Appendix 3A

Literature Review on the Handling and Treatment Methods for Contaminated Sediment

Evaluation and comparison of alternative handling and treatment methods

The contaminated sediments are a worldwide environmental concern. Sediment beneath the floating dock may be contaminated with chemicals (e.g. TBT) discharged from the maintenance deck. The handling methods of contaminated sediments depend on various aspects of consideration including national legislations, the nature of contaminants, quantity, the future use of the area, technology, cost and social acceptability.

The handling and treatment methods can be categorized into three approaches:

- leave the sediments in place
- in-situ treatment
- ex-situ treatment and disposal

Leave the sediments in place

Leaving the sediments in place is one of the handling approaches. If the conditions are appropriate, natural sedimentation will bury or contain the contaminants at their original location.[1] This approach allows the contaminants to degrade under natural conditions.

Its key advantage is that it can minimize the risk from handling and disposal of the contaminated sediments. Regardless of the cost and the effectiveness of the treatment methods, the sediment removal involves dredging operations during which the suspended sediments, even if uncontaminated, is a source of concern. Re-suspended contaminated sediments may induce the release of the buried contaminants. This may lead to the release of more toxic substances under aerated condition during the dredging operation. The potential impacts on the benthic organisms include the loss of submerged aquatic vegetation, inhospitable area for crustaceans, mortality, reproduction decrease and slower growth of molluscs, the habitat of corals (e.g. reduce species diversity, less live coral, lower growth rates, decrease in calcification and slower rates of reef accretion) and the burial of hatching area for fish.[2]

This method also avoids the generation of other environmental impacts of the by-products from treatments e.g. possible leachate from solidified sediment, space for disposal and noxious emissions from thermal desorption and incineration. It is also the most economical option. This option is appropriate when the pollutant discharge source has been halted, and burial or dilution processes are rapid. This option may not be viable if the area will be developed in future (e.g. reclamation) and continuous monitoring of the recovery progress will be required.

Examples of application:

Kepone, a toxic insecticide and fungicide, entered the James River in Virginia, USA through effluent discharge from the manufacturer and contaminated the river sediment. Because of the high partition coefficient, the majority of kepone was found in the sediment. Since Kepone was banned from being manufactured and used in 1975, the kepone concentration in the surface sediment began to decrease significantly. The contaminants were diluted and buried by fresh sediment. Kepone concentrations in fish were found significantly reduced in 1983 and the restrictions on all commercial fishing were lifted.

Dredging and stabilization have been assessed to evaluate the feasibility of mitigating the kepone contamination. Neither of these options was feasible, either economically or environmentally. This no action decision was based on the fact that natural sedimentation buried the kepone-contaminated surface sediment making kepone unavailable to biota. However future dredging of the sediment for navigation is restricted as dredging might expose the kepone-contaminated sediment.[1]

In-situ treatment

In-situ sediment treatments include capping, solidification/stabilization, biological treatment, chemical treatment methods and ground freezing. In consideration of the cost and the effectiveness, in-situ capping is a potentially economical and effective approach for remediation of contaminated sediment. A number of sites have been remediated by in-situ capping operations worldwide.[3] A layer of clean sediment covers the contaminated sediment so as to isolate the contaminants from the environment. The major advantage of this method is that the need to remove contaminated sediments is eliminated. However this will depend on the water current of the surrounding environment. The imported sediment will be flushed away under strong current, and thus frequent replacement of sediment will be required. Moreover water diversion is not possible in the sea. Some disturbance of the contaminated sediment is expected during the placement of clean sediment. The transportation cost of the delivery of clean sediment to the site will be the major handling cost. This option is not viable if the area will be for navigation and require reclamation for future development. A simple description /explanation should also be given to solidification, biological treatment and ground freezing. Copy the description from the table.

