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Merits of a Scenario Approach in Dredge Plume Modelling

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Abstract
Dredge plume modelling is a key tool for quantification of potential impacts to inform the EIA process. There are, however, significant uncertainties associated with the modelling at the EIA stage when both dredging methodology and schedule are likely to be a guess at best as the dredging contractor would rarely have been appointed. Simulation of a few variations of an assumed full dredge period programme will generally not provide a good representation of the overall environmental risks associated with the programme. An alternative dredge plume modelling strategy that attempts to encapsulate uncertainties associated with preliminary dredging programmes by using a scenario-based modelling approach is presented. The approach establishes a set of representative and conservative scenarios for key factors controlling the spill and plume dispersion and simulates all combinations of e.g. dredge, climatic and spill scenarios. Impact zones are derived from the modelling of the individual scenarios through established impact criteria for key environmental receptors, and an "envelope" of impact zones is derived by combining all the individual scenarios. The impact envelopes for different receptor types readily identifies receptors at risk, while a wealth of information that can be extracted from the individual scenarios forms a solid platform for taking environmental objectives into account in optimisation of the final dredge programme. Requirements for the approach to be applied as well as advantages gained from the scenario approach are discussed, and the typical application as part of an EIA outlined.

Keywords: Sediment plumes, Scenario modelling, Dredge plume modelling, Impact assessment

1. Introduction

The release of sediments into the water column of the marine environment is an unavoidable effect of most marine construction works. In particular operations involving sea-bed dredging, sediment disposals and reclamation works often generate sediment plumes which may carry finer fractions of sediments far from the source through the actions of currents and waves. The resulting increase in turbidity and sedimentation rates may impact sensitive environmental receptors, and most projects involving dredging and reclamation therefore require EIA approval.

Dredge plume modelling is an invaluable tool for quantifying dredge spoil dispersion and sedimentation. The overall assessment of impacts and the design of dredge campaigns rely on the dredge plume modelling strategy as a way of delineating environmental impacts. In this paper, focus is not on the plume modelling tool itself but rather on how to incorporate the tool into the context of a broader EIA framework. The demand for reliable methods and suitable modelling strategies that properly delineate *likely* as well as *worst case* impact zones has grown as a consequence of increasing environmental awareness and requirements for mitigation of potential impacts. Defining modelling strategies that take appropriate account of the inherent uncertainties that exist at the EIA stage and provide reliable decision support for the environmental evaluator is a key component in the early stages of a dredge plume modelling programme.

It is the author's opinion that many dredge plume modelling programmes, which are set up to provide the environmental footprint of the assumed dredging programme as closely as possible, may not take account of the inherent uncertainties at the EIA stage, and therefore potentially misinform the EIA process.

The objective of the present paper is to provide a summary of some of key uncertainties and challenges that need to be addressed through the modelling, and outline how these, given the right circumstances, can be effectively addressed through a scenario modelling approach.

2. Uncertainties in dredge plume prediction

At the EIA stage of a proposed dredging operation there will usually be significant data and knowledge gaps, which implies that at this stage numerous assumptions are required. A major challenge for EIA dredge plume modelling is thus how to accommodate uncertainties related to assumption of key components of the operation while maintaining the value of the modelling. Some of the typical components which are often only loosely defined or poorly mapped at the EIA stage include:

- The dredging programme and dredging methodology
- Sediment characteristics throughout the area to be dredge.
- Spill rates from the dredging operation, which is linked to both of the above.

- Hydraulic conditions during the period of dredging.
- Limitations to climatic data (i.e. winds, waves, currents, bathymetries etc.).

The dredging programme and methodology determines where, when, for how long and partly at what rate sediments are released into the water column. Often the EIA-study is carried out prior to the design of the dredge programme and information available for setting up the plume modelling is at best indicative. In some cases the EIA-study and dredge programme design are carried out in parallel, often leading to several rounds of updates to dredge schedule and methodologies during the EIA study. The actual detailed programme will generally be planned by the dredging contractor, who is typically only appointed after EIA approval. In all cases, the programme is likely to change - even during execution in the case of larger programmes of significant duration. Key assumptions related to dredge methodology, production rates and timing therefore need to be made for the prediction of spills to be modelled.

