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Release of heavy metals from sediment bed under wave-induced liquefaction

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ABSTRACT

Sediments in lakes and coasts can release metals into water via static diffusion and especially resuspension. The resuspension under sediment liquefaction may severely affect the concentrations of metals in water. In this study, flume experiments were carried out twice to study the release of two metal combinations (Zn and Pb; Zn and Cu), respectively. Each experiment included three phases: consolidation; non-liquefaction and liquefaction. Results showed that total Zn concentration at liquefaction phase increased by a maximum rate of 26 compared with the consolidation phase. The concentration of particulate Zn at liquefaction phase increased by a maximum rate of 8.30 compared with the non-liquefaction phase. The average concentration of dissolved Zn at the liquefaction phase increased up to 0.24 times from the consolidation phase. Total Zn concentration at the non-liquefaction phase increased by several times compared with the consolidation phase. Metals were homogeneously distributed in the liquefaction layer through wave actions.

1. Introduction

Abundant heavy metals have been released into lakes and coasts by sewage discharge, atmospheric deposition, and surface runoff along with the rapid industrial development (Ndzangou et al., 2005; Yu and Li, 2010). Because of strong adsorption capacity, the sediments in lakes and coasts become sinks of heavy metals (Förstner and Müller, 1973; Van den Berg et al., 2001; Yu et al., 2001). As the external condition varies, these adsorbed heavy metals will be released from the sediments into the overlying water, causing recontamination to the overlying water and potential hazard to aquatic organism. Therefore, this problem has raised worldwide concern (Cheng, 2003; Nayar et al., 2004; Stoffers et al., 1977).

Sediments in lakes and coasts release heavy metals into the overlying water through static diffusion and especially resuspension (Atkinson et al., 2007; Bi et al., 2009, 2011; Simpson et al., 1998). Adsorption–desorption of suspended sediments (SS) occur under different hydrodynamic conditions and will affect the concentrations of heavy metals in aquatic systems (Hatje et al., 2003; Zhang et al., 2007). Many methods have been pioneered to investigate the heavy metals release process during resuspension. Such efforts included, in situ observation of the heavy metals distribution in both the dissolved phase and suspended particulate matter in coastal lagoons under various conditions (Beltrame et al., 2009); daily monitoring of heavy metal concentration corresponding to sediment resuspension by on-line high-frequency measurements (Superville et al., 2014); particle entrainment simulator (Calvo et al., 1991; Cantwell and Burgess, 2004; Cantwell et al., 2008) and pneumatic annular flume (Zheng et al., 2013) for simulating sediment resuspension.

Studies found that sediments were susceptible to resuspension under hydrodynamic disturbance (Booth et al., 2000; Reddy et al., 1996). The strong hydrodynamics under extreme weather events can cause liquefaction in the sediment bed (Tzang et al., 2009; Xu et al., 2011). In subaqueous delta of Yellow River, China, the sediments were prone to liquefaction, meanwhile, a mass of fine soil particles flow through seepage into the overlying water with the pore water. More suspended particles were under liquefaction phase than non-liquefaction phase, and these particles were relatively small in size (Xu et al., 2011). These particles have very complex physicochemical properties and can remarkably impact the concentrations of heavy metals. However, no reliable data in

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extreme weather events can be acquired through in situ observation or online monitoring; the simulation with particle entrainment simulator and pneumatic annular flume did not include the resuspension of liquefied sediments.

In view of this, the purpose of this study was to investigate the variation of heavy metals during resuspension of liquefied sediments. Specifically, the contents of the study were to observe the concentration of heavy metals in overlying water and within the sediment bed under three scenarios, (1) consolidation phase (I), this phase was intended to serve as a baseline scenario with no wave action was exerted, water and sediment remained in the static state; (2) non-liquefaction phase (II), where wave actions were exerted on sediment bed and the sediment became resuspended; and (3) liquefaction phase (III), where wave actions were exerted on sediment bed and led to the sediment bed lost shear force and behaved like a fluid, and a large amount of sediment were resuspended.

2. Materials and methods

2.1. Experimental equipment

The experimental equipment was a flume ($14.0 \times 0.5 \times 1.5$ m^3, Fig. 1). One side of the flume was a wave maker that generated waves during the experiments, the other side was a riprap constructed with crashed rock with a slope (14°) to dissipate the interference caused by wave reflection.

2.2. Experimental design

Wave flume experiments were carried out twice (experiments A and B), and the design of experiment A is introduced below.

2.2.1. Preparation of sediment bed

The characteristics of the experiment soil collected from the Yellow River subaqueous delta are shown in Table 1. The soil was classified as sandy silt in accordance with Shepard's triangular classification (Shepard, 1954).