Examples of application:

At the Denny Way project, a layer of sandy capping sediment was spread over a three-arce contaminated near-shore area with water depths of 20 to 60 feet. A combination of a sewer outfall discharge and combined sewer overflow had contaminated the site with lead, mercury, zinc, PAHs and PCBs.[3]

At Eitrheirn Bay in Norway, a composite cap of geotextile and gabions was constructed as a remediation project in a fjord at an area contaminated with heavy metals. A total area of 100,000 square meters was capped, in water depths of up to 10 meters.[3]

Shing Mun River in Hong Kong had been heavily polluted in the 1980s due to rapid increase of population in Sha Tin, indiscriminate discharge from industrial, commercial, livestock and domestic sources. The accumulation of contaminated sediments over the past few decades adversely affected the water quality. It also released obnoxious odour at times, and suppressed the development of a balanced ecology within the river system. In-situ bioremediation process, Limnofix, was employed, which involves the injection of chemicals (oxidant) to convert organic matters to harmless carbon dioxide and water. The level of AVS, which is the source of obnoxious odor, in the treated sediment, has dropped from the initial concentrations ranging from 5,800mg/kg - 150mg/kg to 310mg/kg - <5mg/kg. The removal efficiency is over 90% (ranging from 90.3% to 99.9%) after treatment.[4, 13]

Ex-situ treatment and Disposal

Ex-situ treatment and disposal involve the dredging operation. The dredged contaminated sediment is removed from the original site and delivered to the treatment or disposal facilities. There are several treatment and disposal methods developed. They include biological treatment, dechlorination, solvent extraction, soil washing, thermal desorption, solidification/stabilization (S/S), incineration and confined disposal facilities (CDFs). Among these treatments, S/S is most commonly adopted in Hong Kong for the treatment of contaminated sediment/soil. S/S is also a promising treatment technology for containing and immobilizing dredged material contaminants within a disposal site. The technology has also been applied in Japan and in the United States.[4] The advantages of this method are that the treated sediment in the form of concrete can be reused for public filling and the contaminants removed from site will not limit the future use of the area. There is a constraint if the marine sediment contains high water content. Pre-treatment is required to remove the water. Moreover dredging operation will be required to remove the contaminated sediments, which will suspend the contaminants. These off-site treatment methods usually require secondary treatment of the by-products such as wastewater, noxious emissions and solid waste.

Examples of application:

Sediments at the New York/New Jersey Harbor were contaminated with Organochlorine pesticide, PAHs, PCBs, Dioxins and Furans, and metals.[3] S/S was adopted in the treatment of the contaminated sediment. The treatment of the material was done in a barge.[5] Stabilized materials have been used as structure fill at a parking lot and capping brownfield site in New Jersey.[6]

Heavy metals and Arsenic, was naturally accumulated at San Tin, Hong Kong. During the construction of San Tin Eastern Main Drainage Channel[7], the excavated contaminated sediment with high concentration of Arsenic (ranging from 32.2mg/kg to 360mg/kg) was solidified in accordance with the Type 3 disposal criteria under the Technical Circular No. 3/2000[8]. The treated sediment was delivered to public fill for reuse.

The sludge on the barge from Rotterdam Harbour, The Netherlands, is contaminated with TBT. The TBT levels in the harbour are high, up to 0.4mg/kg sediment and well above the Dutch acceptable levels in sediments (0.0007mg/kg). Annually, approximately 20 million tons of sludge is dredged from the harbour, of which 16 million tones is dumped in the North Sea, just outside of the Port of Rotterdam, and 4 million tones, classified as heavily contaminated, is disposed of in a special depot.[9] Papegaaiebek (Parrot's Beak) site in Rotterdam is a 40-ha upland CDF specially designed for highly contaminated dredged material from Rotterdam Harbour. The site was designed with a 2mm-thick HDPE liner and leachate collection system.[10]

The details of different types of handling, treatment and disposal methods for contaminated sediments are summarised in Table 1.

