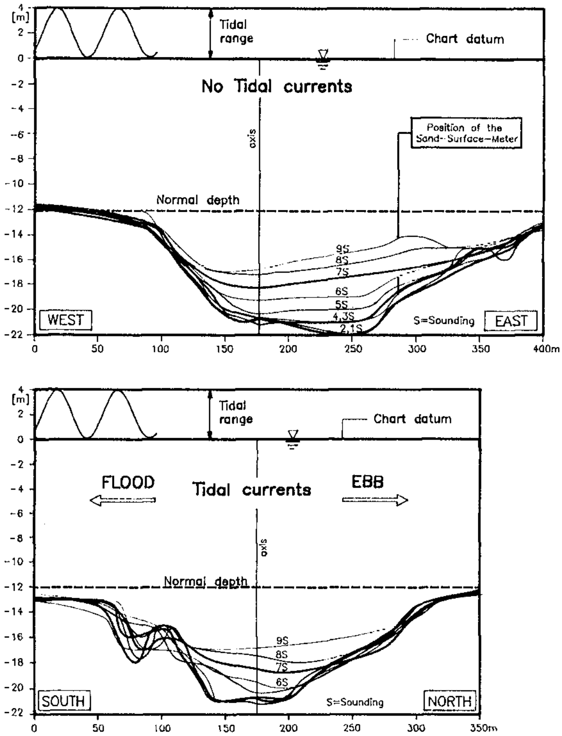

Figure 4. Cross-sections in the center area

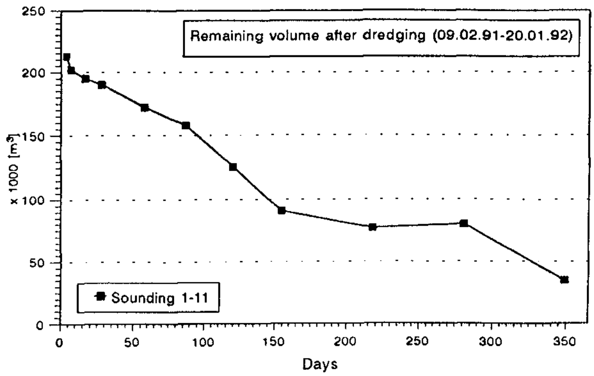

Figure 5. Re-sedimentation in the depression

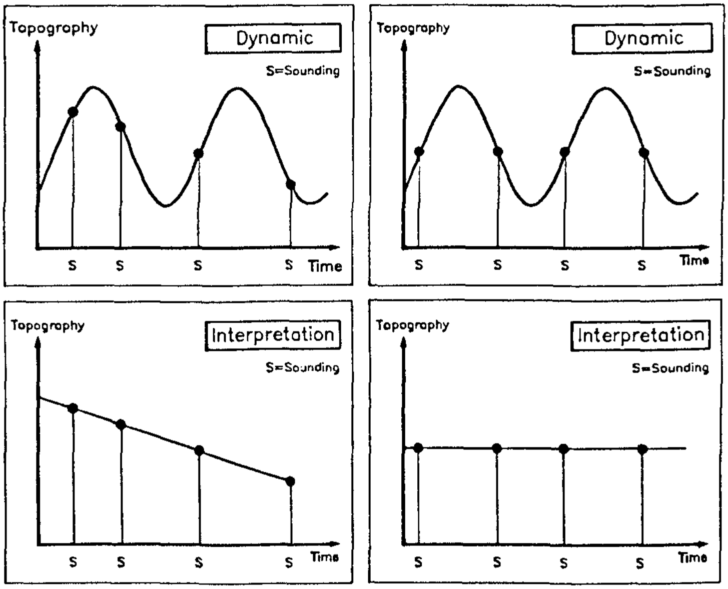

Figure 6. Uncertainty in the Interpretation of Soundings

In Fig. 7, a sketch of such specific measurements under water should give an impression how such devices give a sort of microscopical view of the complex processes. The newest generation of these instruments is also qualified to observe transport processes above the bottom (bed load). In its application for observing sedimentation in the introduced dredging contour, the constant time interval was 60 minutes, the range of measuring 1.5 m and it was supported by diver inspections. One system exchange was necessary. For a period of approx. two months, digital information was collected continuously and the original results are displayed in Fig. 8. Sedimentation in the first two weeks was almost linear. After that, some discontinuous steps were measured. Between the following linear gradients, two periods without significant sedimentation are conspicuous. The average sedimentation rate over the two month period was calculated at 4.1 cm/day.

