Study on the Effect of Density Change due to Suspended Fine Sediment on Tsunami Force

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ABSTRACT

This study examined the characteristics of suspended fine-grained sediment due to tsunamis through hydraulic experiments and confirmed the vertical density distribution of turbid water containing sediments. The experimental results showed that the maximum density of turbid water containing sediments was about 1.2 g/cm³. Then, we conducted additional experiments in which tsunamis of different fluid densities using salt water were impacted on a seawall. The results showed that the tsunami wave height was smaller, and the wave force was larger under salt water with larger density. Furthermore, a numerical simulation confirmed the same trend as in the experiments.

KEY WORDS: Tsunami force, sediment transport, fluid density, hydraulic experiment, numerical simulation, OpenFOAM

INTRODUCTION

In the 2011 Great East Japan Earthquake, a so-called black tsunami that engulfed sediment was observed (Imamura, 2022). The deposits left after the black tsunami came to be well known in the world because it widely appeared on the land surface with black color. The field survey reported that about 40 cm of sludge had accumulated after the tsunami. It is known that large proportion of this tsunami deposit consists of silty and clayey material by Nakamura and Komai (2021). In general, it is important to estimate the suspended sand concentration and fluid density in terms of the characteristics of tsunami and sediment in order to properly evaluate the tsunami loads acting on coastal structures. FEMA (Federal Emergency Management Agency, 2019) and ASCE (American Society of Civil Engineers, 2017) assume the specific gravity of suspended sediment is 2.5 and the vertical mean volume concentration of sediment in seawater is 7%. Also, the tsunami wave force is calculated by assuming the minimum density of the fluid to be 1.1 times, including the suspended sediment of seawater (1,128 kg/m³). These criteria are considered appropriately when the fluid density is as large as that, but the mechanisms of the tsunami force including the sediment is not yet clear. For appropriate design against tsunami wave force, it is necessary to quantitatively evaluate the effects of density and viscosity changes due to sediment content on the tsunami wave force. Most of the studies on sediment transport by tsunamis have focused on relatively large sized sediments. Based on massive dataset of the tsunami deposits by the 2011 Great East Japan Earthquake, Goto et al. (2014) identified a possible upper threshold of tsunami sedimentation. They found that sediment concentration, which is defined as a ratio of deposit thickness to the local flow depth, can be approximated by a constant value of 2% over the coastal plain of the Sendai Bay, northeast Japan. Matsutomi and Konno (2018) investigated the dependence of the density of tsunami inundation water with sediment on the Froude number and the sediment grain size based on small-scale moving bed experiments and showed that the maximum density of tsunami inundation water with sediment can reach 1.2 g/cm³.

On the other hand, only a few studies have focused on fine particles (i.e., a few micrometers in diameter) such as mud and sludge, and there is currently no established mud transport model by tsunami. Kise and Arikawa (2019) analyzed black sediment samples collected at a fishing port in Miyagi Prefecture after the tsunami caused by the 2011 Great East Japan Earthquake and found that the fluid density was 1.13 g/cm³ and the median particle size was 6.74 μm. They also conducted moving bed experiments using silt and sand to investigate the relationship between fluid density and tsunami wave force. The results indicated that, the angle of the wave front at the tsunami impact varies with increasing the fluid density, in some cases becomes close to parallel to the wall surface, which lead to significant large wave forces. However, the vertical distribution of the density has not been measured. In this study, we first focused on the suspension characteristics of the sediments that lead to black tsunami, conducted a moving bed experiment using sediment models with a few μm particle size for fine sediments, and obtained the vertical concentration distribution of the suspended sediment. In addition, the viscosity of the sediment models was measured and the relationship between the viscosity and the suspension characteristics was discussed. Then, we focused on the effect of fluid density on tsunami forces and conducted a tsunami impact experiments for several fluid densities adjusted by using salt water. In addition, the numerical simulations using OpenFOAM were performed to reproduce these experiments. These hydraulic experiments and numerical simulations were conducted to investigate the relationship between the fluid density, the wave profiles and wave forces of tsunami.