Rewert Wurpts and Patrick Torn

15 Years Experience with Fluid Mud: Definition of the Nautical Bottom with Rheological Parameters

Rewert Wurpts

Rewert W. Wurpts graduated in 1967 as a hydraulic engineer from the Technical University of Hannover, Germany. He then joined the dredging division of Ph. Holzmann, working on dredging projects worldwide.
In 1986 he went to work at the State Government of Niedersachsen, where he is responsible for R&D, specifically for dredging and surveying for the port of Emden. He has been President of the Central Dredging Association since 2000.

Patrick Torn

Patrick Torn graduated as a Civil Engineer from Bremen University of Applied Sciences in 1991. He then became a Technical Assistant in Labor für Wasserbau (Maritime Construction) at Bremen University of Applied Sciences, until 1994 when he was appointed to his present position as Scientific Assistant in the Institute of Hydraulic Engineering at the University.

Abstract

In the contract of 1954 between the German Federal Waterways Administration and the newly formed Water and Land Federation Emden-Riepe, the Federation relinquished agricultural land within the Emden-Riepe Lowland to the Association of Port Operators to accommodate sediment from the Port of Emden which at that time was still classified as mud. This policy continued through the 1980s. During the privatisation of maintenance dredging in 1986, first concepts to reduce the, at that time, considerable amounts of sediment were drawn up. The costs of maintaining the nautical depths in the Port of Emden were significant, and in 1990 the provincial government issued an order to stop flushing in Riepe. Since 1990 the layer in the Outer Harbour of Emden has been kept in its natural balance in situ, by using a dredging system that was specially developed in Emden. The question of whether the technique developed in Emden can be adapted for other harbours with a higher sand content has triggered a series of tests which are also discussed.

Introduction

Since 1954 wetlands within the Emden-Riepe Lowland were used to accommodate sediment from the Port of Emden which at that time was still classified as mud. In the following years the Emden Port Operators demanded an average area of approx. 200 ha of lowland per year. On average about 120 ha of this area were flushed, dried, drained and recultivated. Some 80 ha were returned to agricultural use after about five years. Until the end of the 1980s the average amount of flushed mud was 4.0 million m^3/a. About 1.5 million m^3 were taken from the Inner Harbour and about 2.5 million m^3 were taken from the Outer Harbour of Emden.

In the course of privatisation of maintenance dredging in 1986, first concepts to reduce the, at that time, considerable amounts of sediment were drawn up. Although the flushed areas were ecologically valuable lowlands, the costs of maintaining the nautical depths in the Port of Emden were significant. Therefore, in 1990, the provincial government issued an order to stop flushing in Riepe.

ORIGIN OF THE EMDEN SEDIMENT

The location of the area to be maintained can be seen in Figure 1. By investigating the microbial strain (fresh water formations) in the sediment it became evident that the upper course of the River Ems is the source of the suspended particles in the harbour [6]. Like the River Weser [1], the Ems transports a significant sand fraction of about 20% as a result of the high tractive force on the Ems bottom. In contrast, the tractive force on the bottom of the Emden Outer Harbour is negligible; a measurable sand influx into the Outer Harbour could not be traced up to now.

The River Ems carries an average suspended load of about 900 mg/l in the water column. During certain tidal phases the concentration can reach up to 1600 mg/l and more. Because of the density difference this suspended material has the nature of quickly entering so-called calm zones. Situated on the Lower Ems, the Harbour of Emden is the largest retention zone for these formations of suspended material; since the turbid zone of the River Ems has moved upstream towards Papenburg in the past years, the harbours of Papenburg, Weener, Leer and Jemgum have also become affected by sediments from the tidal Ems. By this, one can presume that the adjoining harbours are also part of the Ems equilibrium.

These interrelations are especially clear in the Outer Harbour of Emden (Figure 2). The top horizon is recorded with a high frequency (210 kHz) and the bottom one with a low frequency (15 kHz). The green line represents the required nautical depth for Emden at 8.5 m below chart datum. The volume between these two frequencies is about 418 000 m^3 and has hardly changed since it was first measured in 1989.

This layer of suspended material is in a state of equilibrium. Quantities excavated from this layer by dredging operations returned after a few days time. Both echo horizons move closer together towards the Ems because high current forces prevent the formation of a detectable layer of the finest particles. The detectable distance between the horizons, which is about 3 metres in the Outer Harbour, decreases to 60 cm in the Ems. This shows the impact of the current and tide effects in the Ems. Within the Outer Harbour, tide and current have no effect; here it is solely the density effect that influences the suspended material.

This explains the rapid refilling after dredging operations because the cut dredged into the suspended material was directly replenished by the density effect – the local material deficit was balanced with re-flow from the surrounding area. This leads to the conclusion that there is a constant exchange between the fluid mud layer in the Outer Harbour and the sediment pool in the Ems.

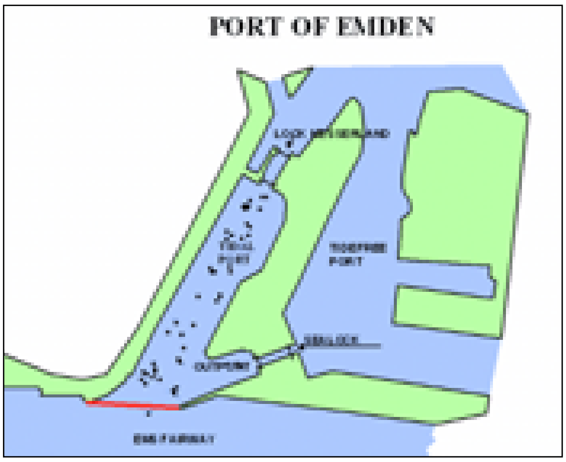


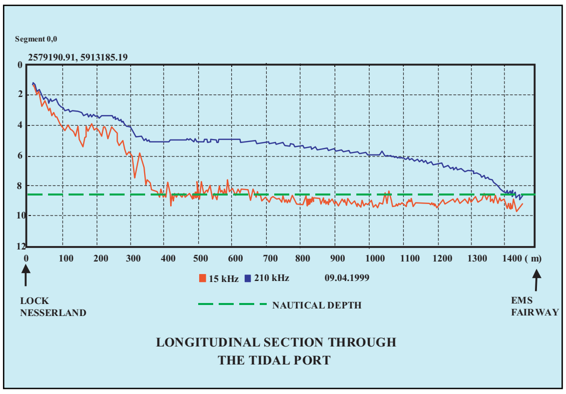
Figure 1. Location of area to be maintained at the Port of Emden.