Combined with wind, tide, current and wave measurements, direct observation of the boundary layer especially provided deeper insights(Fig. 9). During a strong gale of up to Bft No. 8, the sedimentation rate increased to 18 cm/day. After the event there was a period without significant sedimentation. This remarkable process during a higher energy level in the watercolumn is an indication for the sedimentation potential on the bottom which is mobilized during such periods in the form of a suspended charge. Afterwards, the bottom in general showed an over-proportional absorption capacity before reaching standard conditions of "normal" sedimentation.

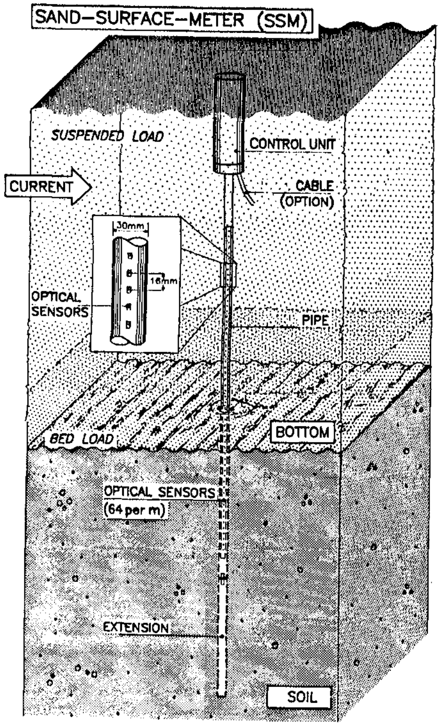

Figure 7. Field Measurements with a Sand-Surface-Meter (schematic)

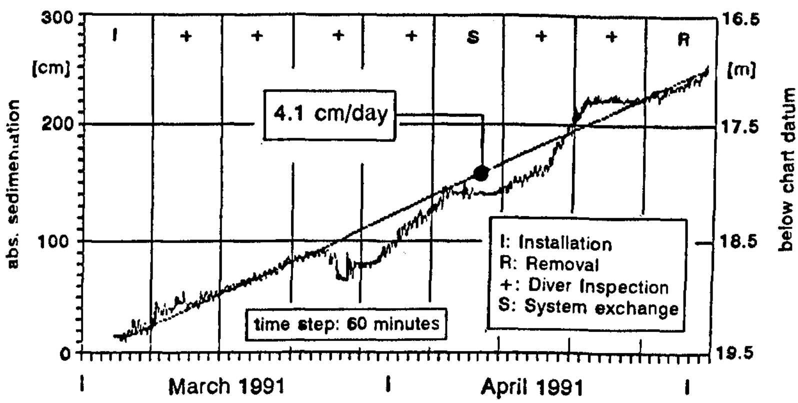

Figure 8. Sedimentation in the Center Area (Continuous Observation with Sand-Surface-Meter)

