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Flood Risk Assessment of Offshore Artificial Islands Induced by Heavy Rainfall

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Abstract: Our study area is the west artificial island of the immersed tunnel of the Hong Kong-Zhuhai-Macao Bridge. The offshore artificial island is created by reclaiming land, and it serves as a critical link between the subsea tunnel and the bridge. Heavy rainstorms may result in flooding of the artificial island, which threaten the safety of traffic on the island. Our study is mainly about flood disasters and assessing the damage to cars on the artificial island. The coupled hydrodynamic model of the artificial island is created to simulate flood disasters for three return periods of rainfall. The maximum flood depth distribution and car damage are analyzed for rainfall scenarios. The method described in this paper would provide technical support for offshore engineering flood prevention and risk assessment.

Keywords: Flood risk assessment; Offshore artificial island; Rainfall; Hydrodynamic model

1 Introduction

The Hong Kong–Zhuhai–Macao Bridge (HZMB) is located in the Pearl River Estuary in Guangdong Province, which is one of the regions with the strongest economy in China in Figure 1 (Hu et al., 2015; BBC, 2018; HZMB, 2022). The HZMB connects Hong Kong, Guangdong Zhuhai and Macau, which greatly facilitates transportation between cities. The HZMB is about 55-km which is the longest bridge-tunnel sea crossing in the world. The HZMB is a complex transportation project that includes bridges, an undersea tunnel and artificial islands.

Some studies analyzed the undersea tunnel and bridge structure safety of the HZMB (Wang et al., 2018; Dai et al., 2019), but few studies have considered the disaster and safety of artificial islands. Extreme weather disasters, such as typhoons, heavy rains and storm surges, are common in the region (Yang & Qian, 2019). Weather disasters would cause serious flooding, which threatens the safety of the artificial islands (Li et al., 2018). The artificial islands were created by reclaiming land in the sea and served as a traffic channel between the tunnel and bridge for daily transportation and sightseeing (Xiao et al., 2020). Flood simulations and car safety assessments for artificial islands are critical due to the weather disasters and their important role.

Many academics have studied floods in various regions using hydrodynamic models and numerical simulations (Luo et al., 2018; Wang et al., 2018; Hsiao et al., 2021). For example, Hsiao et al. (Hsiao et al., 2021) proposed coupled models to simulate coastal floods under extreme conditions and quantify the effects of compound floods under climate change conditions. Under various environmental factors such as sea level and subsidence, the hydrodynamic model is used to simulate flooding under various scenarios (Wang et al., 2018). Luo et al. (2018) established a flood inundation model to analyze water depth and inundation area under extreme rainfall types to manage urban floods. Sun et al. (2021) used a drainage hydraulic model to evaluate the flooding caused by heavy rainfall in large cities and proposed related drainage measures. These studies focus on large-scale cities, but few studies have focused on the flooding of marine traffic projects.

2 Study area

The HZMB is located in the Lingdingyang sea area of the Pearl River Estuary in Guangdong Province, China. The study area in this paper is the western artificial island of the immersed tunnel in Figure 1. It covers an area of about 100,000 square meters, with the east-west length of 630 m and the north-south length of 200 m, as shown in Figure 2. There are drainage pipes, buildings, roads, and other infrastructure on the island. The island includes the main road in the middle (red area) and secondary roads on both sides (blue area). The island's main road is an open section of the road from the west. It extends eastwards into the island's interior as a buried tunnel and then connects to the immersed tunnel.

