The influence of contaminated sediment backfill technology (CSBT) on bed stability through flume experiments

Xiaocui Li 1*
1 State Key Laboratory of Hydro-science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China
*Corresponding author's e-mail: lixc17@mails.tsinghua.edu.cn

Abstract. Bed stability is directly related to sediment resuspension and internal pollutant release, which provide an important physical basis for natural water internal pollution control. Contaminated sediment will release accumulated pollutants into the overlying water because of the instability of the riverbed and become a potential source of internal pollution. In this paper, the influence of contaminated sediment backfill technology (CSBT), i.e., the calcination of dredged sediment into ceramsite after dewatering and pollutant fixation, followed by backfilling to the dredged area, on bed stability was investigated through flume experiments. Acoustic Doppler velocimetry (ADV) was used to measure the hydrodynamic characteristics in the flume. The results show that CSBT can increase bed stability and make the water-sediment interface clear. In addition, the porosity increased after backfilling ceramsite, increasing the effective expansion of oxygen. This study provides a new idea for river and lake ecological management and environmental restoration.

1. Introduction
Sediment is the natural habitat of many benthic organisms and an important material for maintaining the ecology of natural waters, such as rivers, lakes and reservoirs [1-2]. For example, the water and sediment regulation function of the Three Gorges Reservoir (TGR) [3] has a certain impact on flood control [4], shipping, irrigation and the ecological environment in the mainstream and downstream reaches of the Yangtze River. Sediment also takes on all kinds of environmental substances in water, such as nutrients, heavy metals and organic pollutants, and some or most of them are deposited on the beds of rivers and lakes [5], becoming an important reservoir of nutrients and becoming an internal pollution source in rivers and lakes [6]. Contaminated sediment may release pollutants into the overlying water because of bed instability, i.e., changes in hydrodynamic conditions, leading to eutrophication [7-8], algae blooms, and black and malodorous conditions, threatening the security of the environment and ecology and affecting people's ability to use the body of water.

Contaminated sediment can be treated by both in situ and ex situ methods [9]. The former does not reduce the total amount of pollutants in the sediment, and the pollutants after stabilization may be released into the overlying water body again when the water environment changes [10-11]. However, the strong disturbance produced by ex situ methods easily causes fine sediment resuspension, which leads to the exposure of deep polluted sediment. Therefore, contaminated sediment backfill technology is used for remediation of contaminated sediment, which combines ex situ sediment dredging with in situ remediation by capping; i.e., the dredged sediment is calcined into ceramsite after the dewatering process and pollutant fixation and then backfilled to the dredged area [12]. For example, the technology of dredging first and then capping was adopted in Biwa Lake (Japan) to control phosphorus release from
sediment [13].

Flume experiments are an effective tool for establishing a bridge between small-scale hydrodynamic experiments and field observations [14-15], and a circulated flume was designed in this paper. Acoustic Doppler velocimetry (ADV) was applied to measure the flow velocity in the flume. In this paper, the influence of contaminated sediment backfill technology (CSBT) on bed stability was studied by flume experiments. CSBT enhances bed stability, clarifies the sediment-water interface, and changes the vertical distribution of dissolved oxygen.

2. Materials and methods

2.1. Contaminated sediment backfill technology (CSBT)
This technology was first proposed by Professor Fang Hongwei of Tsinghua University [12], and its components include environmental dredging, dewatering, detoxification, ceramsite calcination, and ceramsite backfilling. CSBT can dramatically remove most surface-contaminated sediment by dredging and capping using dredged sediment in the original area, avoiding the introduction of foreign materials into the original region. Dredging is undertaken to dredge the contaminated sediment in the water body to reduce the release of pollutants from the sediment to the water body and create conditions for the restoration of the aquatic ecosystem. Thin-layer dredging is mainly used to achieve environmental dredging. Dredged sediment is usually used as a basic fertilizer for farmland, vegetable fields and orchards or for road and civil soil, with increasing attention being paid to reduction, harm elimination and resource utilization in the treatment of dredged sediment. However, because of its high water content and toxic and harmful pollutants, it is necessary to first dehydrate and dry dredged sediment, then treat it to render it harmless, and finally reuse it to prevent secondary pollution to the surrounding environment. At present, there are two processes to produce ceramsite: the calcining method and the noncalcining method [16]. Contaminated sediment backfill technology uses the calcining method to produce ceramics to meet the stability requirement of backfilling ceramics. Finally, the ceramsite is backfilled to the original dredged area.

