STRATEGY FOR REMEDIATION OF CONTAMINATED FJORD SEDIMENTS IN NORWAY

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ABSTRACT

Norwegian fjords are typically threshold fjords with little circulation forming deep anoxic basins. The absence of major rivers results in slow sedimentation rates and a general fine sediment texture. Near urbanised areas the fjords form the ultimate sink for pollutants released to the marine environment. Since navigation maintenance is seldom an argument for dredging activities in Norway, the question arises as to what the optimal remediation strategy would be. Disturbance of the sediments by dredging or other engineering activities might not result in a general improvement of the environment. To be able to answer this question, the long-term stability of the contaminated sediments has to be determined both with respect to physical as well as chemical properties. Using this approach alternative remediation strategies can be developed with a beneficial environmental result. Two examples of this approach are presented: the active use of anoxic basins for sub-aqueous sediment containment in the Oslo fjord and capping by land reclamation in Drammensfjord.

RÉSUMÉ

Les fjords norvégiens sont typiquement des fjords barrières à faible circulation formant des bassins profonds anaérobiques. L'absence de rivières majeures entraine des taux de sédimentation faibles et une texture générale fine des sédiments. Aux alentours des zones urbanisées, les fjords forment le réceptacle ultime pour les polluants relâchés dans l'environnement marin. Puisque l'entretrien de la navigation est rarement un argument pour les activités de dragage en Norvège, la question d'une stratégie optimale d'assainissement se doit d'être posée. L'agitation des sédiments par dragage ou autre activité d'ingéniérie peut ne pas aboutir à une amélioration générale de l'environnement. Pour être capable de répondre à cette question, la stabilité à long terme de sédiments pollués a été déterminée à la fois vis-à-vis de leurs propriétés physiques mais aussi chimiques. En utilisant cette approache, des solutions alternatives d'assainissement peuvent être développées avec un résultat avantageux pour l'environnement. Deux examples de cette approche sont présentés: l'utilisation active de bassins anaérobiques pour contenir les sédiments sous-marins dans le fjord d'Oslo, et le recouvrement par le défrichement de terrain dans le fjord de Drammen.

1. INTRODUCTION

In Norway serious contamination of marine sediments has been found in more than 120 areas (SFT, 1998). This has resulted in restrictions on the consumption of fish and fishery products in 24 fjords and harbours covering 820 km^2 (SFT, 2000). The cost of preventing further deterioration is estimated at 1.1 billion USD, while improvement of the present day situation to a level which doesn't pose a danger to the ecosystem is estimated to cost 3.5 billion USD.

The Ministry of the Environment has identified the abatement of contaminated coastal, fjord and harbour sediments as a top priority for the coming years (MD, 2002). However, large gaps in the required knowledge to solve these problems exist. Priority areas are:

- Development of technological solutions
- Documentation of efficiency of solutions
- Quantify environmental response after contaminant reduction

Extensive experience and knowledge has been gained internationally; however, transfer of this knowledge must be adapted to consider the conditions typical in many Norwegian fjords. Threshold fjords with little circulation, forming deep anoxic basins are common. The absence of major rivers results in low sedimentation rates and generally fine textured sediments. These naturally defined conditions impose an understanding of the chemical and physical stability of contaminated sediments when assessing potential remediation methods.

2. STABILITY OF CONTAMINATED SEDIMENTS

To be able to assess the efficiency of sediment remediation options a proper understanding of the physical and chemical stability of the contaminants is required. This will allow a prediction of contaminant mobilisation and migration under various environmental stresses. A schematic overview over the main processes determining the stability of contaminants in sediments is shown in Figure 1.

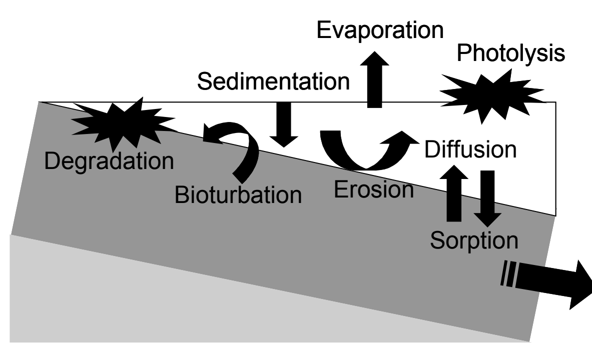

Figure 1. Main processes determining fate and transport of contaminants from sediments.