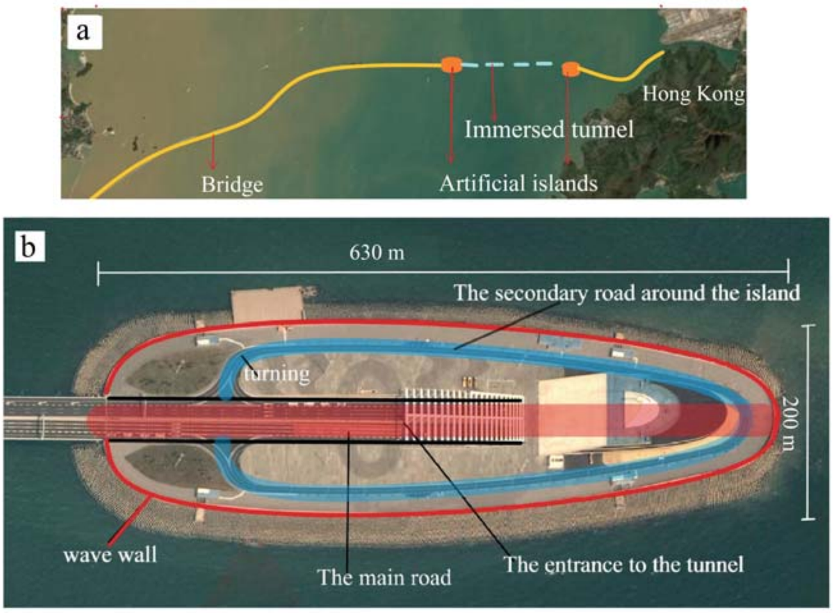

Figure 1. Hong Kong-Zhuhai-Macao Bridge: (a) geographical location; (b) west artificial island

3 Flood model

Mike Flood is a coupled hydrodynamic model for the numerical simulation of water flow in drainage and surface (DHI, 2020). It is widely used to evaluate flood disasters in coastal areas (Jamali et al., 2018). This study coupled the 1D drainage model (Mike Urban) and a 2D surface overflow model (Mike 21) based on Mike Flood. The drainage network and surface flow models are coupled using manhole connections, so they can accurately represent the interactions of water flow in the drainage network and the surface. This study establishes the coupled hydrodynamic model to simulate waterlogging under heavy rainfall scenarios and then assess car damage in flood on the artificial island.

Mike Urban is a drainage system model for the rainfall-runoff process and flows simulation in the pipe network (DHI, 2019; Hernes et al., 2020). The unsteady flow in the pipe flow model is solved by the conservation of momentum and mass via the Saint-Venant equation (DHI, 2019). A one-dimensional (1D) drainage network model of the artificial island is established by Mike Urban. The model catchments are divided using the Tyson polygon method. The water into the pipe network is released through the outlets. The surface of the island includes buildings and roads, and the impermeability rate is 0.85 in the model. The study area is bounded by the artificial island's outermost wave wall, which is divided into 105 sub-catchments. The drainage network in the model has 128 pipes, 108 nodes, and 10 pipeline outlets that link to the outside. The drainage network and surface model are coupled through manholes. Figure 2 shows the surface elevation and drainage system of the artificial island.

The hydrodynamic model of Mike 21 is numerical modeling for the simulation of water levels and flows (DHI, 2017; Wang et al., 2018). It simulates unsteady two-dimensional flows in one layer fluids (vertically homogeneous) based on the conservation of mass and momentum in the vertical direction (DHI, 2017). A two-dimensional (2D) surface flow model of the artificial island flood was established to simulate the water flow on the ground surface using Mike 21. The model includes building a surface elevation model and establishing the grid of the island. Figure 2 shows the artificial island surface elevation. A wave wall outside the artificial island is set as a closed boundary. The hydrodynamic model uses 0.5 m × 0.5 m square grids to spatially discretize the research region into 560,000 grids. The locations of open drainage channels on the island surface are locally lowered. The main road gradually goes down the slope into the tunnel from west to east, and the longitudinal gradient is about 3%. The outer circle of the model is the closed boundary and the eastern boundary of the tunnel is an open boundary and water flows out freely.