A total of 457.022 g $Zn(NO_3)_2{\cdot}6H_2O$ was dissolved into tap water and then mixed with 50.0 kg of soil to form uniform slurry (30% water, 2200.7 μg/g Zn). A total of 520.476 g $Pb(NO_3)_2$ was dissolved into tap water and then mixed with 54.0 kg of soil to form uniform slurry (30% water, 6631.1 μg/g Pb). To guarantee the interaction between heavy metals and soil, we left the slurry solutions as-prepared to stand for 2 days before use. Besides, other soil was thoroughly mixed with tap water to form uniform slurry of 46.5 and 5.5 cm with 30% water on the bottom of the flume, and a 2.5 cm layer of Zn deposition was sandwiched between them. On the top was the 2.5 cm layer of Pb deposition and 3.0 cm of slurry (Fig. 2).

Table 1
The characteristics of experiment soil.

Composition	Sand	Silt	Clay
Particle size (mm)	0.063–1.00	0.004–0.063	<0.004
Fraction (%)	20.47	69.67	9.86

2.2.2. Release of metals from sediment bed

The flume experiment included three phases in a sequence: consolidation (I), non-liquefaction (II), and liquefaction (III), shown as the following flow chart (Fig. 3).

Phase I lasted for 10 days. Three water samples were collected from the horizontal position at 15.0 cm above the sediment bed, but laterally located from 65.0 cm, 130.0 cm, and 195.0 cm to the left, respectively (Fig. 2). The water samples were acidified with nitric acid after centrifugation, and then stored at 4 °C.

Five wave-height levels (5.0, 8.0, 11.0, 14.0, and 16.0 cm, each lasting for 240 min) were imposed on the sediment bed at phase II. The wave parameters of experiment A are shown in Table 2. During the wave action scenarios the sediment bed did not experience liquefaction. Water samples were collected at 0, 10, 20, 40, 60, 90, 120, 180, and 240 min from the same sampling position and with the same method as at phase I. The turbid water samples for each time interval were collected simultaneously, and from along the center line of the flume.

During phase III, artificial disturbance was exerted to the middle of the sediment bed to form a local soft region, where the liquefaction of the sediment bed was triggered. The sediment bed was subjected to four wave-height levels (8.0, 11.0, 14.0, and 16.0 cm, each lasting for 240 min). The water samples and the turbid water samples were collected from the same locations as phase II at a certain time interval.

The soil core samples were collected by a piston corer at 90.0 cm from the left side of the sediment bed after each phase, respectively (Fig. 2). All sediment cores were separated into 2-cm segments, that is, 0.0–2.0, 2.0–4.0, etc.

The design of experiment B was similar to experiment A except that a Zn deposition layer (2263.0 μg/g) and a Cu deposition layer (2735.0 μg/g) were packed respectively above the bottom of the flume at 46.0–48.0 cm and 52.0–54.0 cm in the sediment bed. The sediment bed experienced three wave-height levels (5.0, 8.0, and 11.0 cm, each continuing for 240 min) during both phases II and III. The deposition layer of heavy metals and wave parameters are shown in Table 3.

2.3. Analytical methods

The concentrations of Zn, Cu, Pb were determined by water and sediment standard analysis methods from Specification of Oceanographic Survey (Wang et al., 2012b). The concentrations of dissolved Zn, Cu, and Pb were determined by a flame atomic

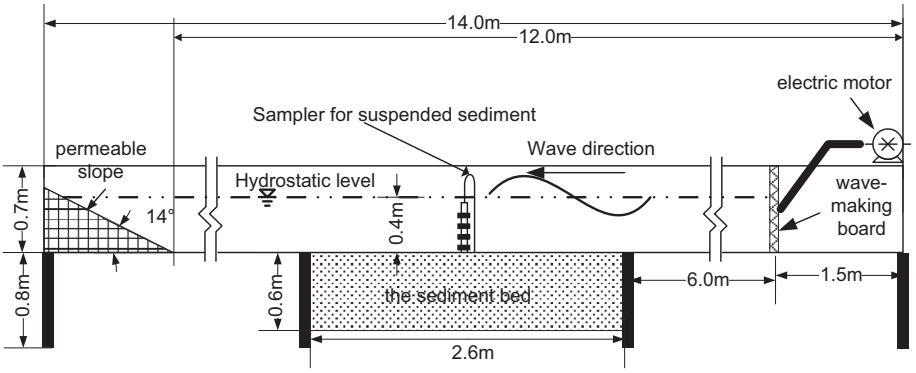

Fig. 1. Layout of wave flume.