As a result of the general depth of Norwegian fjord systems, there is a less frequent need for maintenance dredging. Large-scale remediation will therefore be initiated by environmental requirements. However, remediation and construction works will often exert extreme changes in physical/chemical conditions compared to natural processes. These stresses might result in a deterioration of the present day situation over a defined period of time. An overview over the main sediment processes influenced by anthropogenic activities is shown in Table 1.

Table 1. Anthropogenic influence on critical sediment processes (after Deliman et al. 2001)

Process	Anthropogenic influence
Sorption	Mixing with uncontaminated water
Dissolution	Redox mitigated dissolution by mixing with oxic materials
Erosion	Changes in surface structure increased resuspension
Mass flow	Loading and disposal of sediments under physical unstable conditions

The majority of contaminants is often found in the fine fraction (< 75 µm), while the coarser material is less contaminated (Murray et al. 1999). This would present a method to separate uncontaminated from contaminated sediments by particle size fractionation. However Norwegian fjord sediments are dominated by silts and clay (tab. 2) resulting in low recoveries of uncontaminated sediment. Recent research has in addition shown high levels of organic pollutants (PAH and PCB) in the coarse fraction near urbanised areas indicating a strong particle association as well as origination of the contaminants (Eek et al. 2003).

Table 2. Overview over contaminant levels and physical parameters in selected Norwegian harbours (Oen et al. 2003).

Parameter	Oslo Bjørvika	Drammen Harbour	Sandefjord Fjord
Particle size:			
2-75 µm (%)	71	48	57
< 2 µm (%)	20	39	27
Cd (mg/kg)	4.27	0.47	0.58
Hg (mg/kg)	6.15	0.33	0.95
Pb (mg/kg)	342	45	24
PAH_{16} (mg/kg)	40.8	32.8	24.0
PCB_7 (mg/kg)	0.026	0.014	0.049

As a result of anoxic conditions in the fjord sediments the availability of heavy metals is limited under sulphate reducing conditions (Lee et al. 2000; Schaanning et al. 2000). Resuspension in an oxic environment might however result in oxidation of the sulphide mineral phases and release of heavy metals (Simpson et al. 1998; 2000). Interaction with oxides in sediment capping material was also found to have a potential for heavy metal release (Eek et al. 2002).

To understand stability of the contaminants stored in marine sediments under various anthropogenic stresses, an integration of chemical and physical understanding of the contaminant solid matrix interaction is required. Based on this knowledge alternative remediation solutions can be designed.

Two examples from Norwegian sediment remediation plans are presented; a sub-aqueous containment in the Oslofjord and land reclamation in the Drammen river estuary. Sub-aqueous containment in Oslofjord requires specific knowledge of the anoxic conditions local to the area and how these influence the long-time stability of the sub-aqueous confined disposal facility. Land reclamation in the Drammen river estuary illustrates methods of quantifying and documenting sediment stability under construction works to ensure successful capping with minimal environmental impact.

3. SUB-AQUEOUS CONTAINMENT

The sediments in Oslo harbour have been contaminated as a result of industrial dockyard activities, municipal wastewater, and small rivers draining from industrial areas. In addition, boat and highway traffic have contributed to the contamination. A layer varying in thickness from 0.1 to 2.7 m is highly contaminated by heavy metals and organic contaminants (tab. 2). To be able to prevent spreading resulting from boat traffic as well as to carry out maintenance dredging for the first time in 11 years, 780,000 m^3 of in-situ contaminated sediments are currently planned for removal (NGI, 1996; 1999).

The deeper parts of the Oslofjord form a basin where anoxic conditions prevail (Fig 2). These basins can be actively used for sub-aqueous containment of the contaminated sediments since exposure of the marine ecosystem is unlikely as long as physical stability and resuspension of the sediments can be prevented.

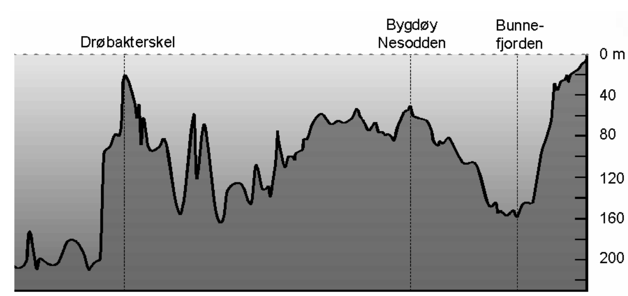

Figure 2. Depth profile of the Oslofjord from the entrance at the threshold at Drøbakterskel (left) to the innermost parts near Oslo (Bunnefjorden). A distance of approximately 50km (Oslo Harbour, 2001).

