CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081041

Risk Assessment and Treatment of the Heavy Metals Contaminated Sediments via Stabilisation and Dewatering in Geotextile Tubes

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In this study, the heavy metals contaminated sediments were from the sewage reservoir with an area of 850,000 m^2. To measure the concentrations of heavy metals in sediments, 484 grid sampling points was set with a grid size of 40 m × 40 m. The sampling depth was in the range of 0.75 - 1.5 m. The concentrations of As, Cd, Cr^{6+}, Cu, Pb, Hg, and Ni were then measured in the laboratory. Subsequently, the single factor index and Nemerow index method were used to evaluate the potential risk of heavy metals in sediments. The results show that the maximum Nemerow index is 12.6, which is mainly from the contribution of Hg, Cr^{6+}, Cd, and As. The total contaminated sediments were calculated as 445,634 m^3, of which 336,081 m^3, 85,721 m^3, 23,832 m^3 are slightly polluted ($1 < P \le 2$), moderately polluted ($2 < P \le 3$) and heavily polluted ($P > 3$) sediments. The combined technology, integrating the dredging, stabilisation of heavy metals and flocculation in the pipeline, dewatering in geotextile tubes, are proposed for the treatment of sediments. After dewatering, the slightly and moderately polluted sediments were artificially constructed as a landfill for further landscape planting, while the heavily polluted sediments were sent to a cement plant for further treatment. After the implementation of the project from May to December 2019, all the heavy metals polluted sediments were treated well with high stability and low environmental risk.

1. Introduction

Heavy metals contamination has become a worldwide problem of disturbing the normal functions of rivers and lakes. Sediments, as the largest storage and resources of heavy metals, play an important role in the metal transformations (Peng et al., 2009). Rapid urbanisation and industrialisation have resulted in the accumulation of pollution in the sediments. An important part of sediments treatment prior to disposal is the reduction of the volume by dewatering to reduce the costs of transportation and handling (Qi et al., 2011). Some commonly used dewatering processes are mechanical dewatering, dewatering in geotextile tubes and so on. The dewatering of the dredged sediments through geotextile tubes have become increasingly common. A standard approach to designing geotextile tubes in the geotechnical aspect has also been established (Kim et al., 2018). After dewatering, stabilisation/solidification (S/S) or cement kiln co-processing can stabilize the heavy metals. S/S is a promising technology for alleviating the bioavailability and toxicity of heavy metal in the environment. For example, Zhang et al. (2020b) reported the solidification/stabilisation of arsenic (As) using the metallurgical-slag-based binder (MSB) with different dosages of calcium hydroxide (CH). In our group, a packaged technology featuring the dredging, stabilisation of heavy metals and flocculation in the pipeline, and dewatering in geotextile tubes were developed for sediments treatment (Zhang, 2017).
In this study, the heavy metals contaminated sediments were from the sewage reservoir with an area of 850,000 m^2. The content and distribution of heavy metals (As, Cd, Cr^{6+}, Cu, Pb, Hg and Ni) in the sediments were determined. The ecological risk of heavy metals was evaluated using the single factor index and Nemerow

Paper Received: 30/03/2020; Revised: 10/05/2020; Accepted: 15/05/2020
Please cite this article as: Jiang Y., Liu Z., Cui M., Su R., Liu Z., Zhang J., Huang R., 2020, Risk Assessment and Treatment of the Heavy Metals Contaminated Sediments via Stabilisation and Dewatering in Geotextile Tubes, Chemical Engineering Transactions, 81, 241-246 DOI:10.3303/CET2081041

pollution index method. The contaminated sediments were treated using the packaged technology previously developed in our group as mentioned before (Zhang, 2017).

2. Materials and methods

The heavy metals contaminated sediments were collected and the contents of heavy metals in sediments were measured. The risk assessment of heavy metals was then conducted and the treatment of the heavy metals contaminated sediments was performed.