The magnitude of the layer in the Outer Harbour results from the equilibrium between the influx of suspended material during flood and the discharge of suspended material into the Ems near the bottom during ebb. Since 1990 the layer in the Outer Harbour of Emden has been kept in its natural balance in situ and, owing to its outstanding parameter characteristics, it is still navigable by using a dredging system that was specially developed in Emden.

The yield point

Leaving such a layer in situ does not permit a definition of the nautical depth with conventional criteria. For this reason the definition of the nautical depth was made depending on only one parameter: The yield point. Even a physical density up to 1.25 t/m^3 allows ships to manoeuvre without difficulty in the Harbour of Emden. Only the firm clay layer on the bottom has values

Figure 2. Longitudinal section through the Outer Harbour of Emden demonstrates the interrelations amongst adjoining harbours.



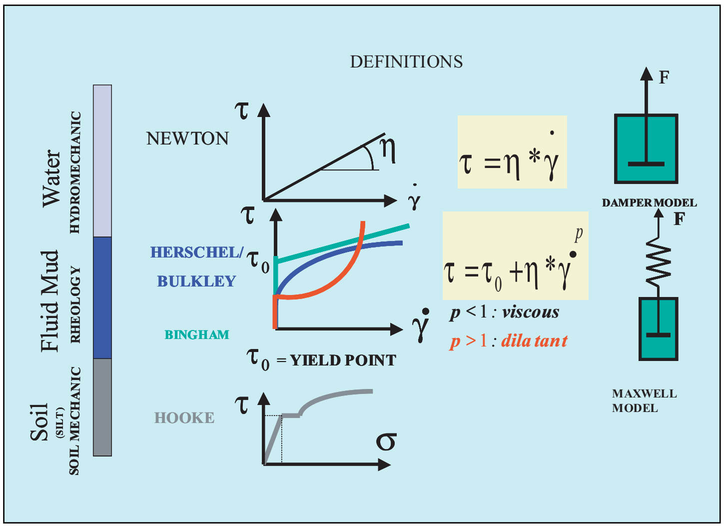


Figure 3. Definitions of fluid mud, comparing the laws of Newton, Herschell/Bulkley, Bingham and Hooks.

between 1.28 and 1.36 t/m^3 and is therefore not navigable.

By 1994 the dredging strategy developed for the Harbour of Emden focussed on not extracting from these in-situ layers but keeping the equilibrium and even increasing the density of suspended material in all harbour basins in order to prevent a density gradient from the Ems to the harbour thus decreasing the density current towards the harbour.

For this reason about 418 000 m^3 and 192 300 m^3 in the Outer Harbours as well as 584 000 m^3 in the New Inner Harbour, that is in total 1.196 mil. m^3, are kept as an in-situ layer on purpose in order to maintain the equilibrium. This is the volume of suspended material between the 210 kHz and 15 kHz echo. This formation of suspended material consists of pure fluid mud.

DEFINITION OF FLUID MUD

Fluid mud clearly belongs to the Hyperconcentrated Flows (HF) formation. These are high concentrated suspensions of solid material together with a low density that have only a slight tendency to consolidate. The close spatial contact between the single particles is filled with microbial slime. Therefore these particles can stay in suspension over a long period of time because this slime is significantly lighter than clear water and hence provides buoyancy. These microbial slimes are generated by the attached bacteria; a fluid-mud layer must therefore be in an aerobic state so that the bacterial cultures have the continuing ability to produce this slime. Although the generated slime fills the gaps between the particles, it significantly reduces the internal friction and causes them to stay in suspension longer. Holding out and "treating" a fluid-mud layer primarily means conserving a microbial budget, i.e. to ensure the production of slime. For this reason it is very important that the aerobic state is kept up. Fluid mud is a pre-stage to mud or silt with which it must not be confused.

This slime has another advantage: The low friction between the particles allows for seagoing vessels to pass through because fluid mud consists mainly of water. Both the high rate of cross-linking of the solid particles and the low shear stress resisting binding strength of the bacterial slime are the reason for the flow capability of fluid mud [6, 12]. As paradoxical as it may sound, it just this high concentration of solid particles that prevents the formation of extensive sediment accumulations that become impassable for ships; it is the high biogenous fraction that delays or even prevents these solid particles from settling.

Flow behaviour

After a five-month stop of all activity in the fluid-mud layer in the Outer Harbour, there was no significant change in the flow behaviour; as soon the aerobic substance has been decomposed and a long-term compression takes place then there is talk of a biogenous consolidation. In practice, the transition from fluid mud to mud is defined by the change from an aerobic to an anaerobic state where large amounts of gas are produced, primarily methane. How older mud formations can be revived to a certain extent and brought into suspension will be presented below.

The most important parameter while dealing with these fluid-mud layers technically in respect of the navigability is the organic content which is 22% on average in the tidal Ems as well as in the Harbour of Emden. The existing insitu layers are naturally not to be classified in terms of Newton, neither can they be regarded as soil for which the laws of soil mechanics apply. The insitu layers mentioned above are rather to be regarded as classic fluid-mud formations.
The relevant differences are shown in Figure 3.

FLOW CAPABILITY

The good flow capability of the fluid mud on the bottom of the Outer Harbour of Emden was discovered for the first time when the cutter suction dredger pumped the slurries that were not considered navigable (approx. 0.5 mil. m^3 per year until 2001) onto the disposal. It has turned out, that fluid mud flows to deeper areas, provided the flow conditions are laminar with a constant gradient towards the deeper areas as well as a suction device over there. Regarding the constantly high output performance of the cutter, it must be assumed that the fluid mud flows towards the point of excavation with a remarkable velocity. On the basis of this experience, an underwater suction system was installed in the

Harbour of Leer towards which the fluid mud will flow along both of the 1000 m long harbour basins at a gradient of 1:1000.