The sediment characteristics, is key to both the spill rates from dredging and the sediment dispersion from the spill source. Dredging in sediment with a high fines content will typically generate higher spill rates and a plume that is potentially carried further away from the source than dredging in coarser material. A basic soil classification for the soil to be dredged (parent material) may be available from geotechnical investigations, but extrapolation of geological layers often has to be carried out from a limited number of boreholes. For smaller projects, it is not uncommon that only surface samples are available for the characterisation of the parent material. For granular parent material (predominantly non-cohesive and non-consolidated material), what is passed through the dredger is not too different from the parent material, and a reasonable correlation between the characteristics of the parent material and the spill rates and characteristics of the spill can be developed from experience. This is significantly more complex for consolidated or predominantly cohesive parent material where the characteristics of the dredge spoil and spill will be highly dependent upon the degree of disaggregation of the parent material during dredging as well as flocculation of fines in the spill. Key parameters related to the sediment characteristics required for dredge plume modelling include the spill rates (also influenced by the type of dredging operation, climatic conditions and the actual operation of the equipment) and the sediment spill characteristics, typically represented by a particle size distribution and/or a settling curve.

The hydraulic conditions during the dredging determine the sediment plume dynamics. Wave and current generated turbulence tend to keep the sediment in suspension, while currents carry it away from the origin. Forcing by tides, wind and pressure systems as well as ocean currents can be equally important for the plume excursion, and all need to be considered in the model setup. Even if tidal currents are a magnitude higher than for instance wind drive currents, the tidal currents may tend to carry the plume back and forth locally, while a weak net current induced by winds or other drivers can carry the plume further away from the origin. Tidal currents can be reliably forecasted by an appropriate hydraulic model, whereas waves and wind and pressure driven currents generally are variable and only can be predicted within given ranges for the intended dredge period. In cases with sensitive environmental receptors within reach of the sediment plume, the climatic conditions during dredging at given locations could well be the difference between no or significant impacts to a given receptor. For such cases, it is critical that the dredge plume modelling is set up to inform the EIA process of the potential risks for given climatic conditions, both to ensure that the potential risks are included in the assessment and to allow for potential mitigation through appropriate planning of the dredging campaign. If, for instance, wind generated waves and currents are seasonal, it is often possible to minimise impacts by appropriate timing of the activities with the seasons. It is crucial for the impact assessment that the dredge plume modelling captures an appropriate range of climatic conditions, noting that it is not necessarily the roughest conditions that will lead to the largest risk of impacts. Calmer conditions may lead to a build-up of higher turbidity levels locally and/or concentrated sedimentation rates in certain areas.

3. Modelling strategies

The modelling strategy determines how the objectives of the modelling are met. This ranges from choice of model(s) over application to the means of impact assessment. To inform the EIA process, impact criteria (tolerance limits) need to be established for each environmental receptor, which will allow the tailored model output to be used to quantify the potential impacts. It is noted that a sound understanding of the climatic conditions, the environmental receptors, the likely plume generating activities and the model capabilities and limitations is required for this assessment. Adjustments to the modelling strategy may be required as the study progresses.

The specific modelling strategy for dredge plume modelling is both site and project specific. Important considerations to decide on the strategy include, but are not limited to:

- Total length of dredge programme
- Types of likely and potential activities

- Key climatic drivers and seasonality
- Key environmental receptors and potential impacts
- Spatial and temporal scales for the potential impacts

The choice of modelling tool(s) ties closely into the dominant climatic drivers and site conditions. If there are significant 3D processes that will impact the plume dispersion, a 3D model is likely required. If not, a depth-averaged model which typically allows a finer horizontal resolution and additional simulations to be carried out for the same computational resources may be a better option.

