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THE ART OF SCREENING: EFFECTIVENESS OF SILT SCREENS

ABSTRACT

One of the potential environmental issues associated with dredging in the marine environment is the increase of suspended sediment concentrations (SSC) by generation and dispersion of sediment plumes. This can be mitigated by source control or by the installation of containment barriers like silt screens. This article focusses on hanging silt screens and describes:

1. *The decision process for deployment of hanging silt screens:* Decisions on the necessity of environmental mitigation measures and subsequently on the viability of silt screen deployment should be made using a receptor-based approach. This starts with the identification of (ecological) receptors and related impact levels, understanding the local environment, checking compatibility with work methods and determining cost and schedule impacts.

2. *Effectiveness of hanging silt screens:* Local hydrodynamic and morphological circumstances determine the effectiveness of silt screens. Results of extensive numerical modeling tests (3D and 2DH) supported by hands-on experiences from dredging projects are used to describe the effect of hanging silt screens on the distribution of SSC in the water under different conditions. Results show that when deploying silt screens it is important to realise that silt screens are flexible curtains; they do not block the flow. Therefore suspended sediments generated at a dredging project will always pass the hanging screen vertically and/or horizontally. Silt screens can only reduce the distribution of SSC by settling if local hydrodynamic conditions are favourable.

3. *Adaptive management strategies as an alternative for silt screens:* When local conditions are not optimal for deployment of silt screens, alternative mitigation measure, such as adaptive monitoring strategies, can be used to manage SSC around dredging projects.

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Above: A silt screen being assembled at a reclamation site in Abu Dhabi. To minimise possible impacts of suspended sediments on sensitive receptors, a silt screen – a flexible barrier that diverts current flows containing increased suspended sediment concentrations – was installed.

Nomenclature

C	=	Suspended sediment concentration [kg/m^3]
C_{max}	=	Maximum C in upstream domain [kg/m^3]
C_*	=	Dimensionless C [-]
E_{in}	=	Inflow effectiveness [%]
E_{ref}	=	Reference effectiveness [%]
Fr	=	Froude number [-]
P	=	Environmental impact potential [-]
Q_{rel}	=	Relative discharge [-]
U	=	Depth-averaged flow velocity [m/s]
W_s	=	Silt screen width [m]
W_*	=	Dimensionless silt screen width [-]
g	=	Gravitational acceleration [m/s^2]
h	=	Water depth [m]
h_{rel}	=	Relative silt screen height [-]
h_s	=	Silt screen height [m]
w_s	=	Settling velocity [m/s]
z_*	=	Dimensionless z-coordinate [-]
θ	=	Velocity ratio [-]

INTRODUCTION

In the past years, dredging contractors have gained extensive experience in the realisation of marine infrastructure projects in environmentally sensitive areas and in related monitoring of the environmental effects resulting from the construction activities themselves. One of these potential environmental effects is the generation and dispersion of suspended sediments during dredging and associated marine construction activities.

In an effort to minimise possible impacts of suspended sediments on sensitive receptors such as coral reefs, project and permit requirements are increasingly asking for the implementation of specific measures such as silt screens, even though local project conditions ensure that effectiveness of deployment is questionable.

Silt screens are flexible barriers that (partly) block current flows containing increased suspended sediment concentrations (SSC). Typically, two types of silt screens are used:
– hanging silt screens that aim to promote downward migration of suspended sediments to a deeper level in the water column to allow for a shorter settling time, and
– standing silt screens which are connected to the seabed by a heavy weight (e.g., immersed pipeline) and kept in vertical position by means of surface floaters (Figure 1).

Generally, hanging silt screens are applied most often as they require less stringent mechanical restrictions and are easier to deploy and maintain.

Silt screens have been subject to research for a few decades. Mechanical and practical aspects have been treated extensively (JBF Scientific Corporation, 1978; Francingues and Palermo, 2005; Ogilvie *et al.*, 2012). Assessments of silt screen effectiveness regarding mitigation of environmental impact have also been made based on measurements in the field and laboratory experiments (Yasui *et al.*, 1999; Jin *et al.*, 2003; Vu *et al.*, 2010; Vu and Tan, 2010).

Despite all these publications, detailed and rigid conclusions on silt screen performance have not been drawn yet. For that purpose, systematic research is needed to supplement results of (incidental) stand-alone field experiments in order to relate the research outcomes to engineering practice. This article presents an integral view on the viability of silt screen application in the field based on extensive modelling results (Radermacher, 2013) in combination with hands-on field experience.

The first part of the article provides an overview of the decision-making process on silt screen deployment from an environmental and operational point of view. Subsequently, the design of reliable and effective silt screens is studied in detail based on operational trials, flume tests and numerical modelling (3D and 2DH) and supported by experiences from dredging projects. Finally, the article suggests alternative measures, including adaptive monitoring strategies, that can be used to manage SSC around dredging projects if silt screens are proved not to be effective.

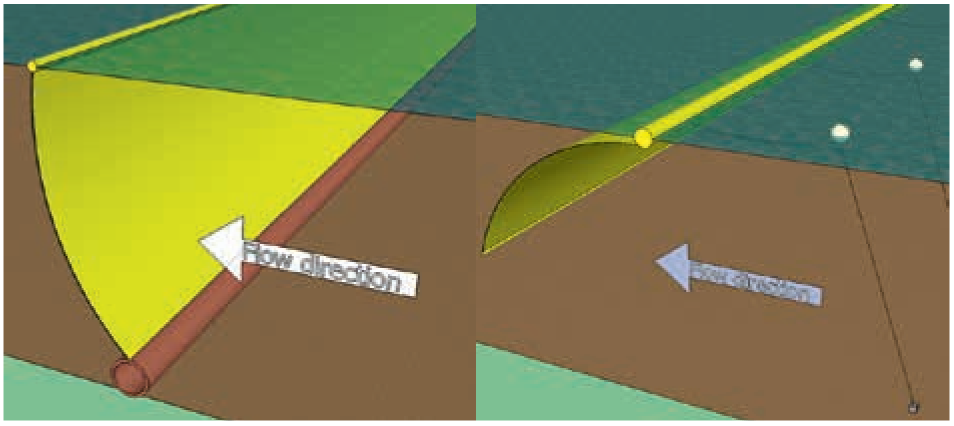

Figure 1. Standing (left) and hanging (right) silt screens.