Table 1 Handling, Treatment and Disposal Methods for Contaminated Sediments

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
• **Leave the sediments in place**				
No Action[1]	• Leave the sediments in place	This method is appropriate when the pollutant discharge source has been halted, burial or dilution processes are repaid, sediment will not be remobilized by human or natural activities, and environmental effects of cleaning up are more damaging than allowing the sediment to remain in place.	• Low cost • Low risk of contaminant spreading	• Relies on natural process such as input of uncontaminated sediments and their integration with in-place contaminated material through dispersion, mixing, burial and biological degradation. • Water quality monitoring programme is required.
Monitored Natural Recovery[11]	• Leave the sediments in place • Relies on natural process to contain or reduce the bioavailability or toxicity of sediments left in-place • Unlike “No Action” approach, source control and an appropriate monitoring program to insure the effectiveness of the processes are required	• The following processes are import to MNR: burial and in-place dilution following deposition of clean sediment and biodegradation or abiotic transformation processes which convert the contaminants to less toxic forms.	• Low cost, limited primarily to monitoring cost • The avoidance of disruptions to the waterbody.	• Contaminated sediment is left in the aquatic environment for the time period during which the natural processes act to reduce the risks, and the potential for future disruption of buried contaminants by storms, floods, or other episodic events. • Long term water quality monitoring programme is required.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
• **In-situ Treatment**				
Subaqueous Capping[1]	• Leave the sediments in place but capping (covering) contaminated sediments at their original location • Underwater capping (covering) of contaminated sediments with cleaner, less contaminated sediments with or without lateral walls. • The cap may be constructed of clean sediments, sand, gravel, or may involve a more complex design with geotextiles, liners and multiple layers.[2]	• The no action alternative does not provided sufficient protection. • Point source discharges have been halted. • The costs and environmental effects of moving/treating contaminated sediment are too great. • Suitable capping materials are available. • Hydrologic conditions will not disturb the site. • Bottom will support the cap. • The area is amenable to dredging.	• Low cost • Low risk of contaminant spreading	• Conflicting uses such as navigation may dictate that contaminated sediments be moved from their original site of deposition. • Water quality monitoring programme is required.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Solidification / Stabilization[1]	• Immobilize sediment and contaminants by treating them with reagents to solidify or fix them	• Contaminated sediments not suitable for removal from their original location	• Reduce contaminant mobility	• Inaccuracies in reagent placement, erosion, long-term monitoring requirements, the inability of the procedure to remove / detoxify contaminants, difficulty in adjusting solidification mixtures / agents for subaqueous settings. • Little is known about the costs of large-scale treatments, their effectiveness, or their possible toxic by-products. • Not feasible in any area where the solidified mass cannot be tolerated (e.g. future construction or dredging)

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Biological Treatment[1]	• Both aerobic and anaerobic biological treatment can effectively treat a wide range of organic contaminants through degradation process.	• Sediment containing organic contaminants	• A wide range of organic contaminants can be treated.	• It does not clean up inorganics. • Partial degradation products (e.g. degradation of trichloroethene, resulting in the formation of vinyl chloride) may be more soluble or toxic than the original contaminants. • The degradation process can be impeded by high organic concentrations, oxygen deficiency, lack of nutrients and low temperature.
Chemical Treatment[1]	• Treating contaminated sediments by neutralization, precipitation, oxidation, and chemical dechlorination.	• Contaminated sediments in stream where diversion for the duration of treatment can be made.	• A wide range of organic contaminants can be treated.	• Potential for secondary impact (e.g. the treatment reagents themselves are toxic, or as a result of potentially toxic degradation products) • Difficult to ensure that the treatment reagents are completely mixed with the contaminated material • Site constraint i.e. only applicable to water streams where diversion can be made.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Limnofix In-situ Sediment Treatment, LIST[12, 13]	• Developed by the National Water Research Institute of Environment Canada. LIST uses specially-designed equipment to inject chemicals directly into contaminated sediments that will enhance bacterial activity and hence contaminant degradation.	• Capable of remediating to sediment depth of about 0.5 meters. • Biodegradation of simple organic contaminants including PAHs, BTXs, and petroleum hydrocarbons.	• Removal efficiency of PAHs and TPHs over 60% and 80% respectively. • Sediment oxidation can control problems created by anoxic sediments such as odours, nutrient release and toxicity caused by sulphides. • Enhanced dredging efficiency through in-place sediment dewatering pre-treatment. • Sediment consolidation and flocculation to produce stable marine sediment surfaces.	• Special chemical injection equipment is required. • The removal efficiency of full scale treatment of heavily contaminated sediment of PAHs and TPHs is unknown at this stage.
Ground Freezing[1]	• The process involves placing refrigeration probes in the sediments at close intervals and cooling them from a potable refrigeration unit. • Ice crystals grow until they coalesce and form a wall of frozen sediment	• Small volumes of contaminated sediments	• Containing and facilitating the removal of contaminants in sediments.	• The process is extremely slow. Each probe can freeze only a small zone about 1.5 feet in diameter. • Costly because of high energy requirements • Not suitable for large volumes of contaminated sediments