This phenomenon is known from dam operation [18]. A density current of this kind is also a laminar flow of stratified liquids. This flow process is significantly influenced by density differences between the layers and the so-called density current on the bottom is induced by higher density of the bottom layer than that of the liquid above it. This problem plays a particular role when it comes to taking countermeasures against silting up of reservoirs [16, 17], as well as in tide influenced river estuaries. The current conditions for steady density currents can be reliably described if one presumes that the density liquids are homogenous and the current is laminar. It can be taken from literature that a gradient of 0.0001 and less is sufficient to permit a density current. It is known from the Sanmenxia Reservoir in China that slurries can travel an amazing distance of over 40 km at a bottom gradient of 1:10000 [4].

PHYSICAL PRECONDITIONS

From a hydrological point of view, suspended load, as a pre-stage of fluid mud, stands between the law of Newton (100% classical fluid) and the law of Hooke (classical soil mechanics) as shown in Figure 3. Fluid mud cannot be rated as a liquid nor can it be classed as soil; it represents a *medium*, consisting of a fluid (represented by the damper in the Maxwell model) and of an elastic mud (spring in the Maxwell model). The yield point that has to be overcome is described by the energy in a spring (elastic part) while the attached damper model describes the following Newtonian behaviour (viscous part). Therefore fluid mud represents a viscoelastic material.

To get an estimation for a yield curve for the Emden fluid-mud, yield curves with increasing concentration were generated in long test series carried out with a rheometer. The results are shown in Figure 4 [8]. This approach resembles the Herschel-Bulkley curve power approach after Ostwald-de Waele (Figure 3) [10]. Tests carried out by Dasch [9] with koaline suspensions and Thomas [10] with limestone as well as Migniot [2] with reservoir sediments gave similar results. Unlike Bingham fluids, these are curves with constantly changing viscosity. They are equivalent to the yield curves of Hyperconcentrated Benthic Layers (HBL) formations [5]. The gradient of the Herschel-Bulkley curve is referred to as the apparent viscosity in the respective points; it changes with each new velocity gradient.

Long-term test series prove how the Herschel-Bulkley curve diverges from the traditional Bingham behaviour

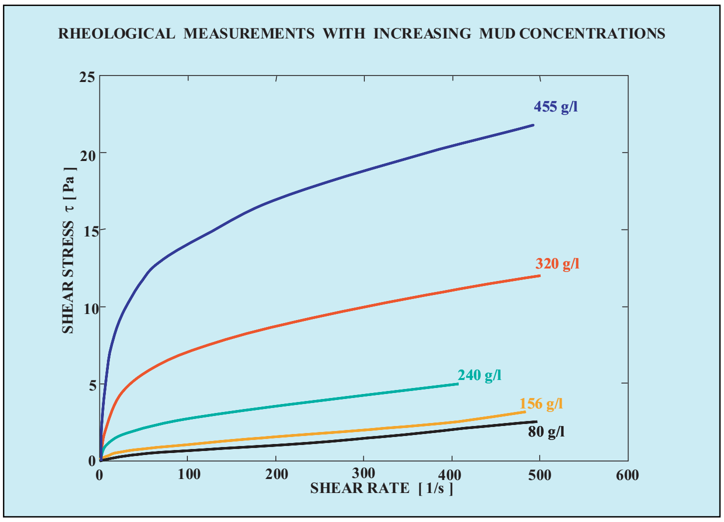


Figure 4. Rheological measurements with increasing fluid-mud concentrations.

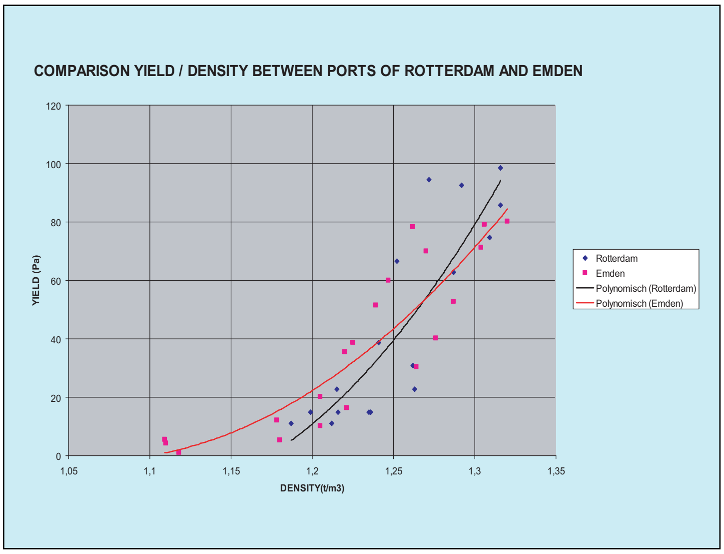


Figure 5. Range of dispersion for Yield/Density in the ports of Rotterdam and Emden.

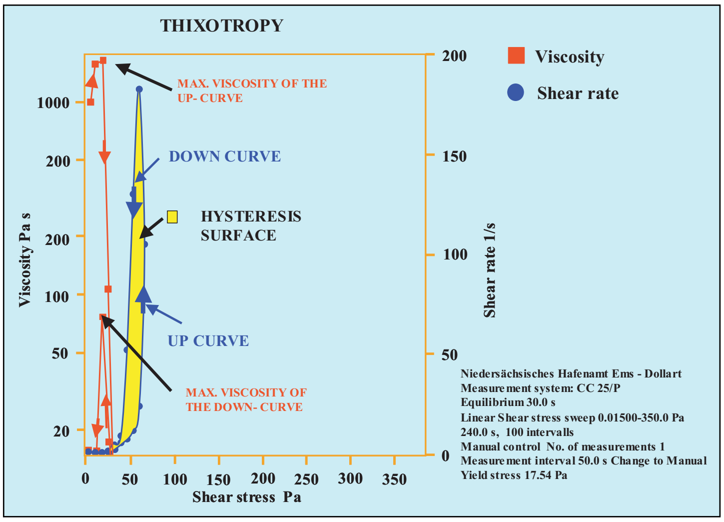


Figure 6. Typical thixotropical behaviour of a fluid mud sample.