DECISION PROCESS: WHEN TO APPLY SILT SCREENS?

Temporary effects of dredging refer to the increase in turbidity as a result of the release of suspended sediments into the water column during the dredging process. Decisions on deployment of silt screens to mitigate these impacts ideally go through the following three steps, effectively using a receptor-based approach:
1. determine the necessity of environmental mitigation measures;
2. determine the viability of silt screen application;
3. installation and operability of a silt screen.

Determine the necessity of environmental mitigation measures

It is important to realise that turbidity occurs naturally and that species of flora and fauna can cope with variances in turbidity levels and in some cases will not be affected by fluctuations resulting from project operations. Furthermore, (natural) sediment plumes can be important for the health of some ecosystems as a source of nutrients (organic matter). In most cases, however, a non-natural increase in turbidity level over an extended period of time has a negative impact on the surrounding environment.

When determining background turbidity values, the natural processes such as river peak discharges and re-suspension of fine sediments during storms need to be taken into account as well as other human-induced activities such as fishing and ship-manoeuvring operations (Aarninkhof *et al.*, 2008).

Once the background values and fluctuations are known, the severity and spatial extent of the project-related sediment plumes and associated potential environmental impact can be determined including the necessity of mitigation measures (see, for example, PIANC, 2010):
– determine presence and type of sensitive receptors relative to dredging/disposal operations, the detectable stress-response of these receptors and the timing (e.g., in relation to coral spawning periods) concerning duration and frequency of the sediment plume;
– determine existing receptor stress levels in combination with the local background conditions regarding, e.g., turbidity levels

Max Radermacher (right) receives the IADC Award for the Best Paper by a Young Author from IADC Secretary General René Kolman at WODCON XX in Brussels, Belgium, June 7, 2013.

IADC YOUNG AUTHOR AWARD PRESENTED AT WODCON XX, BRUSSELS, BELGIUM, JUNE 7 2013

One of the highlights of WODCON XX was the presentation of the International Association of Dredging Companies (IADC) Award for Best Paper written by a Young Author. The award was given to Max Radermacher for his paper, "The Art of Screening, Effectiveness of Silt Screens". Mr Radermacher received his BSc and MSc (cum laude) in Civil Engineering from Delft University of Technology, Delft, the Netherlands and is now a PhD candidate at the same university. His paper focusses on hanging silt screens, describing the decision process for deployment of hanging silt screens, their effectiveness and adaptive management strategies as an alternative for silt screens.

The Award

Each year at selected conferences, the International Association of Dredging Companies grants awards for the best papers written by authors younger than 35 years of age. In each case the Conference Paper Committee is asked to recommend a prize winner whose paper makes a significant contribution to the literature on dredging and related fields. The purpose of the IADC Young Authors Award is "to stimulate the promotion of new ideas and encourage younger men and women in the dredging industry". The winner of this award receives € 1000 and a certificate of recognition. The paper may then be published in *Terra et Aqua* Journal.

resulting from natural processes and other human-induced activities;
- estimate/model the transport of suspended sediment within a plume based on local water depth, hydrodynamic conditions (e.g., tidal/seasonal currents) and sediment characteristics (e.g., settling behaviour); and
- investigate the character of the dredging/disposal operations (e.g., type of equipment, production rate) in combination with the character of the dredged/disposed material (e.g., fines content, in-situ density) as both determine the type and magnitude of the source of a sediment plume.

From the above list, the need for, and type of, environmental mitigation measure clearly has to be determined for every project individually, based on thorough understanding of the local environment. Providing "typical impacts" of dredging operations is very difficult, as these depend on the type of activity, work method and equipment, distance from activity, ambient flow characteristics and particle characteristics (e.g., settling of suspended sediments). Therefore, a fit-for-purpose solution needs to be found based on both the environment *and* the dredging work method to ensure maximum efficacy of a suggested mitigation measure such as a silt screen.

Determine the viability of silt screen application

In present day dredging practice, silt screens are often regarded as the ideal answer to dredging-induced SSC. Admittedly, silt screens have many advantages over alternative mitigation measures in terms of operational implications, production and costs. However, absolute effectiveness of the silt screen regarding reduction of environmental impact should always be taken into account and be a necessary condition to proceed to silt screen placement.

Application of hanging or standing silt screens

Silt screens generally come in two different types – hanging and standing – which in turn can be applied in a number of different configurations (JBF Scientific Corporation, 1978; Francingues and Palermo, 2005; Ogilvie *et al.*, 2012). The choice of screen and configuration type depends on a combination of local hydraulic conditions, the source of suspended sediments and operational demands. Of these three, the local hydraulic conditions are the main limiting factor to the viability of silt screen application, both in terms of constructional failure and failure from an environmental point of view.

Mechanical aspects of silt screens in an open configuration have been treated extensively in literature, leading to the conclusion that hanging silt screens get damaged easily when current velocities exceed 0.5 to 0.8 m/s (Francingues and Palermo, 2005). Explicit limiting values regarding mechanical failure of silt screens of the standing type do not occur in literature. As a result of their full coverage of the water column, standing silt screens have to cope with much higher hydraulic loads than hanging silt screens. Hence the application of standing silt screens in an open configuration is limited to *very* mild hydraulic conditions and geometries which allow weak currents to pass around the screen's side edges. Similar limitations apply to silt screens in a closed configuration.