2.1 Sample collection and analysis

The area of sewage reservoir is 850,000 m^2. According to the technical guidelines on environmental site surveys (HJ 25.1-2019) and monitoring (HJ 25.2-2019), 484 grids sampling points were set with a grid size of 40 m × 40 m (Figure 1). Among these points, 53 grid points (with a grid size of 120 m × 120 m) had a depth of 1.5 m, and the samples were collected at depth of 0.25 m, 0.75 m, and 1.5 m. The other 431 points had a depth of 0.75 m, and the samples were collected at a depth of 0.25 m, 0.5 m and 0.75 m.

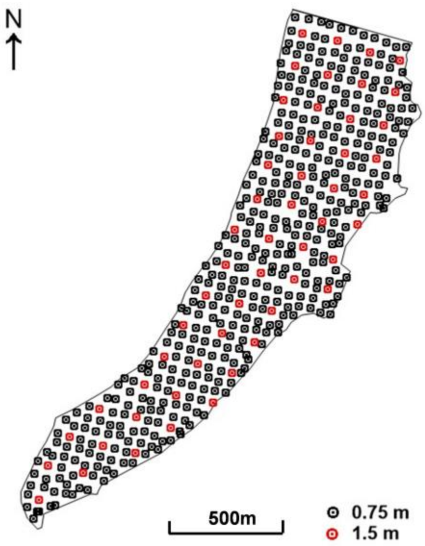

Figure 1: Map of the sewage reservoir and sampling location

Each sediments sample was collected with static pressure sampling and transferred into a 250 ml brown wide mouth glass bottle to keep the sample clean and minimize the time exposed to the air. It is backfilled with bentonite when the depth of boreholes is deeper than the buried depth of the weakly permeable floor. The samples were cooled in a refrigerator at 4 °C and tested in the laboratory with China inspection body and laboratory mandatory approval (CMA) (Vu et al., 2018). According to the technical guidelines, 10 % of the total sediment samples were collected for the repeated test.
For Cr^{6+} ions, the samples were analyzed according to the standard (USEPA3060A & 7196A-1996). For other heavy metal ions, the samples were analyzed by atomic absorption spectrophotometer according to the recommended Chinese national standards (GB/T 17136-1997, GB/T 17138-1997, GB/T 17139-1997, GB/T 17141-1997) (Zhang et al., 2020a).

2.2 Risk assessment of heavy metals in sediments

The single factor index (P_i) is often used for assessing the level of single heavy metal in sediments, and its value is not affected by other non-target contaminants. The P_i was calculated according to Eq(1):

$$P_i = \frac{C_i}{S_i} \tag{1}$$

Where C_i is the measured value of heavy metals; S_i is the standard of environmental quality, which is from (GB 36,600-2018) for Cr^{6+} ions and (DB 12/499-2013) for other heavy metals.
The Nemerow pollution index (Table 1) is widely applied to reflect the total pollution level and evaluate the environmental quality (Li et al., 2014). The Nemerow index was calculated according to Eq(2):

Table 1: Classification criteria for Nemerow index for the evaluation of pollution levels

Level	Nemerow index	Pollution assessment
I	$P \leq 1$	Pollution-free
II	$1 < P \leq 2$	Light pollution
III	$2 < P \leq 3$	Moderately pollution
IV	$P > 3$	Severe pollution

$$P = \sqrt{\frac{(P_{iave})^2 + (P_{imax})^2}{2}} \tag{2}$$

Where P is the Nemerow index, P_{iave} is the average of single factor index for all the heavy metals in sediments, P_{imax} is the maximum value of single factor index for all the heavy metals in sediments.

2.3 Treatment of the heavy metals contaminated sediments

The packaged technology featuring the environmental dredging, stabilisation of heavy metals and flocculation in the pipeline, and dewatering in geotextile tubes was used in this project. The total contaminated sediments were 445,634 m^3, which were removed by three cutter-suction dredgers with a maximum flux of 500 m^3/h, fed as a slurry via a pipeline to the geotextile tubes. The heavy metal stabilizer and flocculants were added to the pipeline before dewatering in geotextile tubes with a cross-section perimeter of 20 m. During 7 months from May to December 2019, the treatment project was completed.