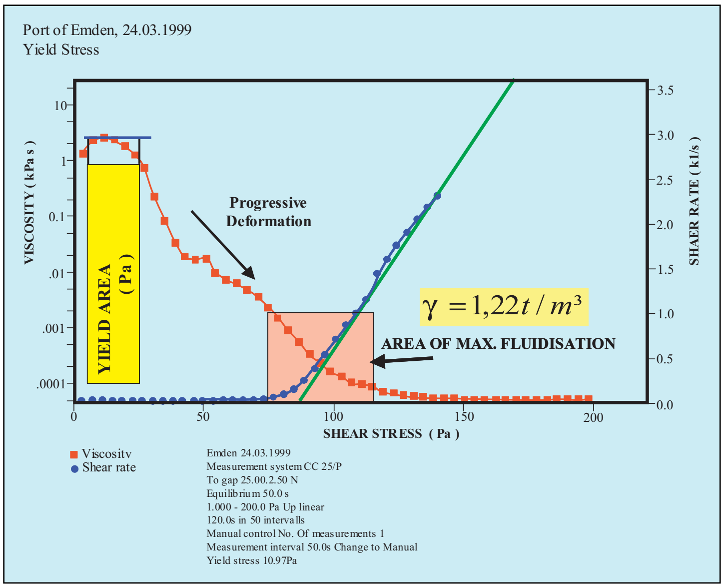


Figure 7. Yield stress at the Port of Emden, 24/03/1999.

in the region of the grid origin primarily because of the high organic content in the fluid mud. Therefore, the Herschel-Bulkley shear equation consists of the sum of a yield point τ_0 and an additional exponential approach after Ostwald-de Waele. If the exponent is p<1, then it is a case of shear thinning i.e. the viscosity decreases. This applies to fluid-mud. If the exponent is p>1 the mass is shear thickening i.e. the viscosity increases with a rising velocity gradient [13]. However, the viscosity, as the first derivative of the Herschel-Bulkley curve, changes constantly in both cases.

THE NAUTICAL BOTTOM

Because of the matching Herschel-Bulkley curve with the fluid mud in Emden, the yield point 100 Pa was chosen to define the nautical bottom; assessing the depth using viscosities was eliminated, because viscosity is subject to permanent change under increasing shear rates. This apparent viscosity therefore can never be a parameter for determination of a nautical depth.

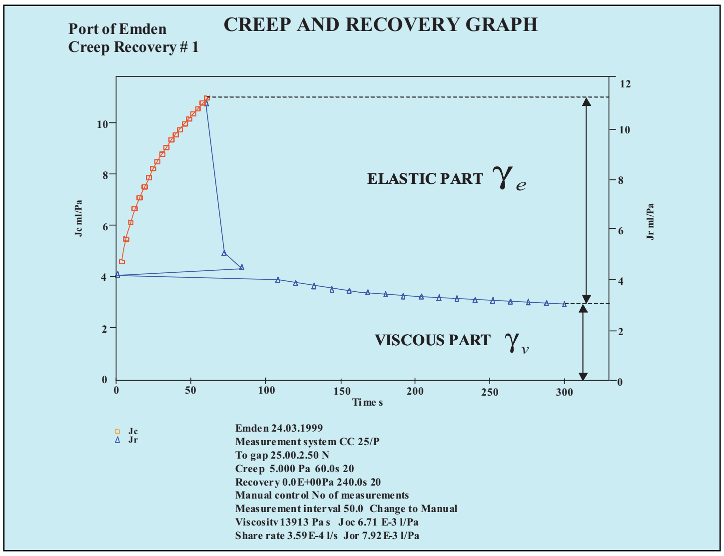


Figure 8. Creep-Recovery Curve at the Port of Emden.

Also the parameter density is only a static dimension anyway, that cannot be taken into consideration as a parameter for ship movement. Accordingly, it is not suitable to determine the resistance against a moving ship. Measurements have shown that the critical density of 1.2 t/m^3 defined by PIANC is exceeded considerably in most cases. The density dimension in the Port of Rotterdam is similar (Figure 5); they are closer to 1.3 t/m^3 than to 1.2 t/m^3.

THIXOTROPY

By definition, a thixotropic substance must not only fluidise depending on the shear duration, it must also regain its firmness after a rest period typical for that substance. Examples for thixotropic substances are paints, cosmetics, pastes and fluid mud. Figure 6 proves the typical thixotropical behaviour of a fluid-mud sample: The yield point of the upward curve is at 17.54 Pa with a maximum viscosity at approx. 1600 Pa*s. The downward curve, however, shows a viscosity of only 80 Pa*s. A new upward curve would reach even less yield and viscosity values. Apart from the shear thinning, it is also the thixotropical behaviour that significantly facilitates the treatment of substances. The fact that the downward curve does not end at the origin of the upward curve demonstrates the decrease of viscosity.

Owing to this decrease of viscosity over time, less effort is needed for, e.g. pumping or traversing through the substance, than would be required for the first "force attack". This explains the phenomenon that is known amongst practitioners that fluid-mud formations can be transported in a pipe over greater distances than clear water with relatively little effort. This is because the mud is homogenous and flows under strictly laminar conditions. This again is influenced by the slime resulting from to the high organic content accounting for the low inner friction.

Shear thinning and thixotropy are completely different rheological properties that must not be confused. Classic fluid mud has both of these rheological properties, as in all other shear thinning substances the viscosity values decrease with increasing shear rates. Contrary to these, the viscosity of shear thickening substances increases with rising shear rates. Examples for these substances are, e.g. sand-water mixtures such as current ripples with an extremely high sand content. Their shear behaviour in the rheometrical experiment shows that the viscosity rises significantly with increasing velocity gradient. Formations of this kind are therefore real obstructions for ship movement that have to be removed. In contrast, the density currents, as long as they have a high-suspended load, as in the case of fluid mud, belong clearly to the visco-elastic fluids.

Preserving a high grade of organic content within a fluid-mud layer demonstrates the following advantages when minimising dredging effort:

1. The more thixotropic properties increase the higher the organic content in the fluid mud.
2. In the region of low velocity gradients (where dredging takes place) the flow process does not behave like a Bingham fluid, instead it is like a Herschel-Bulkley fluid with highly variable viscosity.
3. A high organic content results in a lower yield point. The yield point of an anorganic sample with a concentration of 4.0 mass-% is at about 1000 Pa, whereas the yield point of an organic sample with the same concentration lies only at about 30 Pa [8].
4. Thus a high organic content also leads to a lower viscosity: When using the same samples the viscosity η decreases from 0.3 kPa*s (anorganic) to 0.08 kPa*s (organic) [8].