Viability with regards to sources of suspended sediments

Sources of suspended sediment may occur throughout the complete dredging cycle of dislodging, transport and placement of bed material. Depending on the activity causing dredged material to get suspended in ambient water, initially the transport of suspended sediment can be density-driven (i.e., *dynamic* plumes, mostly occurring in the placement stage) or dominated by turbulent mixing in the main flow (i.e., *passive* plumes). At some distance from the source, dynamic plumes either settle out or proceed as passive plumes.

Hanging silt screens are typically intended to mitigate passive plumes, as they have a distinctly negative effect on dynamic plumes (JBF Scientific Corporation, 1978; Radermacher, 2013). As a result, they should be applied at some distance from dredging activities which involve dynamic plumes. Standing silt screens in turn effectively block near-bed propagation of dynamic plumes.

Installation and operability of a silt screen

Silt screen usage in dredging projects has a (large) operational impact. Most hanging silt screens available on the market are not designed for efficient use in dredging and marine construction projects. Traditional mooring systems require an extreme quantity of anchors. This is unpractical when located in the vicinity of dredging works (interference of anchors and anchor lines with works) or when frequent relocation of the silt screen is required. From an operational point of view, the combination of a robust construction and a substantial reduction of anchoring points is the safest, least expensive and most operationally desirable choice.

When considering hanging or standing screens, experience has proven that the operability of a standing silt screen is limited as a result of its fixation on the seabed. Deployment, maintenance and re-positioning of the screen require more effort in comparison to handling hanging silt screens. Furthermore, the standing screens risk being partly buried by the blocked and subsequently settled sediment. From an operational point of view, hanging silt screens are preferred.

During the installation and operation of a silt screen, the following aspects have to be considered in order to achieve sufficient protection and durability of the silt screen system:

– the availability of sufficient area to assemble the silt screens on shore (see opening photo);
– the presence of spare silt screens to allow quick replacement of damaged silt screens;
– a technical solution which allows the dredging and auxiliary equipment to move in and out of the shielded area; and
– the permanent availability of a support vessel, such as a multicat or multipurpose vessel, to assist in the installation and repositioning of the screen if required.

Following the above, deployment of silt screens at a dredging project have a major impact on the project organisation and costs, especially when requirements state that the dredging site needs to be fully enclosed with silt screens.

EFFECTIVENESS OF SILT SCREENS

From the previous section it has become clear that silt screens of the *standing* type and silt screens in closed formation can only be applied effectively under very mild conditions, mainly as a result of local hydrodynamic considerations. However, performance of *hanging* silt screens in an open formation, as often applied in present-day dredging practice, is questionable. The open character allows currents to pass more easily, which results in lower hydraulic loading, but also in the passage of suspended sediments. The remainder of this section will focus on the effectiveness of hanging silt screens in an open configuration (Radermacher, 2013).

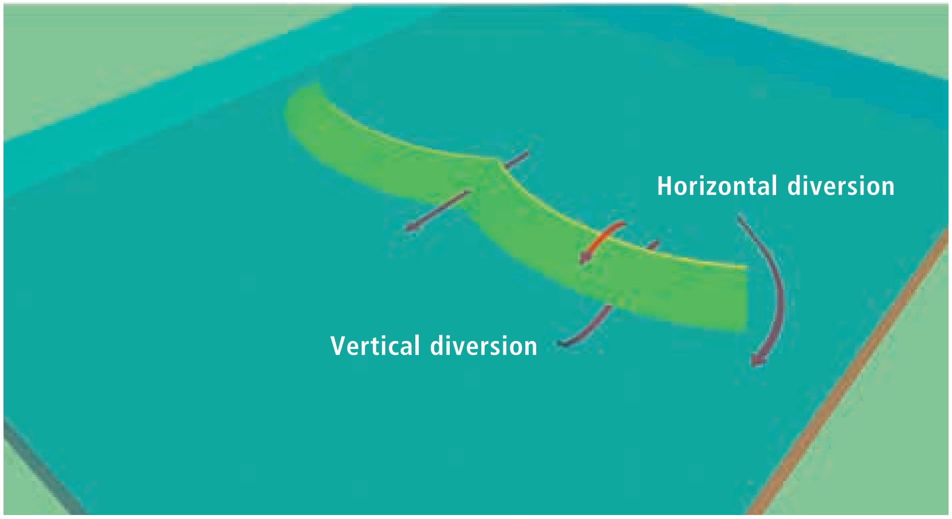

Figure 2. Current flows around a hanging silt screen: Main components are the flow under the screen (vertical diversion) and the flow around the screen's side edges (horizonal diversion).

Current flows around silt screens

Analysis of mechanisms that account for passage of suspended sediment laden currents around silt screens leaves two key processes (see Figure 2):

– vertical diversion, through the gap between the screen's lower edge and the bed; and
– horizontal diversion around the screen's side edges.

Vertical diversion occurs in case of a hanging silt screen in cross-flow, as hydraulic loading causes the flexible screen to flare. Even in the case that the screen height is equal to the water depth, a significant gap will open near the bed. Horizontal diversion is only possible if there are no lateral restrictions (e.g., quay walls, bunds) and therefore mainly applies to silt screens in open water.

Note: In this study, the permeability of a silt screen is assumed to be negligible. This assumption holds in every situation, as flow seeks the path of least resistance. For a silt screen to retain fine sediment particles but allow water to pass through, only very low permeability is allowed. Given this low permeability, significant discharge through the screen is only possible under heavy hydraulic loading, which was said to be impossible for mechanical reasons. Pressure will always be released through vertical and horizontal diversion.