If the total dredge programme is short (a few months), it may be feasible to simulate the entire dredge programme for relevant climatic and spill conditions. This will lead to a number of different footprints of the dredge programme, which can be evaluated individually and feed into the EIA. For this approach, it is necessary to specify the time schedule and sequencing of all components of the entire dredge programme. For longer duration dredge programmes, simulating the entire dredge period may be very time consuming and therefore often becomes a rigid and less practical modelling strategy which potentially limits the testing of different climatic conditions and different spill scenarios. Dredging programmes of long duration will often include different spill generating activities over different seasons and over a significant spatial domain. The dredge plume footprint thus becomes highly dependent upon the modelled schedule and sequencing, which is particularly uncertain for longer programmes. For long, complex dredging programmes, relying on dredge plume modelling of a few full dredge period simulations and providing the environmental footprints of an assumed programme and (typically) a few variations of this does not inform on the risk of different footprints associated with the key uncertainties at the EIA stage.

The so-called scenario based modelling approach is established to overcome some of these uncertainties.

4. The scenario-based modelling strategy

In recognition of the inevitable uncertainties at the EIA stage, it is crucial that the adopted modelling strategy is sufficiently flexible to embrace a range of potential climatic and spill rate scenarios, as well as programme alterations. The scenario-based modelling approach addresses this by typically simulating a large matrix of dredging, spill and climatic scenarios. The definition of the matrix is site and project specific. The area to be dredged is typically divided into segments, the area and location of which may be determined by a combination of likely dredge methodology, material composition, typical distance covered by a Trailing Suction Hopper Dredge (if this is a preferred dredge methodology) climatic exposure, proximity to environmental receptors, etc. The segments will typically overlap if a full coverage is required. For each segment, the likely dredge methodology producing the largest spill rate is identified and established as a dredge scenario. If there is likely to be several dredgers operating in parallel, this is included in the dredge scenarios. For each dredge scenario, a spill rate is assigned taking the geotechnical conditions into account. There is generally significant uncertainty related to the determination of the spill rates prior to the start of dredging (and they may vary significantly even for dredging with similar equipment in similar material). This may be covered by including two or more spill rates, e.g. a “best estimate” and a “worst case” spill rate. Similarly, the climatic conditions likely to be encountered during dredging are defined through a series of climatic scenarios. How these are best defined is site and project specific, but would typically constitute scenarios related to seasonality and key drivers which could e.g. be winds or waves.

All combinations of dredge, spill and climatic conditions (and potential other key parameters) are simulated and the corresponding impact zones derived. By combining all the results, an envelope of potential impacts is produced, from which impact zones and environmental receptors at risk can be readily identified.

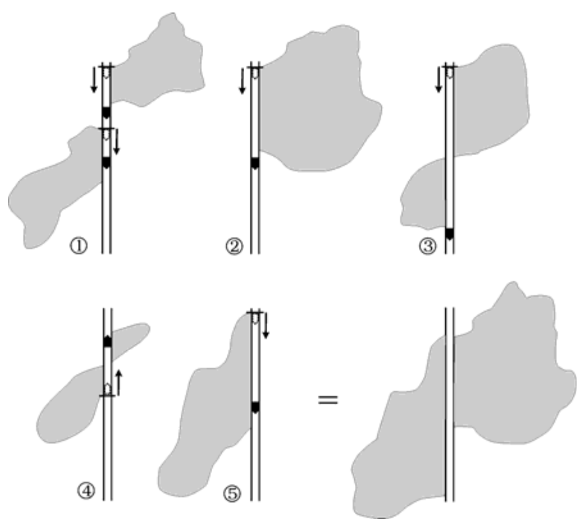

Figure 1 Schematic representation of impact envelope derived from 5 individual scenarios.

Figure 1 illustrates schematically the combination of impact zones from 5 individual dredge scenarios into an impact envelope. For larger, complex dredging programmes, the total matrix can easily be in excess of a hundred simulations, e.g. 10 dredge scenarios each assigned 2 spill rates and 3 climatic seasons each represented by 2 simulation periods would lead to a total of 240 simulations.