CONTROLLING THE NAUTICAL DEPTH

Depth survey in Emden is done with 210 kHz and 15 kHz parallel. For port operations the 15 kHz echo is therefore still the most important frequency, but it too does not accurately describe the existence of the nautical bottom. The 33 kHz echo is definitely not suitable as it lies "on the safe side" compared to the 15 kHz echo; the difference between these two frequencies in the Outer Harbour in Emden is about 0.4 m, which causes 20% higher costs.

Long-lasting test series gave a correspondence between the 15 kHz echo and the yield point at 70 Pa, which defines the nautical bottom in Emden. As a result of still very low yield points, the navigability was increased to 100 Pa to be measured with 12 kHz only, as from 2005.

A different measuring technique called rheometry has to be applied when handling rheological parameters for determining the nautical depth:

1 Shearing is only allowed when conditions are *laminar.*
2 The examined substance should be from *homogenous* substance. In this connection it is worth mentioning that, when judging the navigability, it is not necessary for the sample to be undisturbed. Results from long test series with disturbed and undisturbed samples taken from the fluid-mud layer have shown that the difference is about 5%, which is negligible.

These two basic conditions are applicable for fluid mud.

The Yield/Stress Curve

Important for the navigability is solely the resistance that is put up against the ship's movement. The resistance of "muddy" sediment is generally shear stress dependant. It shows variable viscosities and cannot be determined with a "static" material property such as density.
For this reason the shear strength of dredged sediment has to be determined rheometrically in order to distinguish between non-navigable mud and fluid mud which can still be navigable.

An example for the evaluation principle of such a yield curve for fluid mud from the Emden Harbour is explained in Figure 7: The blue curve shows the shear stress depending on the different shear rates. The red viscosity curve is the first derivation of the blue curve and shows its variable viscosity values. The viscosity reaches is maximum of 1400 Pa*s already at a shear stress value of 11 Pa. Starting from this point the viscosity decreases, i.e. it liquefies.

If the well-known PIANC threshold of 1.2 t/m^3 were applied for this sample, it would not pass this criterion for navigability.

Up to now about 90% of the samples taken from the Harbour of Emden to check navigability have had densities of more than 1.22 t/m^3 and yield points that were under 30 Pa. The dredging method that is applied here has clearly confirmed that the material is navigable up to a yield point of 70 Pa [12]. After further test series, the yield point was raised to 100 Pa in 2005.

Measuring methods, like tuning fork systems that use constant respectively fixed viscosity values, do not give clear values and therefore make it difficult to assess the navigability, because the viscosity according to the Herschel-Bulkley curve remains variable and has its maximum around the yield point at very low shear rates [11].

The Creep/Recovery Test

The creep test is a quick and simple method to make statements about the visco-elastic properties. This test differentiates exactly between the viscous and elastic fraction of the substance. When shear stress is applied to fluid mud it shows properties of elastic as well as viscous deformation (Figure 8). Retraction takes place around the elastic fraction. The viscous deformation γ_v remains.

This difference is very important when judging a dredging strategy: The γ_v -fraction – the viscous fraction of retraction – gives important information about the percentage of a Newtonian fluid in a fluid-mud layer. This fraction does not have to be dredged and removed. The elastic fraction γ_e , as can be seen in the creep/

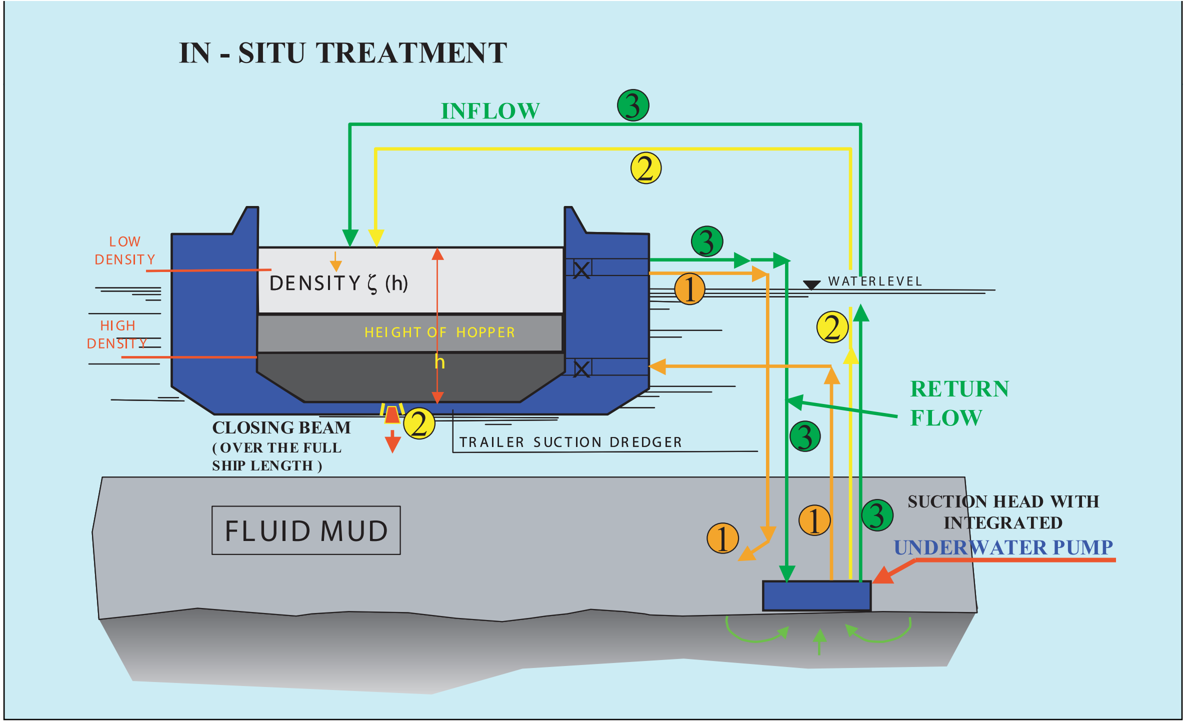


Figure 9. Three possibilities of in situ treatment.

recovery graph, is the fraction of retraction that can build up a resistance when it comes into contact with a ship. The Newtonian fraction in the Maxwell model (damper fraction) (Figure 3) remains irreversibly shifted after load, i.e. it does not retract. Retraction is only caused by the energy fraction in the spring load and this fraction only has to be dredged or conditioned or removed.