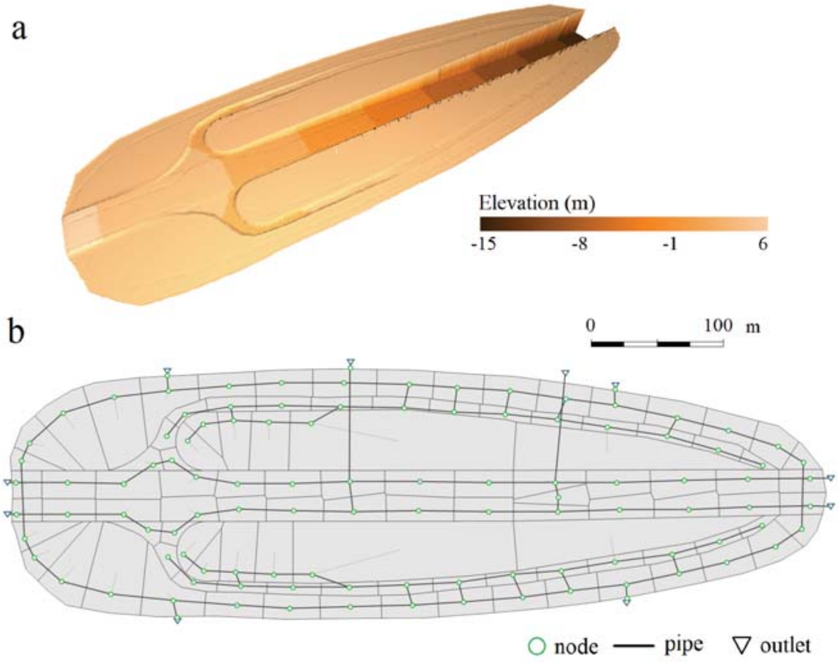

Figure 2. (a) The elevation and (b) drainage of the artificial island.

4 Flood results

The artificial island is situated in the Pearl River Estuary, which has a south subtropical monsoon climate with an average annual rainfall of 1,900 mm. Extreme weather disasters are prone to occur in summer, such as huge waves, storm surges, and heavy rain disasters (Yang et al., 2015; Zhang et al., 2017). The Shenzhen rainstorm intensity formula is derived from 54 years of precipitation data in Shenzhen from 1961 to 2014 (SMB, 2015). The formula is used to obtain rainfall amounts during three return periods and the Chicago rain pattern is applied to obtain 2 hours of rainfall process. Floods on artificial islands were simulated for rainfall scenarios of three rainfall return periods. Figure 3 shows the rainfall depth for three return periods of 20 years (20a), 50 years (50a) and 100 years (100a).

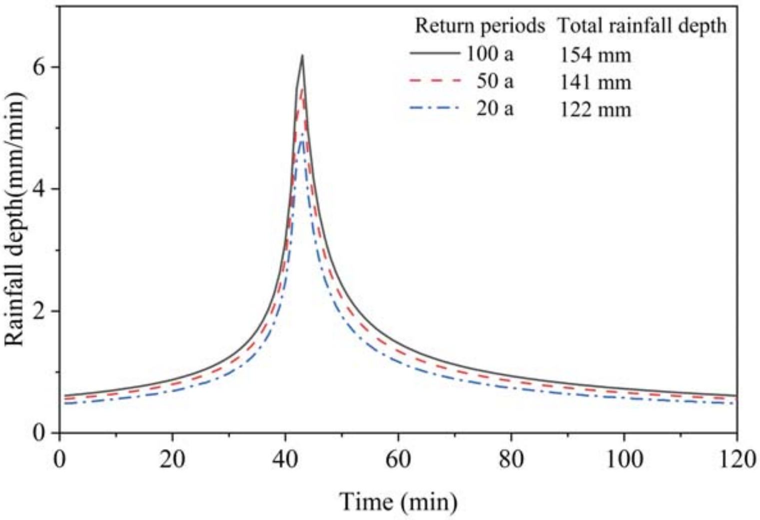

Figure 3. Rainfall depth for three rainfall return periods

The coupled flood model simulates the three rainfall scenarios of the artificial island: 20-, 50- and 100-year. Figure 4 shows the maximum flooding depth under three return periods of rainfall. Flooding is deepest at the turn of the two secondary roads due to the lower elevation at this location. There is a slight flood on the main road on the artificial island. Compared with the three rainfall scenarios, flood depth and range have increased a little. The turnings of the secondary roads are the deepest-flooded parts and the maximum depth is about 0.6 m for the 100-year return period of rainfall. The maximum depth is about 0.03 m for the 100-year return period at the main road.