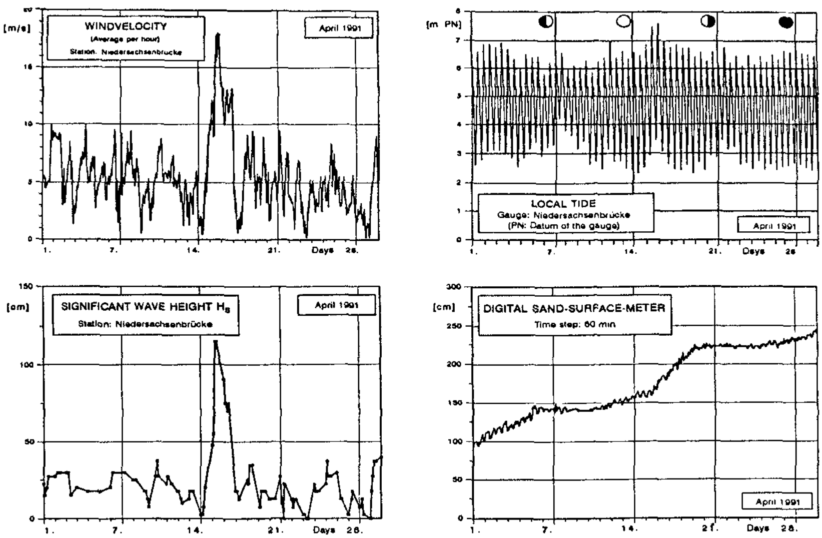

Figure 9. Assignment for the Sedimentation Processes

Theoretical Approach

All present observations and the results of investigations on erosion of beach nourishments (Führböter 1974, 1991) support a non-linear nature for the material on the balance sheet. Führböter based his approach on the assumption that the local, long term wave climate is constant and mentioned the same exponential law known in nuclear physics using the definition of a half-life period. In relation to the erosion processes close to the surface, sedimentation in artificial underwater structures (e.g. channels) is influenced by water depth. Especially due to this hydraulic filter in deeper regions, the assumption of a more constant local transport regime could be supported. Taking a sediment-laden current crossing a channel into consideration, the abrupt change in hydraulic conditions will cause time dependent morphological changes in the channel. The supposed function over time is given schematically in Fig. 10.

Under the assumptions stated above for an analytical expression of the sedimentation processes, the dredged volume V below the natural horizon at time t is the initial information. In the next time step Δt, this artificial volume will be reduced due to sedimentation by an amount of ΔV.

$$-\frac{\Delta V}{\Delta t} = \lambda V \text{ or } \Delta V = -\lambda V \cdot \Delta t \qquad (1)$$

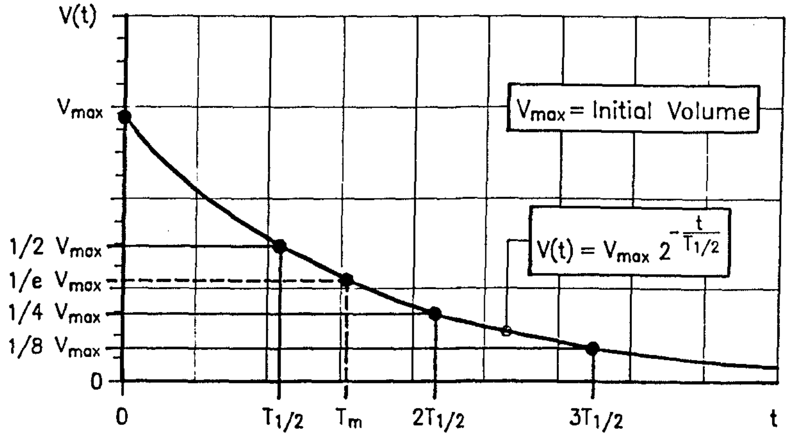

Figure 10. Sedimentation in an Artificial Underwater Depression (schematic)

The negative sign deals with the sedimentation tendency. Very little knowledge is available on the range of sedimentation parameter λ. One step for the evaluation of this value is a part of this paper.

In equation (1), the assumption is included that volume V is constant during time-step Δt, so that the relation will be stabilized with increasing time between each sample (sounding). The transition for the gradient of the secant $\Delta V, \Delta t$ to the differential form (gradient of the tangent) follows at

$$dV = -\lambda V\,dt \quad \text{or} \quad \frac{dV}{V} = -\lambda dt \tag{2}$$

After the integration of eq. 2, the description for the sedimentation during any time is given. The integral for the time 0 with an initial volume $V(0) = V_{max}$ to time t with the remaining volume V(t) has the form

$$\int_{V_{max}}^{V(t)} \frac{dV(t)}{V(t)} = -\lambda \int_0^t dt \tag{3}$$

with the solution

$$\ln V(t) - \ln V_{max} = -\lambda t \quad \text{or} \quad \frac{V(t)}{V_{max}} = e^{-\lambda t} \tag{4}$$