To be able to select an appropriate location for sub-aqueous containment the following criteria were used:

- limited transport distance
- basin should already be contaminated
- anoxic conditions prevail
- thresholds should prevent lateral spreading
- limited water flow rates near the fjord bottom
- basin capacity should exceed dredged sediment volume

Based on these considerations a location at Malmøykalven was selected as most appropriate (Fig. 3). The deepest part of the basin is at – 72.5 m and the maximum water current is less than 3 cm/s, resulting in sedimentation conditions and particle accumulation. Only during short periods of deepwater exchange (7 to 10 days, every other to every third year) is resuspension of sediments expected (NIVA, 1999).

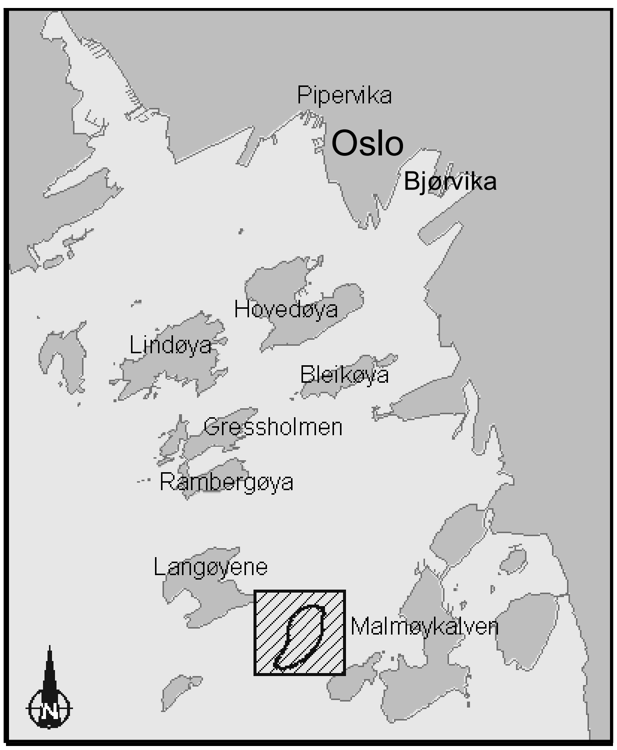

Figure 3. Proposed location of the sub-aqueous containment site at Malmøykalven (Oslo Harbour, 2001).

No benthic organisms have been registered as a result of low oxygen levels in the water column (anoxic below 40 m depth). Additionally, the site has been used as a disposal site for condemned vessels and dredging material.

The thresholds surrounding Malmøykalven have an elevation of -66 m, forming a natural basin with a volume of 390,000 m^3. To be able to contain the total expected volume of contaminated sediments, an artificial threshold of 3 m high will be established at the north-east site of the location. This results in a basin with an area of 350,000 m^2 and a containment capacity of 1,230,000 m^3.

Following placement of the sediments utilising a submerged pipeline, the sediments are left to consolidate. By properly timing the construction works, sediment placement and consolidation can be accomplished without the risk of contaminant spreading in the event of a deep water circulation period. A cap will be placed on top of the sediments to prevent contaminant transport to the water column as well as to increase the physical stability of the disposal site. At present no benthic organisms are registered in the sediments at Malmøykalven. However, in order to guarantee the integrity of the disposal site in the possibility of biota establishment, a minimum cap thickness of 0.5 m is recommended. As a result of compressibility of the dredged material the capping should be carried out in successive layers. The disposal site will be covered with several layers of 10 cm sandy material. In this way potential cracks in the cover as a result of consolidation will be covered by subsequent covers (Fig. 4). The top layer will be gradually coarser to increase the erosion resistance.

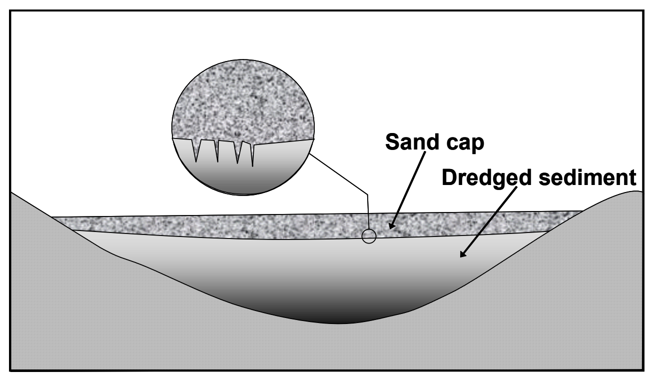

Figure 4. Final structure of the containment system after the cover layer has been placed (Oslo Harbour, 2001).