After treatment, a total of 202 samples were collected from geotextile tubes, including 22 samples of heavily polluted sediments, 180 samples of lightly polluted and moderately polluted sediments. The leaching toxicity test of heavy metals was performed following the extraction procedure with sulfuric acid and nitric acid from standard HJ/T 299-2007. The concentrations of heavy metal ions in the acidic leachate were measured according to the standards HJ 781-2016, HJ 787-2016, GB/T 15555.4-1995 and HJ 702-2014 (Tian et al., 2020).

3. Results and discussion

A total of 1468 sediments samples were collected for analysis. As summarized in Table 2, seven heavy metals, including As, Cd, Cr^{6+}, Cu, Pb, Hg and Ni, were determined with a detection ratio of 41.7 % for Cr^{6+} and 100 % for the other heavy metals.

3.1 The content and spatial distribution of heavy metals

As shown in Table 2, the maximum concentrations of As, Cd, Cr^{6+}, Pb, Hg, and Ni are higher than standard values of environmental quality (S_i). Especially, the S_i value of Hg is 1 mg/kg, while the content of Hg ranged from 0.005 to 17.5 mg/kg with a maximum exceedance multiple 17.5. The content of As ranged from 0.94 to 47.3 mg/kg, Cd ranged from 0.01 to 2.52 mg/kg, Cr^{6+} ranged from <0.5 to 48.0 mg/kg, Ni ranged from 6 to 88 mg/kg, with a maximum exceedance multiple 2.3, 2.5, 8.4, and 1.8.

Table 2: The contents of heavy metals in sediments

Heavy metals	Detection limit (mg/kg)	Minimum value (mg/kg)	Maximum value (mg/kg)	S_i (mg/kg)	Detection ratio (%)
As	0.01	0.94	47.3	20	100
Cd	0.01	0.01	2.52	1	100
Cr^{6+}	0.5	<0.5	48.0	5.7	41.7
Cu	1	1	116	200	100
Pb	0.1	2.0	91.8	90	100
Hg	0.002	0.005	17.5	1	100
Ni	5	6	88	50	100

Figure 2 shows the spatial distribution of heavy metals at 0.25 m. Cd, Hg, and Ni are mainly distributed within the depth of 0.25 m and concentrated near the outfall of wastewater. The contaminated area of Ni is higher than that of Hg and Cd. Cr^{6+} is mainly distributed among the north of the lake with a large contaminated area.

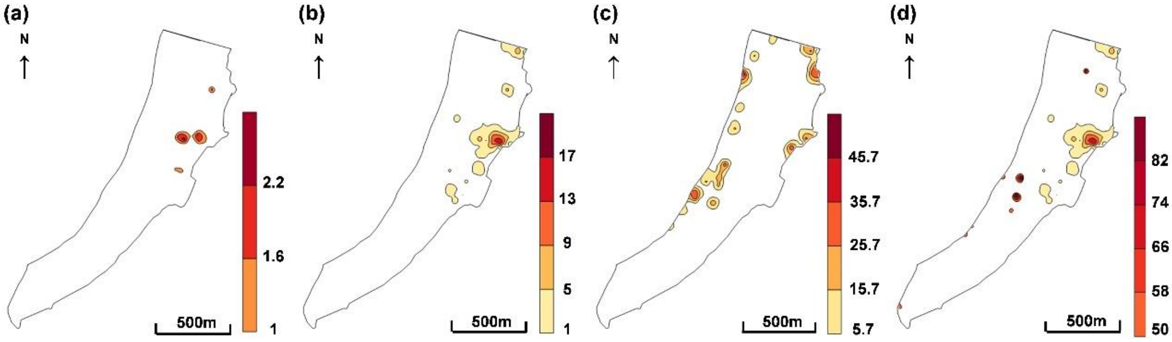

Figure 2: Spatial distribution of heavy metals at a depth of 0.25 m (a) Cd; (b) Hg; (c) Cr^{6+}; (d) Ni.

3.2 Risk assessment of heavy metals in sediments

According to the risk assessment results, the maximum single factor index (Pi) of As, Cd, Cr^{6+}, Cu, Pb, Hg and Ni are 2.37, 2.52, 8.42, 0.58, 1.02, 17.5, 1.76. The order for the maximum Pi values is Hg > Cr^{6+} > Cd > As > Ni > Pb > Cu. The maximum Nemerow index (P) is 12.6, which is mainly from the contribution of Hg, Cr^{6+}, Cd, and As. The maximum P value is much higher than the value of level IV (severe, P > 3).