The sedimentation coefficient λ will be written in the following form

$$\lambda = -\frac{\ln V(t) - \ln V_{max}}{t} \tag{5}$$

the derivative trend with respect to time is

$$V(t) = V_{max}\, e^{-\lambda t} \qquad (6)$$

Equation 6 is in relation to the basic equation for radioactive decay, so this could be used as a basic sedimentation equation in artificial depressions. The evaluation of sedimentation factor λ as the central input parameter is based on experimental investigations. In contrast with nuclear physics, no universal indications are available. The lack of qualified instrumentation for such measurements is only one reason for this limitation. Following the analogy for the sedimentation factor λ, the half-life period $T_{1/2}$ could be used with the definition:

> The half-life period $T_{1/2}$ of an artificial depression is the time for a 50% reduction of the (dredged) volume due to re-sedimentation.

When describing the relation between the half-life period $T_{1/2}$ and the sedimentation factor λ the remaining volume in the depression $V(t_1)$ at the time t_1 could be used

$$V(t_1) = V_{max}\, e^{-\lambda t_1} \qquad (7)$$

After expiration of the time $T_{1/2}$, that means the total time $t_1 + T_{1/2}$ bisected by the artificial volume

$$\tfrac{1}{2}\, V(t_1) = V_{max}\, e^{-\lambda(t_1 + T_{1/2})} \qquad (8)$$

Using both equations above, it follows that

$$e^{-\lambda t_1} = 2\, e^{-\lambda(t_1 + T_{1/2})} \qquad (9)$$

and

$$-\lambda t_1 = \ln 2 - \lambda(t_1 + T_{1/2}) \qquad (10)$$

or

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0{,}693}{\lambda} \qquad (11)$$

The half-life period $T_{1/2}$ is consequently a characteristic value which is independent from the previous sedimentation period. This is important when applying in practical applications. It is common to use the half-life period in a mathematically more simple form

$$e^{-\frac{t\ln 2}{T_{1/2}}} = 2^{-\frac{t}{T_{1/2}}} \tag{12}$$

with the relation for λ the volume V(t) is indicated

$$V(t) = V_{max} \cdot e^{-\frac{\ln 2}{T_{1/2}}t} \tag{13}$$

or

$$V(t) = V_{max} \cdot 2^{-\frac{t}{T_{1/2}}} \tag{14}$$

Another important characteristic value for the behaviour of an artificial structure underneath a stable bottom is the average lifetime T_m.
By adjusting the assessed values, the average stability of the dredged volume defined as the area between the axis V(t), t and the function of sedimentation (eq. 5), it follows that

$$V(t) = V_{max}\, e^{-\lambda t}$$

and from this

$$T_m = \frac{1}{V_{max}} \int_0^\infty V_{max}\, e^{-\lambda t}\, dt = \int_0^\infty e^{-\lambda t}\, dt = \left| -\tfrac{1}{\lambda} e^{-\lambda t} \right|_0^\infty = \tfrac{1}{\lambda} \tag{15}$$

With this, the average stability T_m for the structure result from the reciprocal value of the sedimentation factor λ. A more subordinated value in this context could be the remaining volume after expiration of the average lifetime:

$$V(T_m) = V_{max}\, e^{-\lambda T_m} = V_{max}\, e^{-1} = \tfrac{1}{e}\, Vmax \tag{16}$$