Just like the null-viscosity this dimension is a material property and expresses the yield property of a substance. The higher the rate of yield is the more fluid mud can be deformed under a certain load. The creep test is therefore a simple and quick method to get statements about the visco-elastic properties, split up exactly into viscous (water) and elastic fractions (fluid mud) by percentage.

In practice "conditioning" the elastic fraction of the layer – the percentage has been determined graphically – by applying a special dredging technique that will be explained later has proven successful. Since the beginning of consequent evaluation of these measurements the running time of the hopper suction dredger was reduced from 2000 hours/year (1998) to 900 hours/year (2004). In the same period the ratio between the "treated" mass in the hold of the dredge and the in situ mass has also reduced from 3.49 (1998) to 1.44 (2004).

Dredging Technique

The present dredging contract was awarded first in 1988 and extended step by step after negotiation up to end of June 2008 as a flat-rate with wage and material rise-and-fall clause. The following equipment is on site:

- 1 hopper dredger with a hold of 1150 m^3;
- 1 cutter-suction dredger with 1400 hp pump capacity;
- 1 bed leveller.

At the beginning of the in-1990-developed dredging strategy the cutter-suction dredger had 90% of the work of flushing onto land while the remaining 10% was done by the self-propelled hopper dredger that brought the sediment to the cutter-suction dredger. The bed leveller was used in corners of the harbour that are inaccessible for the larger machines.

Meanwhile until 2004 90% of dredging was carried out by the hopper dredger and from 2002 until July 2003 it was 100%; since 2002 no sediment has been flushed onto the fields of Wybelsum. This complies with the aim of a 100% in situ conditioning of sediment without deposition on land.

In the past 15 years numerous modifications were carried out on the hopper dredger. Especially beneficial was the installation of an underwater pump fitted onto the suction head. This has the advantage that the pump is directly loaded with the water column above and not with a water/fluid mud mixture as is the case with inboard pumps mounted at the water line.

With the underwater pump and degassing methane gas, it is possible to reach a higher density in the hopper than the density at the suction head.

Figure 9 shows how three different extraction methods can be implemented with such a mechanical concept:

- The hold is filled from the bottom with fluid mud (line ①). The underwater pump presses the mixture into the ship at the bottom of the hold; the overflow takes place over the upper edge of the hold.
  The mixture circulates back through a closed piping system and exits just above the suction head. Ultrasonic measurements have shown that ventilated and re-circulated formations remain in suspension above the suction head [11]; the in situ density is thus reduced. This method causes no turbidity.
- The sediment is pumped to the surface of the sediment in the hold; this material is disposed via a transom latch over the whole length of the hold.

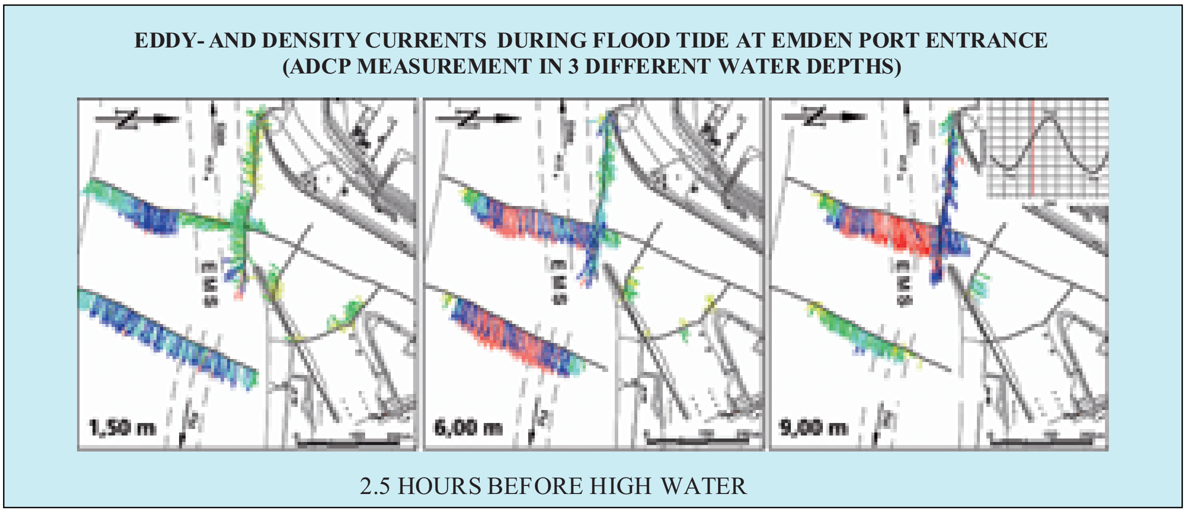


Figure 10. Eddy and density currents during the flood phase in the Outer Harbour of Emden, 10/06/2002.

Doing this makes it possible to allot controlled amounts of sediment onto the bottom depending on how much turbidity is generated. Dumping is not possible. This method is used mainly in the shallower areas of the harbour (line ②).

- The pump fills the hold; the overflow is situated at the top of the hold and by gravity the less dense mixture flows back to the suction head (line ③). Here it is brought back into the transport process which now has a higher concentration. With this method higher concentrations can be reached in the hold. The less dense mixture is drained off at the surface by gravity and without additional pressure the water is conducted back to the suction head with its underwater pump to build up a new transport process. This way it is possible to separate fluid mud from sand that remains in the hold. During a dredging test the density of the sediment in the hold could be as high as 1.93 t/m^3 (!) compared to 1.28 t/m^3 reached with "normal" filling of the hold. However, filling takes about three hours.

The method (3) is not used in Emden as the sand content is almost zero. Methods (1) and (2) are regularly used to bring the sediment in contact with air and to improve its aerobic condition and therefore its organic content before it is put back on the bottom. Fluid mud that is collected in an area of 5 to 6 m^2 around the suction head is distributed over an area of 600 m^2 on the surface of the hold and brought into contact with air.