2.2. Flume experiment setup
The experiment was conducted using a circulated flume of the State Key Lab of Hydro-Science and Engineering at Tsinghua University. The flume was 16 m long, 0.5 m wide, and 0.5 m high, as shown in Figure 1. The water was circulated within the flume by a pump system, and flow regulation was performed with the help of a discharge control system. The test section of the channel is at a distance of 10-13 m from the upstream end of the flume to obtain fully developed flow at the test section and minimize the influence of inflow and outflow in the channel. The bed channel in the flume was prepared using sediment samples, and the thickness was 10 cm. A support layer of 10 cm thickness was placed in the remaining length of the flume to achieve a uniform bed level. A sediment sample was obtained from the river of Tsinghua University, China, and was collected from the bed surface (0-10 cm) using a columnar sampler. The sample was air dried and ground, and the impurities were removed through a 100 size sieve. The experiments were conducted under three discharges, with \( Q_1 = 10.4 \) L/s, \( Q_2 = 13.9 \) L/s and \( Q_3 = 20.8 \) L/s. In the controlled experiment, the surface layer (1 cm) of the original 10 cm sediment sample was manually dredged after backfilling ceramsite to 1 cm. Finally, the hydrodynamic conditions of the original experiment and control experiment were measured by using ADV. The instantaneous three-dimensional water velocity was measured by ADV at the centreline of the test section under each flow discharge. The sampling frequency of ADV was set as 100 Hz, and the acoustic frequency of ADV was 10 MHz for data collection. The interval of adjacent measuring points increased with increasing distance from the bed in the vertical direction; i.e., the interval ranged from 1 to 3 mm when the distance was less than 2 cm and above that it ranged from 5 to 10 mm. The instantaneous velocity was measured in a vertical profile for a duration of 1 minute, and this time duration was adequate to capture the time-independent time average velocity.
Figure 1. Schematic diagram of laboratory flume

3. Results and discussion

Three flow discharges were used in this experiment, $Q_1$=10.4 L/s, $Q_2$=13.9 L/s and $Q_3$=20.8 L/s. Before capping coarse sediment, the bed shear stress is less than the critical shear stress, and the channel bed exhibits clear water conditions under discharge $Q_1$; the bed shear stress is approximately equal to the critical shear stress, and the channel bed is in a critical incipient state under discharge $Q_2$; and the bed shear stress exceeds its critical shear stress, and the channel bed is in mobile conditions under discharge $Q_3$.

The Reynolds shear stress (RSS) can be defined as the exchange of momentum from the flow to the sediment particles on the bed surface and vice versa [17]. The features of turbulent flow (time averaged velocity and RSS) were measured at the centreline of the test section. The streamwise time average velocity was calculated according to equation (1), and the RSS was calculated according to equation (2) and equation (3). Figure 2 and Figure 3 present the vertical distributions of RSS and time average velocity under the three flow discharges of the original experiment and controlled experiment, i.e., before and after capping coarse clean sediment.

\[
\bar{u} = \frac{1}{n} \sum_{i=1}^{n} u_i
\]

\[
\overline{u'w'} = \frac{1}{n} \sum_{i=1}^{n} (u_i - \bar{u})(w_i - \bar{w})
\]

\[
\tau_{uw} = -\rho u'w'
\]

where $u_i$ is instantaneous velocity in the streamwise direction and $n$ is the number of samples. $\bar{u}$, $\bar{v}$ and $\bar{w}$ are the time averaged velocities in the streamwise, widthwise, and vertical directions, respectively, and $u'$, $v'$ and $w'$ are the corresponding components of velocity fluctuations.

Figure 2. Vertical distribution of RSS
It is observed from Figure 2 that RSS increases along the channel bed, which indicates that the momentum transfer is higher from the flow to the bed particles and can sustain sediment transport corresponding to resistance. The peak value of RSS is obtained near the inner layer and then decreases along the bed surface because of the presence of a viscous or rough sublayer in the near-bed region under small and medium flow discharges, i.e., \( Q_1 \) and \( Q_2 \). Under the large flow discharge \( Q_3 \), RSS fluctuates less. Figure 3 displays the profiles of the time averaged velocity against the dimensionless flow depth (\( z/h \)). The time averaged velocity is maximum at the water surface and gradually decreases towards the bed surface due to the collision of bed particles resulting in a deficiency of momentum. As the discharge increases, the vertical time average velocity increases.

Obviously, before capping coarse sediment, the sediment particles are relatively fine and easily suspended, resulting in an unclear sediment-water interface and poor bed stability. After capping coarse sediment, the incipient velocity increases, and coarse sediment particles are not easily suspended under the same hydrodynamic conditions, resulting in increased bed stability.

4. Discussion
CSBT converts the dredged sediment into ceramsite and then returns the ceramsite back into the original dredged area, which has little effect on the shape of the cross-section as a whole. However, with the increase in the particle size of the ceramsite after backfilling, the roughness of the ceramsite will increase, which will have a certain impact on flood control. Therefore, it is necessary to perform a corresponding flood control review in actual projects. In addition, the ceramsite backfill method selected in this study backfills a layer of ceramsite in the original dredging area, and the distance between ceramsite particles is small. It can be seen from the experimental results that this backfilling method can meet the requirements of increasing bed surface stability and reducing sediment flux. From the perspective of economics, a more economical backfilling method can be found later to reduce the cost.

