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# Numerical investigation into the restoration of ocean environments using steelmaking slag

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ABSTRACT

Steelmaking slag has been utilized in shore protection and to improve ocean environments of sea bottom sediments in semi-enclosed areas and coastal regions. This is achieved by reducing dissolved sulphide concentration. In this study, a numerical model is proposed and developed using a Eulerian-Lagrangian model coupled with an ocean circulation model to compute advection-diffusion of dissolved sulphides and fluid-particle interactions between ocean circulation and steelmaking slag. We applied the model to the Fukuyama inner harbour in the Seto Inland Sea and Tokyo Bay and compared our results with field data. The numerical results show good agreement with the field results. We demonstrate that steelmaking slag can control advection-diffusion with regard to concentration of hydrogen sulphide. The steelmaking slag could be a useful material in restoration of ocean environments at enclosed sea areas.

## 1. Introduction

In Japan, enclosed sea areas with complicated geometries and a variety of marine environments have been significantly affected by anthropogenic activities during the last five decades. Many industries are built up in coastal regions surrounding enclosed seas, and urbanisation is also rapidly increasing. In addition, land reclamation and some dredging were required for industrial and urban development, which caused serious environmental issues in a wide range of marine environments in enclosed sea areas. In the northern part of Tokyo Bay, for example, there are many dredging trenches covered with bottom sludge, where oxygen solubility is decreased, especially in summer, and where hydrogen sulphide ($H_2S$) can be also generated. In recent years, oxygen deficiency caused by decomposition of organic matter in bottom sediments has occurred. As a result, blue tide phenomenon is induced annually. Therefore, dredging trenches could be a source of oxygen-deficient water causing blue tide when a northeasterly wind is blowing (Sasaki et al., 1993; Hideaki, 2011; Ichioka et al., 2009).

For this worsening environment in enclosed seas, the Council for Transport Policy of Japan's Ministry of Land, Infrastructure, Transport and Tourism has announced a basic plan for the future port environmental policy. This plan details practical uses of recycled materials such as soil and sand dredged from ports and harbors, especially in enclosed seas (The Ministry of Land T Infrastructure, Tourism J, 2005). Considering the status of the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters (1972) and the Protocol Thereto (1996), in Japan, the Ministry of Land, Infrastructure, Transport and Tourism has proposed practical uses of industrial products and recycled materials including slag because, from the viewpoint of protecting the natural environment, it is not desirable to make use of natural mountain sand or crushed stone instead of these materials (Ministry of the Land, Infrastructure, Transport and Tourism Japan Coast Guard, 2016). The Ministry of the Environment has also demonstrated marine environment improvements in enclosed coastal seas using steelmaking slag (Ministry of the Environment, 2016). These efforts could also make an important contribution to reducing $CO_2$ emissions.

Steelmaking slag, a by-product of steel production, is produced at a rate of about 15 million tons/year. Steelmaking slag has been utilised in constructing social infrastructure such as roadbed material, coarse aggregate in concrete, and as a component of raw materials of cement. Since 1993, the Nippon Slag Association in Japan has been involved in undertaking technological research into the use of steelmaking slag as a material for ground improvement in ports and harbors construction (Ozeki, 1997). The JFE Steel Corporation in Japan has manufactured artificial reefs by using a carbonated steel slag in order to create an

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ideal breeding habitat for seaweeds and coral (JFE, 2004). In recent years, steelmaking slag has included a high amount of iron, and has been utilised to recover shore protection and to improve sea bottom sediments (Nippon Slag Association, 2016). Some researches have been undertaken during the last two decades into promoting practical uses of steelmaking slag's special characteristics in enclosed sea environments. Many studies have found that slag is a useful by-product for removing phosphate and $H_2S$ and for releasing iron in order to promote growth of seaweeds (Kim et al., 2012; Nagai et al., 2014). The solidification process and mechanisms of steelmaking slag at tidelands have been investigated. Furthermore, dredged soil was added to steelmaking slag to examine whether it would prevent solidification (Yano et al., 2016).

More recent works have focused on iron content of steelmaking slag, rocky shore denudation measures and bottom sediment improvement measures in enclosed seas by using Fe ions eluted from steelmaking slag (Hayashi et al., 2014; Hayashi et al., 2011). For example, it was found that steelmaking slag is a useful material for remediation of organically enriched sediments in enclosed sea areas, and was found to suppress $H_2S$ in field experiments at Fukuyama inner harbour (Miyata et al., 2015; Miyata et al., 2016) and Kawasaki port (Hayashi et al., 2013). A review paper has summarised research progress into steel slag utilisation (Yi et al., 2012).

In this study, we propose and develop a numerical model considering fluid-particle interactions between ocean circulation and steelmaking slag to investigate advection-diffusion of dissolved sulphides based on the results of field tests (Miyata et al., 2015; Miyata et al., 2016). The model is also applied to Fukuyama inner harbour and Tokyo Bay, where $H_2S$ is highly toxic and fatal to benthic organisms, as well as causing oxygen-deficient water and blue tide. We demonstrate effectiveness and usefulness of steelmaking slag in restoration of ocean environments at enclosed sea areas.