Further analysis of these two processes is done consecutively in the next two sections. Vertical diversion is investigated by means of 3-dimensional numerical model simulations, making use of Large Eddy Simulation (LES) to account for turbulence closure. Validation data are obtained from laboratory experiments. Horizontal diversion is investigated by means of a 2-dimensional horizontal (2DH) model approach, in which the silt screen is schematised as a discharge relation at a series of internal grid cell edges.

Vertical diversion of flow

Hanging silt screens are intended to promote quick settling of suspended sediments by bringing particles close to the bed (vertical diversion) thereby lowering the extent of the environmental impact.

In order to quantify the effectiveness of a silt screen, the study introduces an environmental impact potential *P*. A silt screen is considered to be effective whenever it is able to reduce *P*.

P is given by the product of the SSC and the vertical level above the bed:

$$P = \int_0^1 C_* z_* \, dz_* \qquad [1]$$
$$\text{with } C_* = {}^{C}/_{C_{max}}$$
$$z_* = {}^{z}/_{h}$$

C_{max} denotes the maximum SSC value upstream of the silt screen and h denotes water depth. It is chosen to use a linear relation between C_* and z_* because the potential environmental impact often scales linearly with SSC and the potential impact time of the sediment particles scales linearly with their vertical distance from the bed.

The study expresses the effectiveness of silt screens as a percentage of reduction of P achieved by the screen. The reference value of this reduction is still to be determined. Many authors have suggested the use of a value upstream (also referred to as *inside*) of the silt screen (JBF Scientific Corporation, 1978; Francingues and Palermo, 2005; Vu *et al.*, 2010; Ogilvie *et al.*, 2012). Note that these authors use C instead of P to compute the effectiveness. This type of effectiveness parameter is coined the inflow effectiveness E_{in} here.

Despite the widespread usage of E_{in} as a measure for silt screen effectiveness, a second parameter is introduced here. A silt screen has to achieve a significant reduction of P. In fact, it is argued here that it should lead to improvement with respect to the reference situation of the same sediment plume in a configuration without silt screen. Effectiveness with respect to the reference situation is coined the reference effectiveness E_{ref}.

The difference with E_{in} lies in the influence of (autonomous) settling of sediment in between the upstream and downstream locations (Figure 3). For very fine particles the difference will be negligible, but if the particle size increases, the difference between both parameters will grow ever bigger. The definitions of E_{in} and E_{ref} are given in equation [2].

$$E_{in} = \frac{P_{in} - P(x)}{P_{in}} \cdot 100\% \qquad [2]$$
$$E_{in} = \frac{P_{ref}(x) - P(x)}{P_{in}} \cdot 100\%$$

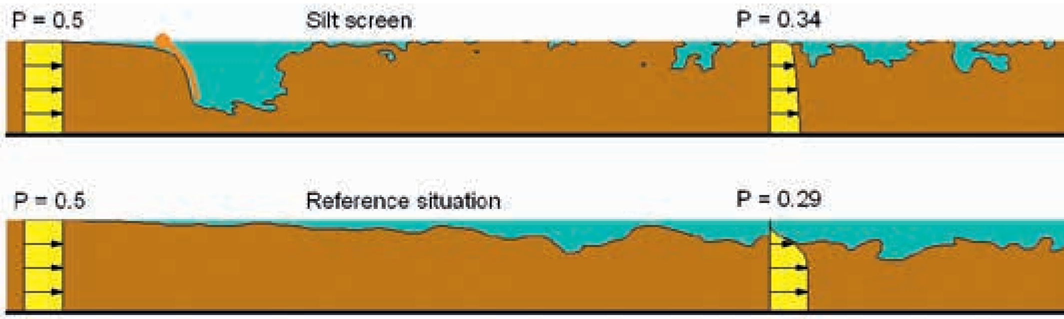

Figure 3. Example of application of percentage of reduction of P achieved by the screen. The yellow profiles represent values of C_*, whereas the value of C_*z_* integrated over z_* is given above each profile. In this situation, E_{in} = 32% and E_{ref} = –10%.

In the study, a large number of numerical model simulations were conducted in order to chart the effectiveness of silt screens as a function of depth-averaged horizontal flow velocity U, silt screen height h_s, settling velocity w_s and the upstream vertical profile of SSC. The water depth is kept fixed, as h only influences the effectiveness of silt screens through the relative silt screen height h_{rel}, being the ratio of h_s over h. The model domain is depicted in Figure 4.

To arrive at a compact and generic representation of the model results, every simulation is characterised by means of two dimensionless groups: the velocity ratio θ and the relative screen height h_{rel} as shown in equation [3].

$$\theta = \frac{w_s}{U} \qquad [3]$$
$$h_{rel} = \frac{h_s}{h}$$

The velocity ratio θ can be regarded as a parameter indicating the favourability of settling conditions. The higher θ, the shorter the horizontal settling distance of suspended sediment. Relative screen height h_{rel} represents two aspects: the initial vertical displacement of suspended sediment and the amount of flow disturbance caused by the silt screen.

For each combination of effectiveness parameter (E_{in} or E_{ref}), upstream SSC profile and downstream x-coordinate, the effectiveness of silt screens is displayed in the θ-h_{rel} plane. As an example, the inflow effectiveness is treated for a uniform upstream SSC profile (uniform value over the full water column) at 6 times the water depth downstream of the silt screen. This is shown in Figure 5.

The triangular markers in Figure 5 indicate actually obtained data points. Contour lines of equal E_{in} are constructed from interpolation. Figure 5 shows a maximum positive E_{in} of 90%. The most positive E_{in} is obtained for large values of theta, which corresponds to large settling velocities. Above $\theta = 5 \cdot 10^{-2}$ (e.g. w_s = 2 mm/s, U = 4 cm/s), the reduction of P with respect to the upstream value becomes significant. For small theta (small settling velocities) the silt screen is not positive, but also not negative: E_{in} = 0%. There is only a very weak relation between h_{rel} and E_{in}; for larger h_{rel}, E_{in} is slightly less. This can be explained by the increased mixing for a larger vertical screen; increased mixing leads to a spreading of SSC to higher z-coordinates, which gives rise to a high environmental impact potential P.