For practical applications, for example maintenance dredging, it is important to predict the time for determining re-sedimentation. Using the results above, this time could be calculated with the knowledge of the sedimentation factor λ respectively the half-life period $T_{1/2}$. If the required part of sedimentation is expressed with the factor p as percentage of the initial volume, it follows from eq. 6

$$V(t_p) = V_{max}\, e^{-\lambda t_p}$$

with

$$V(t_p) = \frac{p}{100} V_{max} \tag{17}$$

or

$$\frac{p}{100} V_{max} = V_{max} e^{-\lambda t_p} \tag{18}$$

and from this

$$\ln \frac{p}{100} = - \lambda t_p \tag{19}$$

the required time t_p as a function of λ

$$t_p = - \ln \frac{p}{100} \frac{1}{\lambda} \tag{20}$$

or as a function of the half-live period $T_{1/2}$

$$t_p = - \ln \frac{p}{100} \frac{T_{1/2}}{\ln 2} \tag{21}$$

Application

Using the information gained by repeated soundings which were a part of the observations made during re-sedimentation in the introduced test dredging, a first application of the theoretical considerations was made. The results are concentrated in table 2.
From equation 5, the respective sediment factor λ is calculated (column 4)

$$\lambda = - \frac{\ln V(t) - \ln V_{max}}{t}$$

After the solution for λ, the half-life period is known as $T_{1/2}$ from equation 11. Furthermore, the average lifetime T_m of the structure is one result. As one example in the last column shows, time t_p describes the span of time in which the artificial structure is refilled up to p = 10 % of the initial volume. The initial dredging volume V_{max} was approx. 210,000 m^3 and the total observation time approx. one year (341 days).

Conclusion

Test dredging in connection with the design of an artificial approach and various observations provided the following main results:

- In general, re-sedimentation of the approx. 210,000 m^3 artificial underwater depression took on an exponential form over a one year period.
- Differences between sedimentation in a crater-shaped underwater structure and a channel as a negative line source exist but are highly influenced by the axis orientation in relation to the efficient current system.
- Based on the repeated measurements with echo sounding, the average sedimentation rate was calculated at 2.4 cm per day. To maintain a constant

depth as substantial as the one demanded for operating conditions, this value which in total equals approx. 9 m of sedimentation per year is important.

Table 2: Test dredging in the artificial approach - Niedersachsenbrücke -

V	ln V	t	λ	$T_{1/2}$	T_m	t_p (p=10%)
[m³]	-	[days]	[1/days]	[days]	[days]	[days]
212,650	12.267	0	-	-	-	-
201,900	12.216	3	0.017	41	59	136
194,530	12.178	12	0.0074	94	135	312
190,140	12.156	24	0.0046	151	217	502
171,780	12.054	54	0.0039	178	256	591
157,900	11.97	83	0,0036	193	278	641
126,200	11.746	116	0.0045	154	222	512
90,760	11.416	151	0.0058	120	172	399
76,530	11.245	214	0.0048	144	208	478
80,390*	11.295	269	0.0036	193	278	641
35,410*	10.475	314	0.0053	131	189	435
Mean value			0.0061	140	201	465
Weighted Average			0.0046	152	220	508

* Uncertainty in the echo sounding execution

- Due to the basic physical limitations of the echo sounding principle on such sloped bottoms, a precise determination of the underwater geometry is not possible (slope error, etc.). Normally, the slope given is too small.
- The average of the directly measured sedimentation rate over a two month period in the center area was determined at 4.1 cm/day by a linear gradient. Using this higher value, 15 m of sedimentation in one year must be calculated for dredging and disposal.
- During a strong gale of up to Bft No. 8, the sedimentation rate increased to 18 cm/day. After the event, there was a period without significant sedimentation which seemed remarkable.
- With respect to the area of the approach (~ 450,000 m²), the definition of the actual sedimentation rate will influence the choice of alternatives.
- In theory, the mathematical consequence is that continuous maintenance dredging in the horizon of the nautical depth will minimize the total quantity. Due to meteorological and hydrological as well as practical aspects, limitations must be considered.

- The need for repeated maintenance dredging in artificial coastal areas is determined by the number of stochastic meteorological events.
- When predicting sedimentation rates over a longer period, it is remarkable that single meteorological events no not necessarily increase the average value. This could be of importance for numerical simulation as well.
- After two years, no indication of the artificial depression could be determined by echo sounding.

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