5. Conclusions
CSBT combines sediment dredging with in situ remediation by capping. The calcination of the dredged sediment and replacement as a cap via backfilling enhances bed stability and dramatically reduces the flux of contaminants from the sediment. Furthermore, CSBT directly uses the dredging sediment in the original area, avoiding the introduction of foreign materials into the original region. Therefore, CSBT can effectively solve the problem of dredging sediment and provide a new idea for river lake ecological management.

Acknowledgements
This study is funded by the National Natural Science Foundation of China (91647210, 11802158), the
Innovation and Intelligence Introduction Program for Colleges and Universities (B18031), and the National Key Research and Development Program (2016YFC0402506).

References:

[1] Fang, H.W., Chen M.H., Chen Q.H. (2008) One-dimensional numerical simulation of non-uniform sediment transport under unsteady flows. International Journal of Sediment Research, 23(4), 316-328.

[2] Huang, L., Fang, H.W., Reible, D. (2015). Mathematical model for interactions and transport of phosphorus and sediment in the Three Gorges Reservoir. Water research, 85, 393-403.

[3] Fang, H.W., Rodi, W. (2003) Three-dimensional calculations of flow and suspended sediment transport in the neighborhood of the dam for the Three Gorges Project (TGP) reservoir in the Yangtze River. Journal of Hydraulic Research, 41(4), 379-394.

[4] Fang, H.W., Han, D., He, G.J., Chen, M.H. (2012) Flood management selections for the Yangtze River midstream after the Three Gorges Project operation. Journal of Hydrology, 432, 1-11.

[5] Alizadeh, M.J., Kavianpour, M.R., Danesh, M., Adolf, J., Shamshirband, S., Chau, K. (2018) Effect of river flow on the quality of estuarine and coastal waters using machine learning models. Engineering Applications of Computational Fluid Mechanics, 12, 810–823.

[6] Li, X.C., Huang, L., Fang, H.W., He, G.J., & Wang, C.H. (2019) Immobilization of phosphorus in sediments by nano zero-valent iron (NZVI) from the view of mineral composition. Science of the Total Environment, 694, 133695.

[7] He, G.J., Fang, H.W., Bai, S., Liu, X.B., Chen, M.H., Bai, J. (2011) Application of a three-dimensional eutrophication model for the Beijing Guanting Reservoir, China. Ecological Modelling, 222(8), 1491-1501.

[8] Huang, L., Fang, H.W., He, G.J., Jiang, H.L., Wang, C.H. (2016) Effects of internal loading on phosphorus distribution in the Taihu Lake driven by wind waves and lake currents. Environmental Pollution, 219, 760-773.

[9] Reible, D., Hayes, D., Lue-Hing, C., Patterson, J., Bhowmik, N., Johnson, M., Teal, J. (2003) Comparison of the long-term risks of removal and in situ management of contaminated sediments in the Fox River. Soil and Sediment Contamination, 12(3), 325-344.

[10] Chen, M., Ye, T.R., Krumholz, L.R., Jiang, H.L. (2014) Temperature and cyanobacterial bloom biomass influence phosphorus cycling in eutrophic lake sediments. Plos One, 9(3), e93130.

[11] Huang, L., Fang, H.W., Fazeli, M., Chen, Y.S., He, G.J., Chen, D.Y. (2015) Mobility of phosphorus induced by sediment resuspension in the Three Gorges Reservoir by flume experiment. Chemosphere, 134, 374–379.

[12] Fang, H.W., Li, X.C., Huang, L., Zhang, T., Han, X., Gao, Q.F. (2019) Ceramization of contaminated sediment backfill technology and its effects of sediment remediation. Water Resources Protection, 35(3), 1-5.

[13] Bona, F., Cecconi, G., Maffiotti, A. (2000) An integrated approach to assess the benthic quality after sediment capping in Venice lagoon[J]. Aquatic Ecosystem Health and Management, 3, 379-386.

[14] Barlow, K., Nash, D., Grayson, R. (2004) Investigating phosphorus interactions with bed sediments in a fluvial environment using a recirculating flume and intact soil cores. Water Res. 38, 3420–3430.

[15] Ussher, S.J., Manning, A.J., Tappin, A.D., Fitzsimons, M.F. (2011) Observed dissolved and particulate nitrogen concentrations in a mini flume. Hydrobiologia, 672, 69–77.

[16] Yang, Y.X., Li, H., Zheng, W.K., Bai, Y., Liu, Z.M., Zhang, J.J. (2019) Experimental study on calcining process of secondary coated ceramsite solidified chromium contaminated soil. Science of Advanced Materials, 11(2), 208-214.

[17] Cheng, W., Fang, H.W., Lai, H.J., Huang, L., Dey, S. (2017) Effects of biofilm on turbulence characteristics and the transport of fine sediment. Journal of Soils & Sediments, 18, 3055–3069.