## 2. Overview of field test

To reduce dissolved sulphide and to suppress formation of hydrogen sulphide gas, the previous field test has been undertaken by the JFE Steel Corporation West Japan Works since 2011 (Miyata et al., 2016). Steelmaking slag was covered by sediment including silt and organic matter in Fukuyama inner harbour with a length of 2200 m, a width of 100 m, and a depth of 2 m, as shown in Fig. 1. The right-hand figure shows the horizontal plane and the vertical section with monitoring points for measuring water quality in the inner harbour. In this harbour, the holding capacity of sewage treatment plant at the head of inner harbour occasionally exceeds and also the untreated sewage including organic matter is sometimes flushed when heavy rainfall exceeds the holding capacity. Sulphate-reducing bacteria can generate $H_2S$ and stinking toxic compounds. The properties of the sediment on the bottom in the inner harbour can be seen in a report by Miyata et al. (2016).

In 2011, the first construction was conducted at Site A with an area of 432 $m^2$. The fine steelmaking slag with a particle size of 5–10 mm was firstly placed, and next the coarse slag with a particle size of 10–25 mm was followed. Further sites were constructed at the neighbouring location of Site B with an area of 2620 $m^2$ and at Site C with an area of 890 $m^2$ in 2012. The slag with a particle size of 30–50 mm was also used with the aforementioned slag. The total thickness of the covered slag was approximately 0.7 m on the silty sediment. The steelmaking slag was mainly the chemical compound made up of Fe, $CaO$, $SiO_2$ and $Al_2O_3$. More detailed chemical compositions of the slag and granite, can be found in Miyata et al. (2016, 2015). The filed conditions such as slag size, covered area and thickness are considered in the numerical model, as mentioned in the next section. Some important parameters such as water quality, gas and benthos were monitored after the construction at distances of $x = -100, -50, 0, 65, 134, 184$ and 244 m from Site A, where there are three vertical observation points to monitor and analyse dissolved sulphides.

## 3. Numerical model

We employed two different models. One was based on a 3D Eulerian-Lagrangian model (Baso et al., 2011) to compute fluid-particle interaction among soil, slag, and tidal flow in a local area. The other one was a quasi-3D Ocean Circulation Model based on the Princeton Ocean Model, POM (Blumberg and Mellor, 1987) to compute global advection-diffusion of dissolved sulphides. Both models were coupled at global sea bottom boundary conditions, where steelmaking slag is covered.

### 3.1. Eulerian-Lagrangian model for the local area

In the local area, to compute multiphase flow considering fluid-particle interactions between soil, slag, and sea water including the water surface, a Eulerian-Lagrangian model (Baso et al., 2011) was employed using both Lagrangian marker particles and a density function as shown in Fig. 2. In this section, the grid-based method is first introduced to compute fluid flow such as currents in ground water and global water elevation and next the particle-based method is explained to compute behaviours of soil and sand in the local area.

#### 3.1.1. Governing equations

The governing equations in this model are the incompressible Navier-Stokes equation, the mass conservation, the advection-diffusion equation for concentration of dissolved sulphide, and the equation of the density function $\phi_I$ for the $I$th phase (Air phase: $I = 1$, Water phase: $I = 2$, Solid phase such as soil and slag: $I = 3$) given by

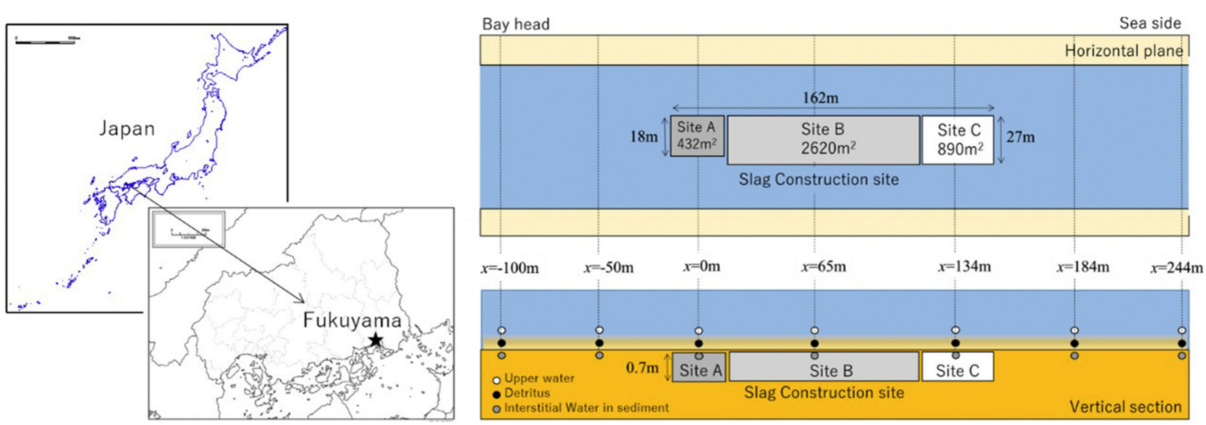


**Fig. 1.** Field test site at Fukuyama inner harbour.