Subsequently, the reference effectiveness E_{ref} is evaluated for the same parameters: At 6 times

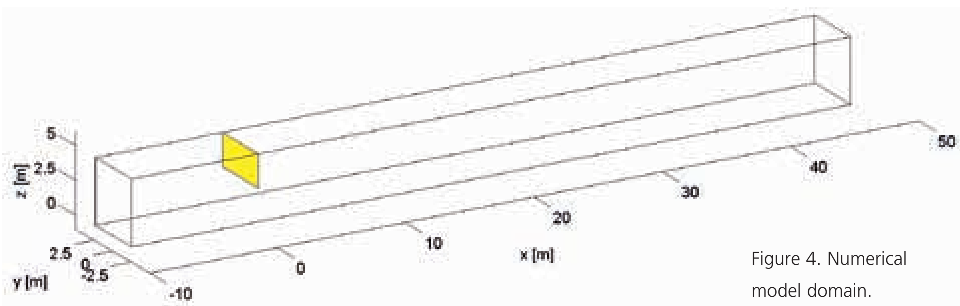

Figure 4. Numerical model domain.

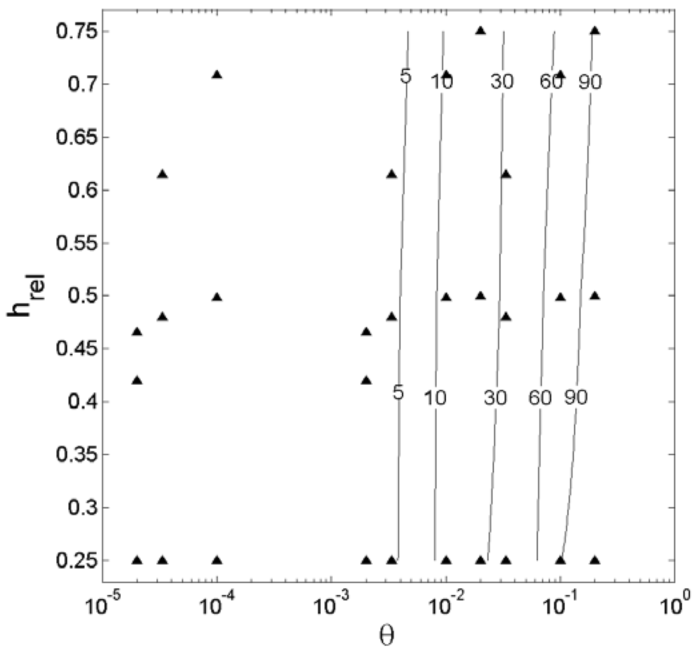

Figure 5. Inflow effectiveness [%] evaluated at 6h downstream of the silt screen, as a function of the velocity ratio and relative screen height, for a uniform upstream SSC profile.

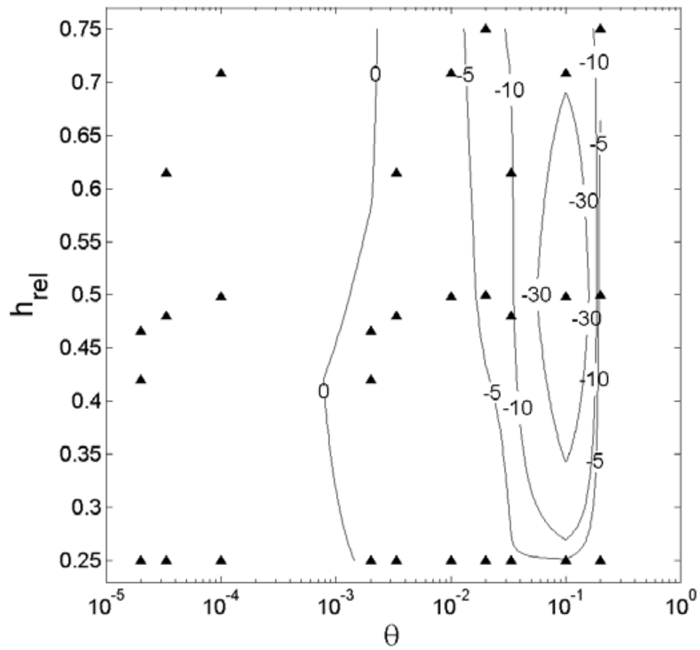

Figure 6. Reference effectiveness [%] evaluated at 6h downstream of the silt screen, as a function of the velocity ratio and relative screen height, for a uniform upstream SSC profile.

the water depth downstream and with a uniform upstream SSC profile (Figure 6). The difference between Figure 5 with E_{in} and Figure 6 with E_{ref} is clear: Although E_{in} showed positive effectiveness of the silt screen in the range of realistic h_{rel} and θ, E_{ref} is never positive in the same range of h_{rel} and θ.

When settling conditions become favourable (i.e., at high θ), the autonomous settling of suspended particles in a reference situation without a silt screen is more than the settling in case of a silt screen. Therefore E_{ref} is negative for larger θ. For low θ, E_{ref} attains values close to 0%, but E_{ref} never becomes significantly positive.

This means that for all realistic θ and h_{rel}, applying no silt screen at all is better. Although the silt screen reduces P compared to upstream (it causes a positive E_{in} in Figure 5), Figure 6 makes clear that the reduction of P would have been even more without a silt screen (never a positive E_{ref} in Figure 6). This direct comparison of E_{in} and E_{ref} makes it clear that E_{ref} is the better parameter to judge the effectiveness of a silt screen, even though it is harder to determine in the field on a dredging site than E_{in}.