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
• **Ex-situ Treatment**				
Biological Treatment[1]	• Bio-oxidation of organic matter by micro-organisms using bacteria, fungi, or enzymes to break down PCBs, pesticides, and other organic constituents into less toxic or innocuous compounds. • Slurry-phase treatment is more costly (US$80-150 per cubic yard (USEPA, 1989e)) than solid-phase treatment (US$50-80 per cubic yard (Torpy, 1989)).	• Slurry-phase and solid-phase treatments are effective on soils, sludges and sediments. • Slurry-phase reactors operate from 15°C to 75°C.	• High removal efficiency for PCP and PAHs	• Biological processes can generate residue streams that may require additional treatment (e.g. wastewater and air emissions). • The presence of heavy metals can inhibit microbial metabolism and thus affects the removal efficiency. • Products of biodegradation may be more soluble and toxic than the original materials. • Process residues such as water, may require further treatment before disposal. • The treatment system is costly.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Biological breakdown of organotins - Lagooning[14]	• Biological breakdown of organotins • Dredged sediment is spread out over a large area and is first dewatered by lagooning (natural removal of water by drainage and evaporation). As the sediment gets more and more oxidized, aerobic bacteria actively oxidize organic material in the sediment, including TBT. • Phytoremediation (i.e. the use of plants to remediate soil or sediment) can be followed after lagooning to enhance the microbiological activity around the plant root system, improving bioremediation.	• Warmer and drier climates can obtain TBT-removal efficiency of above 70%.	• Low investment cost • Large quantities (thousands of cubic meters) can be treated at once and simultaneously in a layer of about 1 meter thick.	• Require land space • Long treatment time (as a period of about six months of West-European summertime weather conditions)

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Dechlorination[1]	• The process heats and mixes contaminated soils, sludges, or liquids within an alkali metal-hydroxide-based polyethylene glycol reagent in a batch reactor. • Treatment costs range from US$200-500 per cubic yard (USEPA, 1990h).	• Effective in detoxifying specific types of aromatic organic contaminants, particularly dioxins and PCBs.	• High removal efficiency of PCB	• Additional treatment of sediment may be required to desorb both reaction by-products and reagent. • The residue wastewater may require treatment before disposal. • The treatment system is expensive.
Solvent Extraction[1]	• The wastes will not be destroyed. The process separates the hazardous contaminants from soil, sludge and sediment, using organic solvents, thereby reducing the volume of the hazardous waste that must be treated. • Depending on the required removal efficiency and contents of contaminated sediments, the cost ranges from US$200-600 per cubic yard.	• Effective in treating sediments containing semivolatile organic compounds (SVOCs) such as PCBs, volatile organic compounds (VOCs), halogenated solvents, and petroleum wastes.	• The solvent can be recovered and reused. • Able to reach high removal efficiency.	• Additional treatments are required for sediments containing large particles, heavy metals and inorganics. • By-products such as solids, water and concentrated organics streams may need further treatment before reuse or disposal.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Soil Washing[1]	• Soil washing is a water-based process for mechanically scrubbing excavated soils and sediment to remove contaminants. • Soil washing removes contaminants from sediment either by dissolving or suspending them in a wash solution. • Treatment costs range from US$200-400 per cubic yard (USEPA, 1990k).	• It is most effective on coarse sand and gravel and least effective on clay and silt. • This technology can treat a wide variety of sediment contaminated with soluble metals, halogenated solvents, aromatics, gasoline, fuel oils, PCBs, chlorinated phenols and pesticides.	• Potential to treat wide variety of contaminants. • High removal efficiency, over 90% for volatiles and 40-90% for semivolatiles.	• This process cannot efficiently treat fine particles, low-permeability packed materials, or sediment with high humic content. • Residual solvents and surfactants can be difficult to remove after washing. • High treatment cost