Oxygen consumption has not been observed by this method; methane gas was not detectable and by constantly "conditioning" respective harbour areas the fluid mud is kept as a bacterial culture friendly environment. Different tests have shown also that consolidated, not-navigable mud with 8 to 10% gas content can be made navigable with simple a re-circulation process by reducing the gas content to less than 3%.

In a "normal" sedimentation process the deeper layers are quickly cut off from the oxygen supply in the water. Larger quantities of organic material in the mud can

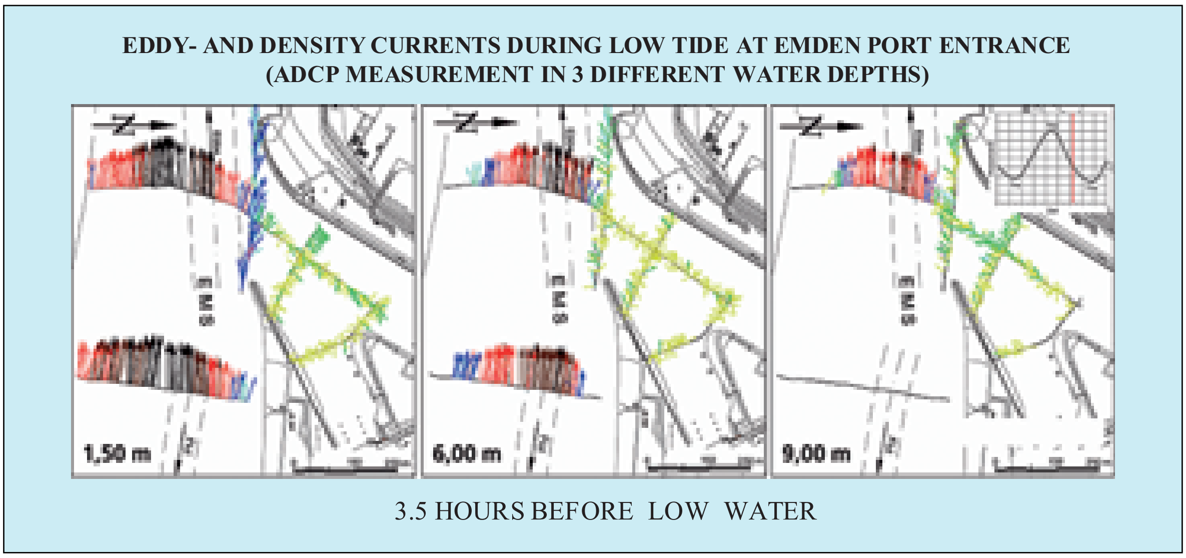


Figure 11. Eddy and Density Currents during the ebb phase in the Outer Harbour of Emden, 04/11/2002.

only be broken down partially by bacteria; biogas is produced. Reduced ferrous, manganese or sulphuric compounds give the mud a black colouring. The treatment method that is put into practice in Emden supplies the deeper layers with oxygen in regular intervals with the following positive effect on the water quality:

- Prevention of biogas; no oxygen deficit in the bottom water layers.
- Complete reduction (mineralisation) of all organic nutrients.
- Increased reduction of organic pollutants, e.g. hydrocarbon (remains of diesel fuel) and TBT.

The permanent lack of nutrients (owing to ideal conditions) leads to increased excretion of slime as well as bonding iron and manganese hydroxides, all of which have a high volume and low density. This gives a higher buoyancy.

This dredging method complies with all known environmental demands. It must not be confused with harrowing or water injection dredging. The latter works by injecting jet water into the bottom that generates a mixture which, provided there is a sufficient slope, induces a density current that moves down the slope.

In Emden no jet water is used, and thus no density current generated because a density current is not possible towards the Ems as the harbour is much deeper than the Ems. A full scale test with an injection dredge that was carried out in 1993 confirmed this: A light outward flow of suspended load towards the Ems was registered in the upper third of the water column, but at the bottom a brisk inward current of water with a high sediment load was generated, because the water injection reduced the density at the bottom.

The fluid-mud bodies in the Outer Harbours are 418 000 m^3 and 192 300 m^3, i.e. there is constantly a total of 610 300 m^3 of detectable fluid mud that varies by about ± 5000 m^3 with the tide whether or not the dredger is in action in the Outer Harbour. The total volume roughly remains constant independent of tidal variation, different river discharge, dredging activity on the Ems or opening or closing the Ems Barrier [15].

In the BMBF (German Ministry of Education and Research) project 03 KIS 019 the turbidity and current conditions between the Ems and the Harbour of Emden were investigated by the Institut für Wasserbau (IWA) of the University of Applied Sciences Bremen [14]. The results from the 10/06/2002 and 04/11/2002 will be taken as examples.

The flood measurements from the 10/06/2002 show the remarkable effect of outward current reaching as far as the Ems fairway in lesser depths while simultaneously there is an inward current in higher depths (Figure 10). During the ebb tide on the 04/11/2002 there is an inward current on the surface and an outward current on the bottom (Figure 11).

During this field campaign ADCP measurements were carried out on several days. The high-suspended load found in the Ems raise problems when measuring with high frequencies (600 kHz). Yet it was possible to verify the density currents into and out of the harbour even during high river discharge periods.

The distinct density effect in the Harbour of Emden around low water is documented in [14]. The density eddy has a clear horizontal axis and it is superimposed on the clockwise ebb current eddy with a vertical axis. Both effects raise the water exchange rate between harbour and Ems.

The reversed effect during flood tide was also recorded. The currents on the bottom are amplified by the incoming salt water from the Ems. Consequently the less salty water is transported out of the harbour in the upper water layers. ADCP measurements have shown that during various neap and spring tides on the 30/10/2002 and 05/11/2002 as well as 04/11/2002 both the in- and outward currents are approximately equal. The fluid-mud layer in the Port of Emden therefore remains in a 100% equilibrial status.

For the interpretation of the results it is irrelevant whether the hopper dredger was in action in the Outer Harbour or not. There is no sign of a continuous backflow of sediment from the Outer Harbour into the Ems.