With different upstream concentration profiles, the effectiveness contours in the θ-h_{rel} plane show different patterns. Generally two different types can be distinguished: Profiles with the biggest sediment load in the lower part of the water column and profiles with the biggest sediment load in the upper part of the water column. In the former case the vertical mixing caused by the silt screen can only do damage: the sediment load was already at its most favourable position close to the bed. But even in the latter case, with an upstream sediment load in the upper part of the water column, the E_{ref} effectiveness never exceeds 10%. Given all the costs and effort needed to place silt screens, a maximum positive effectiveness of only 10% is considered to be too low to apply a silt screen. Even though so far only a continuous supply of SSC upstream of the silt screen has been considered, no positive E_{ref} is obtained for discontinuous supplies either (Radermacher, 2013).

Note: Flow contraction underneath a silt screen can induce a submerged jet flow near the bed. If erodible bed material is available, the high velocities occurring in this jet flow give rise to enhanced erosion and suspended sediments. This additional effect has not been accounted for in the analysis above and, depending on local conditions, might lead to even lower effectiveness percentages.

Horizontal diversion of flow

Despite the considerations presented in the previous section, vertical diversion is in fact the intended effect of hanging silt screens, as it is thought to bring SSC closer to the bed. However, the presence of a silt screen also induces a big resistance to horizontal flow which will naturally follow the path of least resistance. This means that a part of the incoming current will be diverted in the horizontal plane and pass the screen around its side edges if lateral restrictions are absent (Figure 7).

This counteracts the intended usage of silt screens as a vertical current deflector and is therefore an unwanted effect. The amount of horizontal diversion can be quantified by defining the relative discharge Q_{rel}. It denotes the ratio of the discharge passing underneath the screen's lower edge and the total upstream discharge over the full width of the silt screen = Q_V/Q_{tot}*100%. It thus represents the percentage of vertical diversion. Hence the percentage of horizontal diversion is equal to 100%-Q_{rel}.

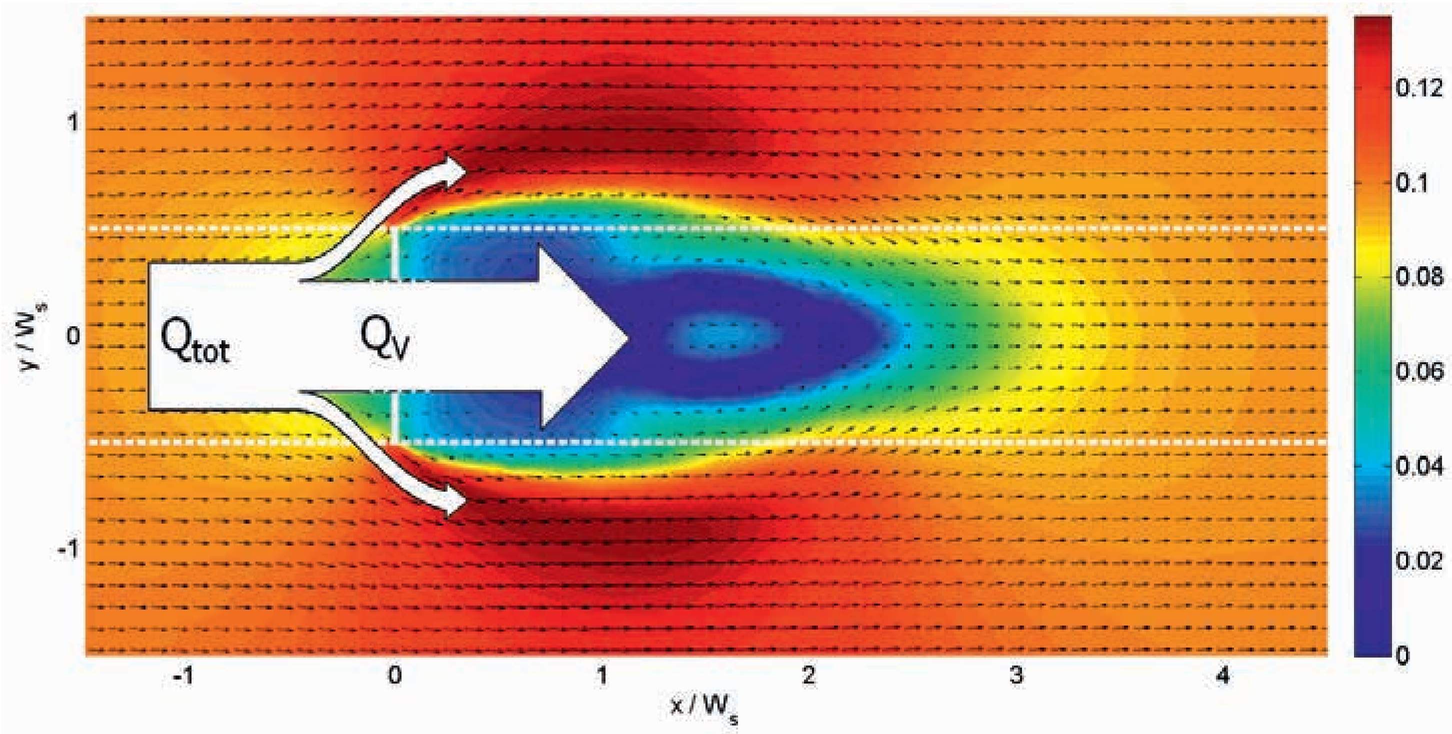

Figure 7. Example of a model current simulation with silt screen. The colours and vector arrows represent magnitude and direction of the depth-averaged flow velocity.

