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Experimental and numerical study on the reduction of tsunami flow using multiple flexible pipes

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ABSTRACT

Oil and gas tanks located in Osaka Bay are highly vulnerable to a tsunami if a Tokai-Nankai-Tonankai earthquake occurs and the consequential tsunami attacks that area. Being inspired by ecologically friendly mangrove and giant-kelps, it has been found that flexible pipes have the capability to reduce wave energy and flow velocity. In this paper, the use of flexible pipes for the reduction of tsunami damage on oil and gas tanks is investigated by means of an experimental and numerical approach. For the experimental study, scaled-model experiments are conducted in the tsunami basin using scaled-model flexible pipes and oil and gas tanks. The tsunami-like wave is generated by the dam break method. Flow velocity in front of and behind the flexible pipes, as well as hydrodynamic forces acting on the model tanks are measured. Experimental results suggested that, from approximately 30 percent to 44 percent of maximum hydrodynamic force could be reduced by the application of flexible pipes. In the numerical approach, 3D CFD simulations are performed for the arrangement of flexible pipes and oil tank, similar to the experimental conditions. A tsunami-like wave is generated by the dam break method and simulation of the flow field is done by solving RANS equations in the open-source CFD toolbox, OpenFOAM. The simulation results show good agreement in terms of flow velocity and hydrodynamic forces acting on the oil tank.

1. Introduction

1.1. Background

When a large-scale earthquake occurs, the oil and gas tanks located in the oil and petroleum industrial parks are highly vulnerable to structural damage, directly caused by the earthquake, as well as the impact load of the tsunami induced by the earthquake. Large-scale oil spills and fires occurred in Kesennuma City, Miyagi Prefecture, Japan during the 2011 Great East Japan Earthquake due to the large-scale earthquake and subsequent tsunami.

According to Kato et al. (2014), the oil and gas spills due to such large-scale earthquakes and tsunamis are categorized into earthquake-oriented and tsunami-oriented mechanisms. The earthquake-oriented mechanisms include: sloshing of oil and gas in the tanks by long period oscillations of the ground, liquefaction of ground under the storage tanks, structural damage of oil and gas storages and non-structural damage of peripheral systems of oil and gas storages, like power supplies. Tsunami-related mechanisms include drifting and tumble of oil and gas tanks, scission of pipes of oil and gas tankers under loading caused by those drifting, collision of oil and gas tankers and drifting debris with oil and gas storages, spreading of spilled oil and gas on land and sea surface, and non-structural damage of oil and gas storages like power supplies.

After the occurrence of the 2011 Great East Japan Earthquake, hardware countermeasures to tsunami-oriented risk were taken according to the policy of Ministry of Land, Infrastructure, Transport and Tourism (2012). These countermeasures include the redesign of port configuration, including concrete tsunami embankments and the setting of breakwaters in the industrial complexes. By the definitions of this institution, tsunami is categorized into two types: Level 1 tsunami which has the probability of occurrence of one time in one hundred years and Level 2 tsunami which has the probability of occurrence on one time in one hundred to one thousand years. For Level 1 tsunami, the breakwater should have the function not only to save the lives of citizens, but

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also to continue the activities of regional economy and port facilities. For Level 2 tsunami, breakwater only needs to save the lives of the citizens and to prevent the occurrence of the secondary disaster. For the industrial complexes, this policy has been applied although secondary disasters will happen if the oil spills occur after the attack of Level 2 tsunami on the industrial complexes. Regulations for the oil tanks have been made by the Fire Defense Agency, Japan (2012). However, there are few regulations for countermeasures to tsunami-oriented risk.

According to the research on hardware countermeasures against tsunami by Tokida and Tanimoto (2012), earth banks showed significant effect on the decrease of tsunami damage. Such earth banks have been reevaluated after the occurrence of the 2011 Great East Japan Earthquake from the viewpoint of the toughness of the earth banks against large-scale tsunami. In addition, a variety of breakwaters have been proposed as countermeasures against large-scale tsunami. These developments include flap-gate breakwater by Kimura et al. (2012), the breakwater with buoyancy-driven vertical piling systems developed by Takayama et al. (2010) and self-spreading sheet-type breakwater by Shimada et al. (2014). The buoyancy-driven vertical piling breakwater has been implemented in Wakayama, Shimotsu Port since October 2013. However, these types of breakwater need huge construction cost and time, resulting in difficult implementation.

From the viewpoints of cost-effectiveness and environmental friendliness, Kato et al. (2014) introduced the use of bio-inspired flexible pipes to reduce the tsunami-related damage. In their work, the hardware countermeasures for the prevention of the secondary disasters caused by a Level 2 tsunami were proposed including earth bank around oil and gas storages and setting of long flexible pipes similar to giant-kelps on the seabed near the oil and gas storages to prevent them from drifting and tumbling, and spilled oil from spreading into urban and port areas.