As shown in Figure 3, with the increasing depth from 0.25 m to 1.5 m, the heavy metals contaminated area gradually decreased. A part of the contaminated zone at different depths reached severe pollution level, in which the zone near the outfall of wastewater suffers from the most severe pollution. The contaminated zone on the northwest side is mainly caused by Cr^{6+}, and the zone near the outfall of wastewater is mainly caused by Hg, Cr^{6+} and Ni.

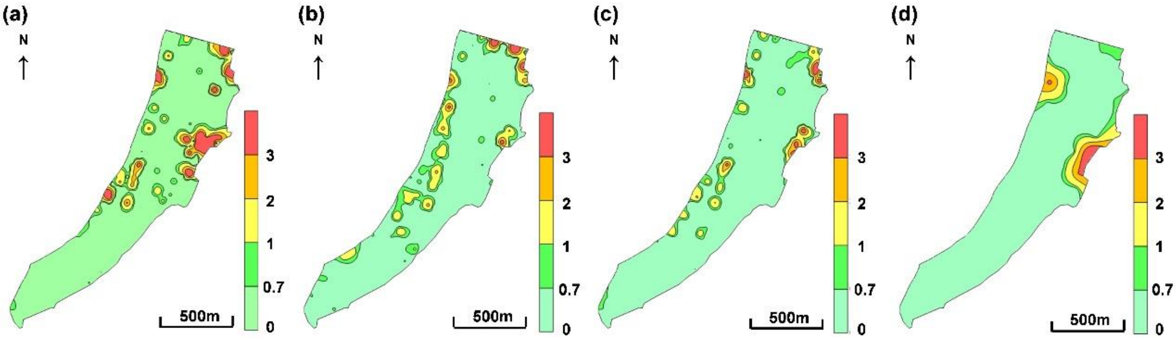

Figure 3: Spatial distribution of Nemerow index at a depth of (a) 0.25 m; (b) 0.5 m; (c) 0.75 m; (d)1.5 m.

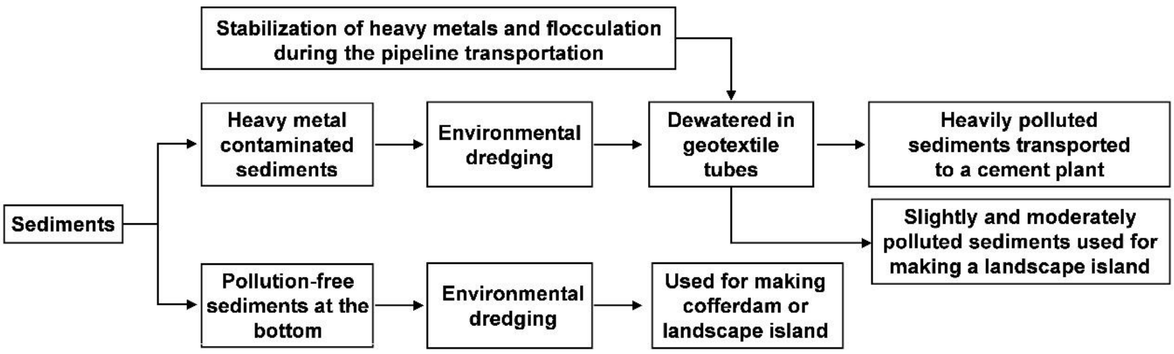

Figure 4: The flow diagram of sediments treatment

3.3 Treatment of the heavy metals contaminated sediments

Figure 4 shows the flow diagram of sediments treatment, in which the heavy metal contaminated sediments was dredged, transported in the pipeline, and dewatered in geotextile tubes. The stabilisation of heavy metals and flocculation occurred during the pipeline transportation. After dewatering in a landfill, the slightly polluted and moderately polluted sediments in geotextile tubes were directly used for making a landscape island, while the heavily polluted sediments were taken out from the geotextile tubes and transported to a cement plant. To keep the capacity of reservoir as a constant, some pollution-free sediments at the bottom were also dredged and used for making cofferdam or landscape island.