The horizontal diversion of a silt screen is investigated by means of a 2DH depth-averaged flow model with the silt screen being represented as an internal discharge formulation. This discharge formulation relates the screen's geometry and the pressure difference between both sides to the discharge passing underneath. A large dataset is obtained by varying U, h_s and the screen's width W_s. The associated values of Q_{rel} are now depicted in Figure 8 as a function of two dimensionless numbers: h_{rel} and Fr / W_*. Here, $Fr = U / \sqrt{gh}$ denotes the Froude number with gravitational acceleration g and $W_* = W_s / h$ represents the dimensionless screen width.

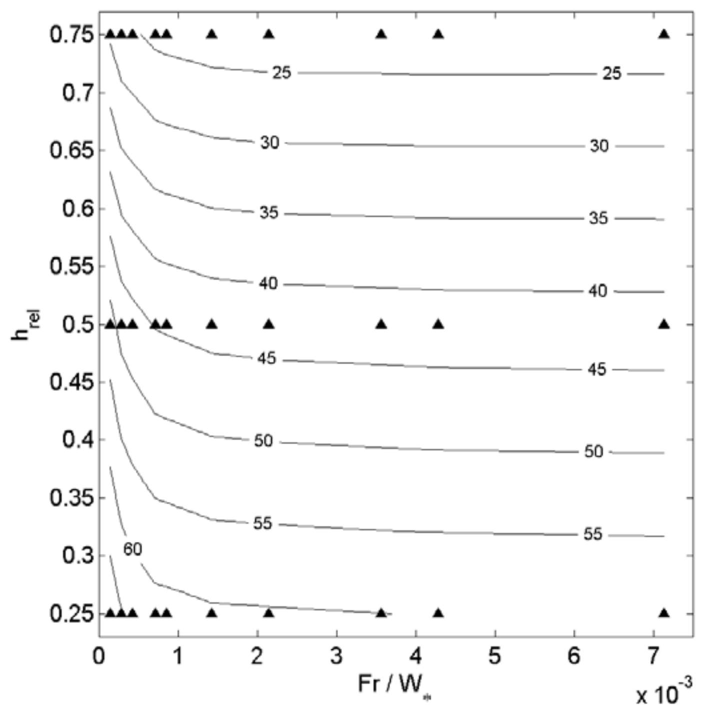

Figure 8. Relative discharge [%] as a function of relative screen height and Froude number over relative screen width.

From Figure 8 it can be derived that for realistic values of Fr / W_* the relative discharge is more or less complementary to h_{rel}. For example, when $h_{rel} = 0.6$, slightly less than 40% of the incoming discharge is diverted vertically. The remaining 60% passes the silt screen around its side edges.

In summary, a silt screen of finite width will give rise to horizontal diversion of sediment-laden flow if lateral restrictions are absent. Hence a dredging plume will partly pass the screen around its side edges, which allows for free spreading of suspended sediment. Using horizontal diversion as a beneficial process, i.e., trying to guide the current away from potential sensitive receptors, has been proved to be counterproductive (Radermacher, 2013).

EXPERIENCE FROM SILT SCREEN APPLICATION IN THE FIELD

The results of the modelling and lab tests described above are supported by observations and experiences obtained during the execution and monitoring of various projects in the field. In fact, based on evaluations of a range of dredging projects in the Arabian Gulf, Caribbean and Pacific Ocean where different silt screen set ups have been applied, the following prerequisites for successful use of hanging silt screens were determined.

Figure 9. At Saadiyat Island, Abu Dhabi the silt screen did not function in the run-off channel as the current velocity measured exceeded the permitted velocity for the screen, even though weighted down. Current patterns formed around the screen causing fast and turbid flows. Further use of silt screens therefore was suspended. Insert, the ballast chain used to weigh the silt screen down (Taelman, 2009).

Operational requirements for effective use of silt screens:

- Space underneath (above in case of standing silt screens) or on the sides of the silt screen is needed to compensate for water level differences and related flows resulting from tidal movements.
- Use strong materials as water flow through the screen is negligible. Field experience has shown that silt screens applied in a marine environment tend to attract extensive marine growth which starts to block the water flow through the (semi-)permeable screen material shortly after the screen is deployed.
- Install silt screens at a safe distance from the dredging operations and navigational routes of auxiliary equipment. Use demarcation buoys to identify the location of the screens.
- Screens need to be heavily enforced by means of ballast chain to allow for a sufficient cover of the water column (see insert Figure 9). Even small currents (< 0.3 m/s) cause the bottom of the hanging silt screen to lift, even when it is weighted down and regardless the depth of the screen.

Environmental conditions for the effective use of silt screens include:

- Low flow velocities (< 0.3 m/s) which allow: (1) the screen to stay vertically in the water and covering an effective part of the water column and (2) the suspended sediments to settle when these are redirected by the silt screen towards the seabed;
- Uniform flow direction perpendicular to the silt screen in combination with other sheltering structures such as a breakwater or a quay wall; this optimises the efficiency of the silt screen (Figure 10).
- Mild wave conditions near the silt screen as the screen can get damaged easily when it is exposed to rough hydraulic conditions;
- Monitoring programmes have shown that the combination of too high waves and too high current speeds can influence the reduction efficiency of silt screens and can even induce longer periods of elevated turbidity as a result of extra mixing induced by the turbulence around the silt screen;
- Single suspended sediment source: If there is more than one source (e.g., river discharge, other dredging or reclamation works) the screen will lose its effectiveness as turbidity plumes can come from multiple directions (see Figure 11);
- Deployment within 500 m range from turbidity source is preferable to minimise dispersal of suspended sediments; deployment directly upstream of a sensitive receptor is also possible;
- If only a small part of the water column is blocked, sediment is not forced deep enough to effectively improve settlement to the seabed. The local flow field around the silt screen causes additional stirring of fine sediments into the water column. As a result, plume decay times increase.