PRACTICABILITY IN OTHER HARBOURS

The question of whether the technique developed in Emden can be adapted for other harbours with a higher sand content has triggered off a series of tests in which rheological profiles for different sand contents and grain sizes were compiled. The results are widely scattered, depending not only on the sand content, but even more on the grain size. It is however certain that if medium sand is added to pure fluid mud this mixture reacts shear thickening at an earlier stage of the shearing process, i.e. the shear stress increases with increasing velocity gradient. The measuring instrument fails with larger grain sizes because of the slit between the viscosimeter and rotation piston. From literature [2] it can be taken that shear thinning and thixotropical properties can be found up to a sand content of 30%.

The grain diameter of the sand was uniformly 250 µm and it became apparent that although the density increased the yield point remained almost unchanged up to a sand content of 30% and decreases the higher the sand content. This is a reasonable result as the silt content, which is the cause for the viscous behaviour, is very low. Measurements made in the Mississippi

Harbour in Rotterdam gave similar results. However, compared to the results from Migniot [2] they were lower by a factor of 5. The reason could be that the sand in the Mississippi Harbour is much finer than in [2].

According to the author's experience these results are of little practical use. The grain sizes of the sand fractions found in dredged sediment from the most estuaries cover a wider spectrum which makes it difficult to make statements about the rheological parameters. Practical experience has shown that a sand content of up to 10% with grain sizes between 60 and 200 µm can be accepted without worry. With higher sand contents it is recommended to filter the sand with the dredging method described above (line ③ in Figure 9) before bringing it back to the bottom.

The organic content is significantly lower when there is a higher sand content. This degrades the rheological properties, i.e. the yield point and the viscosity go up. Also the higher sand content is responsible for a significant derivation from the Herschel-Bulkley curve in the region of low shear rates. The dredging method used in Emden can very well be used in other harbours as seen in Figure 12 where the results of 103 mud samples are shown. The viscosity bandwidth is relatively low, but this is because these are the values "after" having reached the maximum viscosity (Figure 7). However, the tendency is more than clear. The yield values from 50 to 90 Pa are from Central America / Guyana (approx. 60 Pa) and Indonesia (70 to 100 Pa). The maximum sand content of these samples was 10%. The middle group contains results from IJmuiden, Vlissingen, Delfzijl, from the Ems and from different harbours along the Schelde (30 to 60 Pa). The results from Bristol, Liverpool, Rotterdam, Brunsbuettel, Harwich, Leer and Emden are scattered between 5 and 30 Pa. Especially in this zone of low yield points the values are close together [10].

The Emden method is applicable in the latter harbours and, depending on the "treatment" technique (Figure 9), also in all of the other harbours with a sand content of less than 10% in the mud. As soon sand content exceeds 10% extraction of this sand before conditioning of the remaining fluid mud is recommended (see line ③ in Figure 9).

Results and Outlook

Significant improvements were attained with this new dredging method. Judging the navigability with rheological parameters has finally led to the decision to leave the fluid mud in situ and to keep it navigable by "conditioning" it regularly.

Since 1989 The NHED has spent a total of about 400 000 Euro for hard- and software, which is relatively little compared to expensive civil works, e.g. CDW-constructions, for changing the current direction in the entrance of the Emden Harbour. It is also notable that the dredging method developed in Emden has fulfilled all the ecological demands up to this day.
Technically speaking the dredging technique in Emden should not to be regarded as injection dredging, as the fluid mud sinks to the harbour bottom by gravity rather than being pumped. Likewise this method must not be confused with harrowing. Furthermore this method has no negative consequences on the oxygen content. An oft-raised question as to whether the sediment flows back into the Ems was clarified by extensive investigations carried out by the University of Applied Sciences Bremen, Institut fuer Wasserbau [14, 15]. The constant fluid mud volume of 618 000 m^3 in the Outer Harbours clearly shows the existing balanced condition.

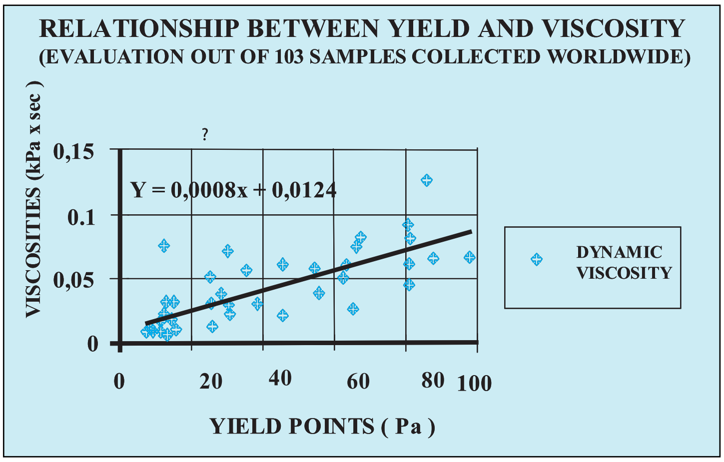


Figure 12. Range of dispersion between Yield Point and Viscosity at other harbours (103 mud samples).

Conclusions

The following conclusions can be drawn from the past 15 years of experience with fluid mud in the Harbour of Emden:

1 Exploiting the local specific equilibrium reduces the amount of dredged sediment.
2 The use of rheological parameters allows for selective dredging.
3 Common soundings with 12- 5 kHz come closest to nautical bottom defined with rheological parameters.
4 Soundings with 210 kHz are not suitable.
5. Soundings with 33 kHz are not suitable, as they would result in a much higher dredging effort.
6 The yield point is at 70 Pa that will be increased to 100 Pa.
7 Payment is lump-sum with incentive, not on a m^3 basis.
8 The method of treatment keeps the mud layer in a good ecological condition.
9 The good quality of the harbour water is ensured.

An optimal cost minimisation has been reached: 90% of the cost are hire charges for the dredging equipment. The remaining 10% are costs for labour, material and survey boat. The annual costs have decreased from € 13.5 mio in 1988 down to € 1.2 mio in 2004.

Still more effort has to be put into further minimisation (minimisation bid):

1. Taking bed samples and determining the rheological parameters in the laboratory is time consuming; a wide-area ultrasonic investigation of sediments with lines of equal yields (Isoyields) has given some promising results [11]. This will be reported in due course.
2. The aim is to reduce the present "treatment factor" between in-situ volume and hopper volume of 1.44 even more in the future with increased selective dredging.

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