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Thermal Desorption[1]	• A method of removing volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs) from contaminated sediments. • The treatment consists of heating the soil matrix at a temperature below combustion, typically 93°C to 538°C, evaporates the VOCs and some SVOCs and drives off water. • Treatment costs range from US$110-470 per cubic yard, dependent on the site size, the contents of sediment and cleanup standards.	• It is applicable to the separation of organics from refinery wastes, coal tar waste, wood treating wastes, creosote contaminated sediment, hydrocarbon contaminated sediment and any contaminant with boiling point up to 538°C. • Contaminated sediment, for material handling purposes, must contain at least 20% solids.	• This results in a large reduction in waste volume. • More effective than some other processes, such as solvent extraction because it volatilizes more organics due to its higher operating temperature.	• Sediment contains objects greater than 1.5 inches needs to be removed. • High fractions of fine silt or clay can generate fugitive dust, causing greater dust loading on downstream air pollution control equipment. • Not as effective as high temperature incineration because it only evaporates the VOCs and some SVOCs, while incineration destroys all the organics.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Solidification / Stabilization[1, 5, 6]	• A technique that mixes reactive materials with solids, semi-solids, and sludges to immobilize contaminants. • Cement-based solidification, silicate-based solidification, and microencapsulation are available in market. • Silicate additives can stablize a wider range of materials than cement. • Treatment costs range from US$30-165 per cubic yard.	• The technique is most successful in wastes with inorganics and metals. • Cement-based and silicate-based have been relatively more successful in treating hazardous wastes.	• The technique provides virtually total containment of insoluble metals. • Possible reuse of treated sediment for public filling[5] • Less expensive than thermal desorption, dechlorination, solvent extraction, soil washing and incineration.	• Not effective on volatile organics. • Its effectiveness on organics or other leachables is inconclusive. • Increase in volume requires more space for disposal.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Thermal Treatment - Incineration[1]	• It is most widely used for destroying organic contaminants. • Three common incineration systems are rotary kiln, circulating fluidized bed and infrared. • Organic contaminants are volatilized at temperatures greater than 1000F in the presence of oxygen resulting in combustion and destruction of the contaminants. • Treatment costs range from US$475-1,350 per cubic yard.	• Incineration techniques have been applied to halogenated and non-halogenated volatiles, semivolatiles, PCBs, pesticides, dioxins/furans, organic cyanides, and organic corrosives.	• Incinerators typically achieve greater than 99% destruction for organics.	• It is not effective on heavy metals. • Expensive • Additional handling / treatment of by-products such as residue contaminants in ash, gaseous emissions and wastewater is required.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
• **Disposal**				
Capping[1]	• Ex-situ disposal • Deposit sediments in the bottom of a natural depression or to dig a hole in the bottom and place the sediment in by hydraulic pipeline with or without a submerged diffuser, direct placement with a clamshell, or release from a bottom-dump scow.	• 70 feet deep sites were most often chosen. • Navigation channels	• Relatively lower cost and lower risk than in-situ and ex-situ treatments. • This can avoid multiple sediment handling steps. The sediment could be transported in the same device from which it will be discharged.	• Suitable disposal and capping site is required. • Dredging equipment for each case needs to be evaluated based on sediment and capping material characteristics and disposal site considerations. • The accuracy of placement relies on site-specific placement technique. • Water quality monitoring programme is required.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Confined Disposal Facility (CDF) – Upland, near-shore and in-water[1, 7, 11]	• Ex-situ disposal / treatment • CDFs are engineered structures designed to retain dredged material. • The primary goal is containment and solids retention. • They can be constructed entirely away from the water, partially in water near the shore, or completely surrounded by water. • The cost ranges US$5-20 per cubic yard.	• Contaminated sediment needs to be removed from their original location e.g. near navigation channel, harbour, ports etc.	• An attractive and cost effective method of dredged material disposal. • If properly located and constructed, they can isolate contaminated sediment from the environment fairly well. • Some treatments can be effected in the CDF, such as biodegradation. • Much cheaper than biological treatment and dechlorination method.	• Lack of suitable space • Problems in acquiring permits • Transportation expenses • The potential for contaminant migration into groundwater and surface drainage of contaminated water, and plant and animal uptake of contaminants • It is still uncertain if the bioremediation in CDF is a viable alternative treatment method for contaminated sediment[15].
Landfills[1]	• Disposal of the dredged contaminated sediment in or on controlled land area and covered in the manner that isolates them from the environment.	• Contaminated sediment needs to be removed from their original location e.g. near navigation channel, harbour, ports etc.	• Contaminated sediment is isolated from the environment.	• The landfill space is limited. Large amount of contaminated sediment may not be allowed. • In Hong Kong, marine sediments are not disposed of at landfills, but marine dumping site e.g. East Sha Chau instead.

Handling and Treatment Method	Details	Suitable Condition	Advantages	Disadvantages / Inadequacies
Open sea disposal[6]	• Disposal of the dredged material to designated marine disposal sites	• Categories L and M (passing biological test) sediments.	• Contaminated sediment is centralized within the designated marine disposal sites controlled under Marine Fill Committee (MFC) of Civil Engineering Department, Hong Kong. • Low cost	• Only applicable to Categories L and M (passing biological test) sediments. • Seriously contaminated sediment (Category H sediment failing the biological dilution test) needs special treatment / disposal.

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