Dedicated field experiments at a dredging project in the Arabian Gulf have shown that, for very specific applications, silt screens are an effective measure to mitigate dredging-induced turbidity levels. These applications include sheltered reclamations in enclosed basins (SSC decrease to 25-40% of original level) and the unloading of barges through open bottom doors (SSC decrease to 20-25% of original level). However, it should be noted that charting the flow field in full detail from field measurements is not possible. The effectiveness percentages have been determined from comparison of single point measurements of turbidity values (instead of *P*) on both sides of the silt screen ('inflow' type of effectiveness parameter instead of 'reference' type).

ADAPTIVE MANAGEMENT STRATEGIES AS AN ALTERNATIVE TO SILT SCREENS

The use of silt screens is in fact a mitigation measure specifically aimed at reducing sediments already in suspension. As has been described in detail above, only a limited number of local environmental circumstances and/or dredging and construction work methods allow for effective deployment of silt screens.

Figure 10. A hanging silt screen at a dredging project in the Arabian Gulf at a reclamation discharge was applied successfully in combination with a breakwater and minimal current velocity.

In many cases determining measures that focus on source control and specifically on minimising the actual generation of suspended sediments into the water column is more effective. This can be done by designing smart dredging and construction procedures supported by verification monitoring and modelling programs, so-called adaptive management strategies. This will allow for effective SSC management and reduction of related environmental impacts.

The aim of adaptive management (see Figure 12) is to improve the specific project's environmental management through "learning by doing" and using feedback to adjust construction operations to better meet the project objectives (functional requirements and environmental objectives [PIANC, 2009]). Adaptive management is incorporated in the design of the dredging operation work methods and comprises a combination of proactive and responsive measures.

Proactive management measures aim to optimise the design of the work method in terms of limiting potential environmental impacts of the dredging, both on the short-term (same temporal scale as the dredging execution period) and longer term. Responsive management involves the continuous incorporation of new information and lessons learned (e.g., monitoring data, project

Figure 11. A silt screen application at a dredging project in the Caribbean with reversed effect caused by natural variation in suspended sediments as a result of a nearby river discharge (courtesy of Kent Reid).

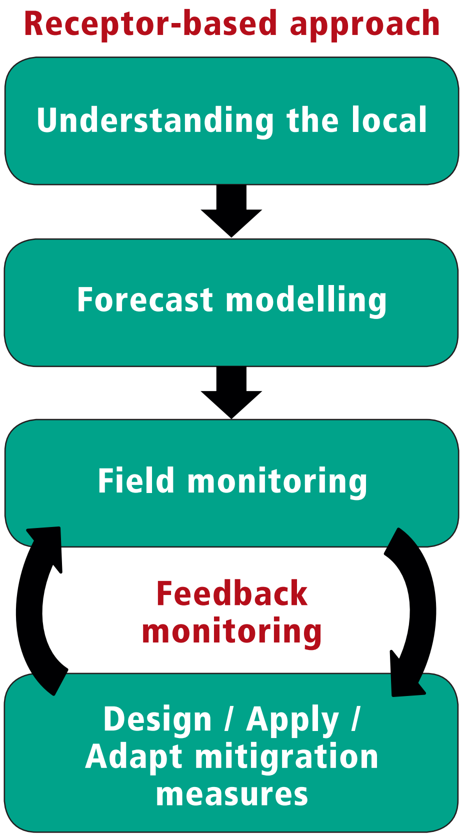

Figure 12. An adaptive management strategy.

experiences) in the management programme to effectively respond to a situation.

This strategy enables the project team to:
– fully understand and control the transportation and fate of fine sediments around dredging operations;
– adopt an early warning response mechanism to potential exceedance of environmental limits;
– test environmental compliance of future dredging/disposal scenarios; and
– design appropriate contingency measures.

In many cases, this adaptive management strategy is more effective than simply applying generic mitigation measures such as silt screens as it focuses on reducing the suspended sediments at the source. However, when implementing an adaptive management strategy, the following considerations should be taken into account:
– Adapting dredging procedures could have serious implications for the production rates, progress of work and often involve additional costs.
– Adaptive management is more cost-effective when applied at more complex dredging projects lasting for at least several months or longer.
– Besides optimising dredging procedures, adaptive management involves verification of effectiveness of the measures taken. Verification methods could include a combination of baseline sediment and marine habitat monitoring, feedback monitoring and hindcast and forecast sediment modelling.
– Adaptive management should be an integral part of project preparation to avoid unforeseen delays and costs.

CONCLUSIONS

This article aims to treat the effectiveness of silt screens in an integral way. Main insights on silt screen effectiveness are:
- Hanging silt screens in an open configuration do not achieve a significantly positive performance in mitigating the potential environmental impact of suspended sediment, regardless of local flow conditions and silt screen geometry.
- Silt screen effectiveness must be rated with a reference effectiveness parameter (comparing the situation with and without silt screen), not with an inflow effectiveness parameter (comparing downstream with upstream of the silt screen) as has always been done up to now.
  Hanging silt screens often have a positive inflow effectiveness, but this study shows that in the case of a current, even with a positive inflow effectiveness, it would have been better to have no hanging silt screen at all: The reference effectiveness is not positive.
- Flow contraction underneath hanging silt screens actually leads to enhanced erosion if erodible bed material is available.
- Silt screens in an open configuration give rise to a significant amount of horizontal flow diversion, which counteracts the intended use of silt screens as a vertical current deflector.
- Adaptive management strategies are a viable alternative to the application of silt screens.

The conclusion of this study is that hanging silt screens in an open configuration, as often applied in present-day dredging practice, are not effective in reducing the environmental impact of dredging projects.

The recommendation is to integrate the insights about silt screen effectiveness as described here in the decision making process regarding mitigation of potential environmental impact of suspended sediments, using a receptor-based approach and adaptive management strategies. Relying solely on silt screens, even when local conditions ensure that their effectiveness is negligible (or even adverse), hinders progress in the protection of the marine environment.

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