In addition to the parameters througd in Sections 2 and 4 of this paper, some model parameters may also strongly affect the plume dispersion and potential impacts. Whereas the hydrodynamic and wave models can be calibrated and validated to field data, this is not as simple for the sediment dispersion model, in particular prior to the start of dredging. A set of important parameters is for instance related to the exchange of sediment between the water column and the sea bed (typically represented by critical shear stresses for erosion and deposition and erosion coefficient(s)). Best estimates of these parameters are typically established based on experience from previous dredging programmes under similar conditions, and a sensitivity analysis may be carried out.

5. Applicability of scenario approach

For the scenario approach to be feasible, it is generally required that impacts can be derived from relatively short simulation periods. Key requirements for the simulation period include:

- Impacts to critical receptors can be suitably quantified from the period.
- Ability to represent climatic conditions
- Ability to represent dredging conditions

Tides are usually an important consideration for plume dispersion and with potential significant differences between neap and spring tides, a 14 day neap spring tidal cycle is considered essential to encompass the main tidal induced variations within an analysis period. Environmental receptors are typically impacted by a combination of stress levels and duration with the ability to cope with "severe" conditions (e.g. in the form of high turbidity levels) for "short" periods of time, and lower stress levels for more extended periods of time. The period for impact assessment must thus accommodate statistical analysis that caters for both short and somewhat extended duration events. DHI has over many years and projects developed and had good experience with impact criteria based on exceedence probabilities derived from 14 day neap-spring tidal cycles.

In addition to the analysis period (e.g. 14 days), the numerical model will need a "warm-up" period to ensure that both hydrodynamics (a matter of hours up to a couple of days) and sediment plume characteristics (depending on site conditions, but usually a matter of days up to a couple of weeks) are well established. A "warm-up" period in the order-of-magnitude of a week is usually ample for sediment plume modelling. A conservative approach is to conduct full month simulations, i.e. in excess of a 14 days neap-spring cycle warm-up.

If sediment re-suspension is significant and it is considered important to maintain the full history of the dredge spill in the model for the impact assessment, longer simulation periods may be required, and it may not be possible to use "short" scenarios. The effects of re-suspension can partly be accounted for by priming each simulation with an initial map of sediments previously spilled, in particular along all areas previously dredged (assuming overflow of hopper/barges and other spills settling in and along dredge corridors) and within any spoil grounds within the model domain. The history of sediment transported further away from the source through continued re-suspension, transport and re-settling is, however, not easily accommodated in short term scenarios. Whereas this process over an extended period of time can transport sediments far from the source and increase the area influenced by the dredging, it is the authors' experience that including a map of sediments along the previously used dredge and dumping areas together with the spills over a 14 day warm-up period captures the incremental impacts from sediment re-suspension well in most cases. This is, however, site and project specific and needs to be addressed carefully when choosing the simulation period.

If the process of re-suspension of released sediments is a significant factor for the EIA and if it is crucial to track spoils and maintain the full "history" of the released sediments throughout the dredge period then modelling based on a scenario approach is not an obvious modelling strategy and full-dredge period simulations may be the only way forward.

6. Benefits of scenario approach modelling

A key advantage of the scenario modelling approach is that the derived impact envelope is generally not dependent on the dredging schedule, although it does depend on the sequencing if several operations which can generate overlapping plumes are carried out in parallel. Other key features and advantages include:

- Fast simulations for individual scenarios (assuming fairly short duration simulations can be applied). The turn-around time can e.g. be of significant importance when feedback from model results is required as input into project-related decisions. Fast simulations can also be utilised to simulate a larger number of scenarios or converted into higher resolution of the model and processes involved.
- Capturing potential impacts from a large matrix of potential climatic, dredge and spill conditions. The possibility of simulating a large number of scenarios thus ensures that critical conditions in time and space can be captured, and a "total envelope" for the potential impacts can be developed
- Greater flexibility in terms of testing different scenarios, performing sensitivity analysis and adapting/testing new conditions as they are developed through the course of the project

- Impacts from changes to a given dredge programme, both in terms of timing and use of different approaches if the associated spill rate can be assessed, are easily assessed.