Once capping is completed, diffusion through the cap will be the only remaining pathway of contaminant transport. Aqueous solubility of the organic contaminants found in the sediments is very low and as long as anaerobic conditions prevail, heavy metals will remain in sulphide mineral complexes (Eek et al. 1998). However questions remain concerning interaction with oxic minerals in the cap. Long term studies are needed to verify these assumptions (NGI, 2003a).

Uncertainty remains concerning gas release from the anoxic sediments. Methane solubility in water is limited, however as long as the permeability of the cap is sufficiently high gas accumulation is not very probable.

4. LAND RECLAMATION

Holmen Island, in the estuary of the Drammen River, is used as industrial terminal by the Drammen harbour authorities. Expansion of harbour activities required land reclamation of 125,000 m^2 (fig. 5). The water depth in the area varies from 0 to 31 meter and an estimated 3 mill. m^3 of fill material is required. To be economically feasible, tunnel spoil rock from a nearby tunnelling project was used. The blast rock originates from alternating shale limestone layers and is therefore of a finer grade.

The bottom sediments in the area planned for land reclamation were found to be highly contaminated with PAH (tab. 2). Covering the contaminated sediments with unpolluted fill material would improve the environmental conditions considerably. However, the use of blast rock as filling material could result in resuspension and mass flow of the contaminated sediments and thereby increase contaminant transport to unpolluted areas of the fjord. To prevent mass flow during back-filling, a 3 m high rock-fill threshold was established surrounding the reclamation area.