1.2. The idea of bio-inspired flexible pipes

According to the field surveys on Andaman coast of Thailand carried out by Tanaka et al. (2007), mangrove species,'*Rhizophora apiculata*' and '*Rhizophora mucronata*' were effective in providing protection from tsunami damage by increasing friction and reducing tsunami flow energy, as well as trapping floating objects by means of their aerial roots. However, the aerial roots can heavily disturb the marine traffic and thus, mangroves are not suitable for use as a tsunami prevention mechanism for oil and petroleum complexes located near the shore. On the other hand, giant-kelps (*Macrocystis pyrifera*) also have wave energy reduction capability according to Rosman et al. (2013). Being inspired by such bio-friendly tsunami reduction mechanisms, we developed the bands of multiple flexible pipes for the prevention of oil spills from industrial complexes caused by large-scale tsunamis. In this paper, the use of multiple flexible pipes as a mean for tsunami damage reduction is introduced as one way of hardware countermeasures.

1.3. The use of flexible pipes for tsunami damage reduction

As shown in Fig. 1, for the calm condition, the pipes are to be wound up and connected to a compressed air source such as a compressed air container or air compressor via a remotely operated solenoid valve. This arrangement is placed on the seabed in front of the industrial parks that hold the oil and gas storages. In the emergency condition, the solenoid valves are opened, letting the compressed air into the flexible pipes, with enough air pressure to stand the flexible pipes being upright. Such flexible pipes arrangement can be constructed in conjunction with the other tsunami countermeasures such as earth-bank arrangements. Fig. 2 shows the schematic of one of the possible arrangements of a band of flexible pipes with quay walls in front of the oil storage tanks. Circulating water tank experiments were conducted by Kato et al. (2014) to study the effect of tsunami force reduction by the use of a band of flexible pipes and an earth bank. In their experiment, the tsunami flow was represented by a uniform flow with the velocities corresponding to Level 1and Level 2 tsunamis. The hydrodynamic force acting on a model oil-tank was measured for the cases with and without the flexible pipes. However, the effects of tsunami run-up and wave impact load were not considered in their work. Therefore, it is still necessary to understand such unsteady phenomena for the development of flexible pipe.

1.4. Purpose of this study

The purpose of this study is to investigate the reduction of the wave-load acting on the oil and gas storage tanks induced by an unsteady tsunami wave by the use of flexible pipes, with the consideration of wave-impact load. To achieve this purpose, we carried out scale-model experiments in the tsunami basin by creating unsteady tsunami-like wave. Moreover, CFD simulations were carried out to investigate the effect of width of the pipe arrangement in the cross-flow direction, based on the experiments. This work is organized as follows. Firstly, the experimental approach is presented, with the choice of wave-basin, the arrangement of the sensors and the discussions of the measurements. Next section includes the numerical analysis using CFD, with the validation of the CFD results against the experiments. Then the effect of the width of arrangement in the cross-flow direction is considered from numerical results.

2. Tsunami basin experiment

2.1. Tsunami tank

Tsunami tank tests were carried out using scaled-model pipes and oil and gas tanks in order to study the tsunami force that can be reduced by using flexible pipes. A tsunami wave tank was used to generate tsunami-like waves in order to study the tsunami attack on oil storages at scale-model. The schematic of the tsunami tank is shown in Fig. 3. The total length of the tsunami tank is 44 m while the diameter of the spherical tank used in the experiment is 0.1 m (10 cm) and the difference of water level between reservoir and the experimental tank is 0.25 m (25 cm). Thus, in order to show the whole experimental arrangement focusing on the flexible pipes and the tank model, the schematic in Fig. 3 is drawn using a different scale ratio for the object dimensions of the flexible pipes and the tank model. The photo of the experimental setup is shown in Fig. 4.

The dimensions of the tsunami wave basin are 44 m × 0.7 m × 0.9 m (length × width × depth). The basin length of 44 m is comprised of two slopes: 1/40 slope and 1/100 slope. However, the experimental setup was placed inside the 1/40 slope region in order to generate a tsunami-like wave having a velocity flow of around 1 m/s.

A tsunami wave is a wave with a very long period, which induces an impact force by its wave-head, while the rest of the wave can be assumed to be of uniform flow. Suitable ways to generate a tsunami-like wave include a plunger type wave generator with a very long stroke or to use the dam break method. In this experiment, such a tsunami-like wave was created using the dam break method. Firstly, a water column with a height of 0.25 m was created on the dam (reservoir) side by filling up that side with water while the watertight door is closed, as shown in Fig. 3. Then the wave was generated by manually opening the watertight door. Before