The scenario approach is furthermore ideal for optimisation of the dredge programme and mitigation measures to meet environmental objectives through:

- Easy identification of critical stages or combinations of the simulated variables that generate the largest impacts.
- Optimisation of dredge programme to minimise impacts (e.g. avoiding dredging in critical areas during certain climatic conditions, minimising spill in critical sectors, etc.)
- Quantifying overflow restrictions in given areas to minimise impacts.

The scenario modelling approach is ideal for establishing the understanding of the system that can allow maintaining a large degree of flexibility in the dredge management during implementation. An example of a flexible and adaptive management approach is based on a spill budget (see [1]) which determines the maximum allowable sediment spill for defined zones and conditions on critical variables, e.g. variable with climatic conditions.

7. Overall EIA strategy

The scenario approach in varying form has been applied for EIA assessments for sediment plume generating activities in DHI's South-east Asia offices, and an overall modelling and impact strategy based on the following main components has been developed:

- Identification of environmental receptors within the anticipated potential areas of impact.
- Establishing impact criteria for the environmental receptors. The impact criteria are typically related to medium term exceedences of certain threshold limits for environmental indicators that can be quantified through modelling (typically excess sediment concentrations and sedimentation rates, but could also be for instance light attenuation). The threshold limits and impact criteria are site and receptor specific.
- Identifying the main variables and uncertainties controlling the spillage and sediment dispersion from the dredge programme (or other activities causing impacts).
- Identifying the key spill generating activities for subareas as required and establishing a range of conditions for the above variables to be covered in the modelling. This would typically include both "best estimate" and conservative values reflecting the uncertainties of the input data.
- Establishing a suite of scenarios encapsulating the defined ranges for the main variables.
- Using the suite of modelled scenarios and the established impact criteria to assess the environmental impacts and risks for each individual scenario.
- Establish an envelope of potential impacts by combining the results from all individual scenarios.
- Use the suite of scenarios to identify the critical scenarios in terms of environmental impacts, and use this to develop suggestions to optimisation of the dredge plan and procedures to meet the environmental objectives.

The use of the individual scenario outputs for the impact assessment can be tailored to a given project. Some possibilities include:

Option (1): Producing an envelope for the potential impacts by combining the individual impacts from all the scenarios. This represents an outer boundary for the individual footprints of any dredging programme that is reasonably represented by the various dredge scenarios.
Option (2): Estimating footprints from individual dredge programmes by combining the relevant scenarios to emulate the programme. This does not include the full history of the spill as previously discussed, but will generally provide a reasonable estimate of an impact footprint.

The first approach provides a good indication of the receptors at risk, but should not be confused with an actual "footprint" of the project. The second approach provides an estimate of an actual footprint of the project for a given dredge plan. It should be stressed that this is closely tied in with the assumptions for the dredge plan, and is generally not a good indication of the receptors at risk from the overall programme given the high probability at the EIA stage of changes to the dredge schedule.

The impact zone derived using Option (2) is expected to be a subset of the "envelope" impact zone derived using Option (1). If the individual "footprints" are significantly smaller than the envelope, which will often be the case, there is likely significant scope for optimisation of the dredge programme to minimise environmental impacts. The results from the scenario based modelling approach can readily be used for this optimisation process by "interrogating" the results to e.g. provide information on:

- Which are the critical scenarios to be avoided?
- Which areas can be dredge for a given season with minimal impacts?
- When is a given area best dredged to minimise impacts?

- Which dredge methodology leads to the lowest impacts for given areas?
- If a Trailing Suction Hopper Dredger is used (which has significantly reduced spill during the initial filling of the hopper of each dredge cycle), which areas are most critical and should be targeted for the initial filling with low spill rates?

All this information can feed into the final planning of the dredging and disposal plan to ensure that the environmental objectives are taken into account in the planning stage. Having a full picture of the cause and effects for the spills and impacts will often allow significant mitigation of potential impacts at a much lower cost than other mitigation measures that may be enforced or required to meet management objectives.

8. References

[1]. Dredging and port construction around coral reefs, PIANC report N° 108, 2010.