The total contaminated sediments were 445,634 m^3 and 5 dewatering sites were used in this project. The area of dewatering sites 1-5 was 9,000 m^2, 7,500 m^2, 4,000 m^2, 10,000 m^2 and 3,600 m^2. The accumulated capacity of geotextile tubes in sites 1-5 reached 27,000 m^3, 28,125 m^3, 3,200 m^3, 12,500 m^3 and 3,760 m^3 for the dewatered sediments, with the total height of 3 m, 3.75 m, 0.8m, 1.25 m, and 1.1 m. The typical layout of the dewatering site with geotextile tubes is shown in Figure 5.

Figure 5: Dewatering in geotextile tubes

The moisture content of sediments decreased from 95 % to 30 % after 3 months of dewatering. After dewatering, the sediments were collected from the geotextile tube. The leaching toxicity test of heavy metals was performed and the concentrations of heavy metal ions in the acidic leachate were measured.

Table 3: The concentrations of heavy metals in leachate for the heavily polluted sediments

Heavy metals	Minimum value (mg/L)	Maximum value (mg/L)	GB 5085.3-2007 (mg/L)	GB 8978-1996 (mg/L)
As	0.019	0.063	5	0.5
Cd	<0.0006	<0.0006	1	0.1
Cu	0.05	0.11	100	1.0
Cr^{6+}	<0.004	<0.004	5	0.5
Pb	0.012	0.11	5	1.0
Hg	0.00008	0.00036	0.1	0.05
Ni	0.02	0.1	5	1.0

As summarized in Table 3 and Table 4, the maximum concentrations of As, Cd, Cu, Cr^{6+}, Pb, Hg, and Ni in the acidic leachate were 0.094 mg/L, <0.0006 mg/L, 0.33 mg/L, <0.004 mg/L, 0.11 mg/L, 0.0032 mg/L, and 0.1 mg/L, which is much lower than the values of the identification standards for hazardous wastes (GB 5085.3-2007) and the integrated wastewater discharge standard (GB 8978-1996), indicating that the heavy metals in the sediments were treated well with high stability and low environmental risk.

Table 4: The concentrations of heavy metals in leachate for the slightly and moderately polluted sediments

Heavy metals	Minimum value (mg/L)	Maximum value (mg/L)	GB 5085.3-2007 (mg/L)	GB 8978-1996 (mg/L)
As	0.0035	0.094	5	0.5
Cd	<0.0006	<0.0006	1	0.1
Cu	<0.01	0.33	100	1.0
Cr^{6+}	<0.004	<0.004	5	0.5
Pb	<0.0009	0.092	5	1.0
Hg	<0.00002	0.0032	0.1	0.05
Ni	<0.02	0.09	5	1.0

4. Conclusions

In summary, the concentration and spatial distribution of heavy metals in sediments were measured and their potential ecological risk was successfully evaluated using single-factor index and Nemerow index method. The maximum concentrations of As, Cd, Cr^{6+}, Hg, and Ni are higher than standard values of environmental quality with a maximum exceedance multiple 2.3, 2.5, 8.4, 17.5, and 1.8. The maximum Nemerow index is 12.6, which is mainly from the contribution to Hg, Cr^{6+}, Cd, and As. A part of the contaminated zone at different depths reached severe pollution level, in which the zone near the outfall of wastewater suffers from the most severe pollution. The total contaminated sediments were calculated as 445,634 m^3. The combined technology, integrating the dredging, stabilisation of heavy metals and flocculation in the pipeline, dewatering in geotextile tubes, are successfully employed for the treatment of sediments. The moisture content of sediments decreased from 95 % to 30 % after 3 months of dewatering. After dewatering, the maximum concentrations of heavy metals in the acidic leachate were much lower than the values of the national standards, indicating that the heavy metals contaminated sediments were treated well with high stability and low environmental risk. During the dredging, the release of pollutants, such as heavy metals, nutrient elements (e.g., NH_3-N, phosphorus) from sediments to water is an important issue and the study on the control of pollutants release is required in future.

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