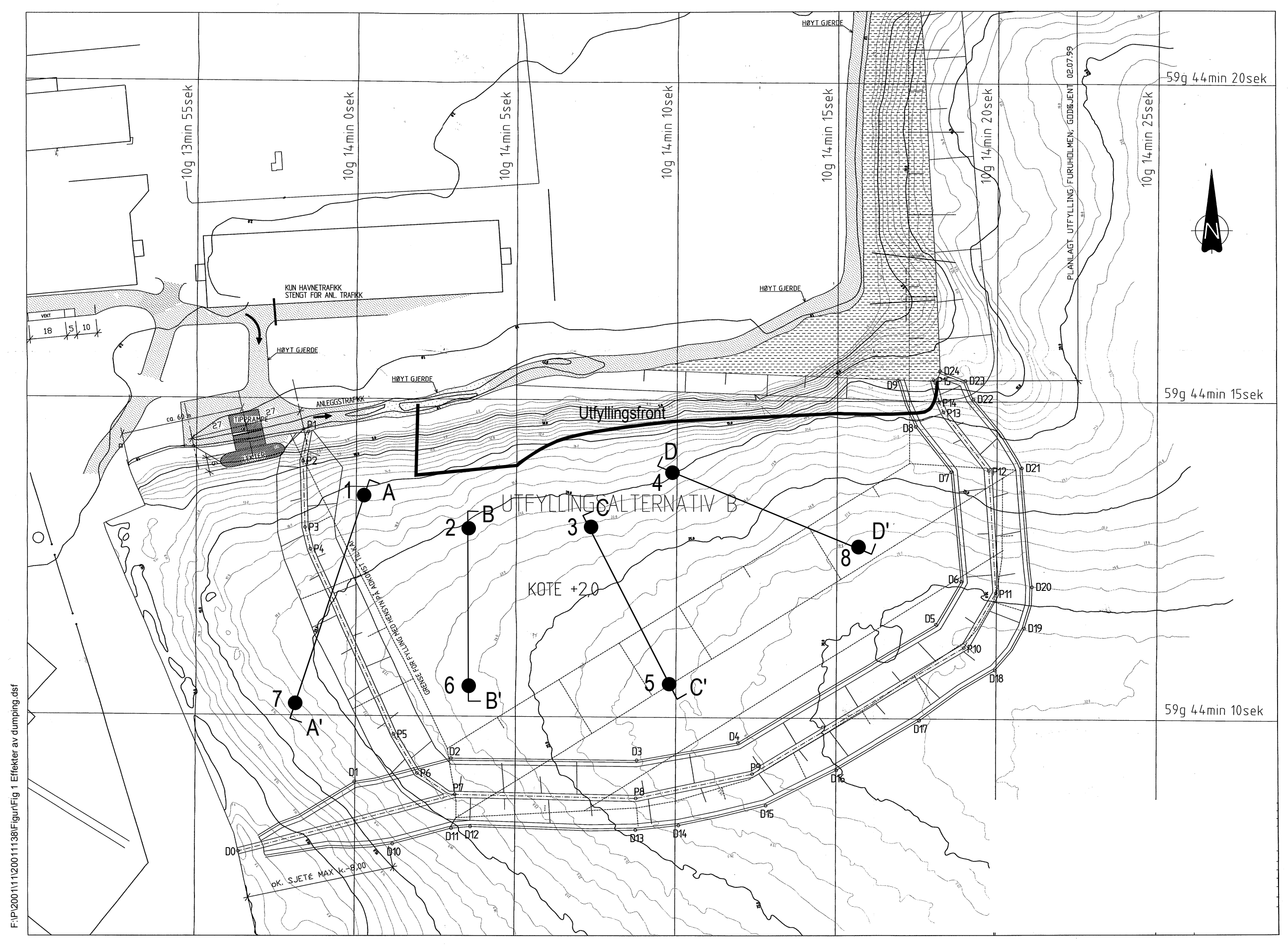

Figure 5. Overview over the land reclamation area at Holmen east, Drammen harbour (NGI, 2002).

To assess the risk for contaminant migration, monitoring during field studies of two different back-filling methods was carried out; back-filling from the main land and dumping from a barge at 20 m water depth.

To study the effect of back-filling from the main land, 8 observation stations were established, 4 stations near the dumping front and 4 stations approximately 70 m away (Fig. 5). Turbidity was measured at 0.5 m intervals in the water column. Turbidity over 3 times the background value was used as trigger value for PAH sampling (NGI, 2003b). Water samples from three of the stations closest to the dumping front (1,2 and 4) showed a PAH content varying from 0.027 to 0.086 µg/l. PAH was only detected at the turbidity maximum, which varied between 3.5, 16 and 3.0 meter water depth for stations 1, 2 and 4 respectively. The PAH distribution revealed however a composition which could not directly be related to the PAH composition of the sediments.

Dumping of 150 m^3 blast rock from a barge showed a clear increased turbidity 20 m away (fig. 6). This increased turbidity was limited to a narrow zone of 4 m, at a depth coinciding with the sediment depth at the dumping site (24 m). A rapid decrease in turbidity was observed after 10 min. Simultaneous water sampling during turbidity measurements revealed that PAH could only be detected in small amounts (0.028 µg/l) at the turbidity maximum 35 min after dumping (NGI, 2002).

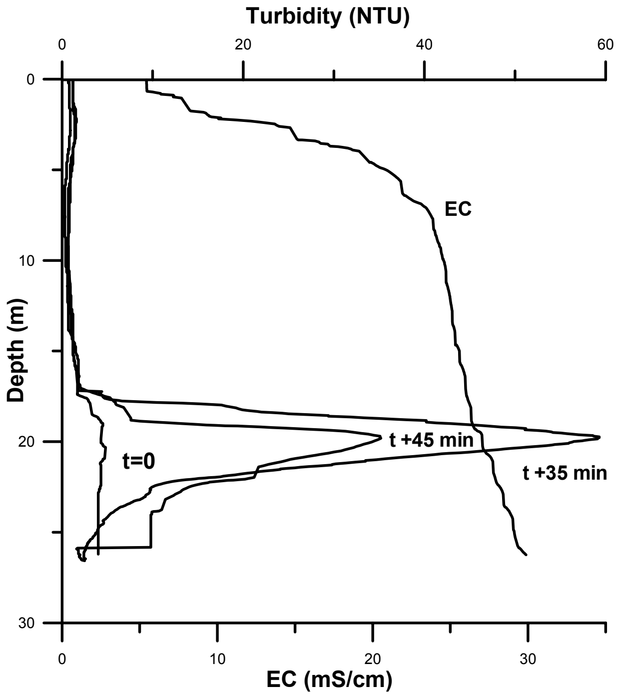

Figure 6. Change in turbidity profile after dumping of blast rock from a barge, the salinity profile shows the influence of the river water in the upper 5 m of the water column.

5. CONCLUDING REMARKS

Disturbance of historically polluted sediments by dredging or other engineering activities imposes considerable stresses on the contaminant/solid matrix which might result in redistribution and release of contaminants into the environment. Knowledge on the long-term stability of contaminated sediment with respect to physical, chemical and biological processes are therefore required for various remediation options as well as for the no-action alternative. This information ensures selection of the environmentally most effective remediation method. Additionally it provides the documentation required to gain public acceptance.

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