As rainfall intensity increases for three return periods, water depth increases a little. The flood depth at the main road during the three rainfall return periods is significantly less than the turnings of the secondary roads. For the rain return period of 100-year, the flooded area above 0.03 m accounts for 25% of the island area. The turnings of the secondary roads are the deepest area of flooding, posing a great danger to pedestrians and vehicles. The water depth in most areas of the artificial island is less than 0.1 m, posing little danger.

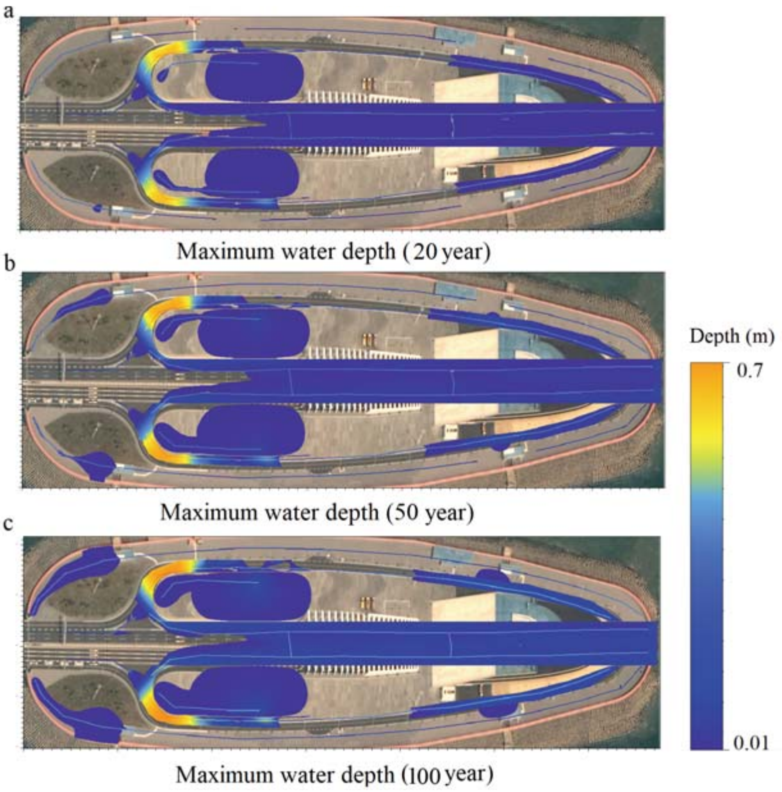

Figure 4. The maximum flood depth for rainfall return periods of 20-, 50- and 100-year

5 Risk assessment of cars

The artificial island is an important transportation hub connecting the bridge and the immersed tunnel with daily traffic. The artificial island is the place to pass from the bridge to the immersed tunnel, and cars pass by every day. Vehicles are the most vulnerable objects directly threatened by flooding that results in great damage to cars and even personal injury. When the flood submerges vehicles to a certain depth, it will cause damage to components or even scrap the entire vehicle. Therefore, it is critical to define the damage degree of cars at different flood depths. The depth damage for cars (FEMA, 2006) was used to estimate the loss to cars caused by the flood, as shown in Figure 5.

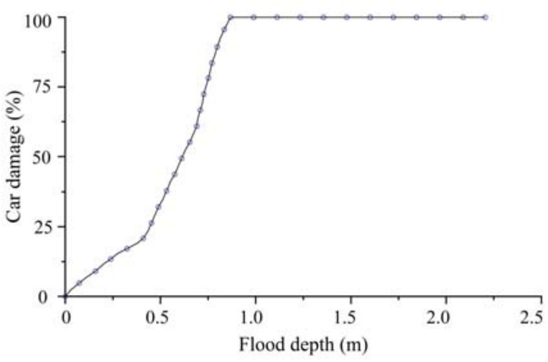

Figure 5. The damage degree of cars emerged in different water depths.

The maximum car damage degree distribution on the island for rainfall return periods of 100-year is shown in Figure 6. The most serious damage occurs at the secondary road turning exceeding 50%. The damage degree on most areas of the island, except for the secondary road turns, is all less than 10%. The turning position of the secondary road has relatively large car damage, so the cars should keep away from this position during heavy rainfall.

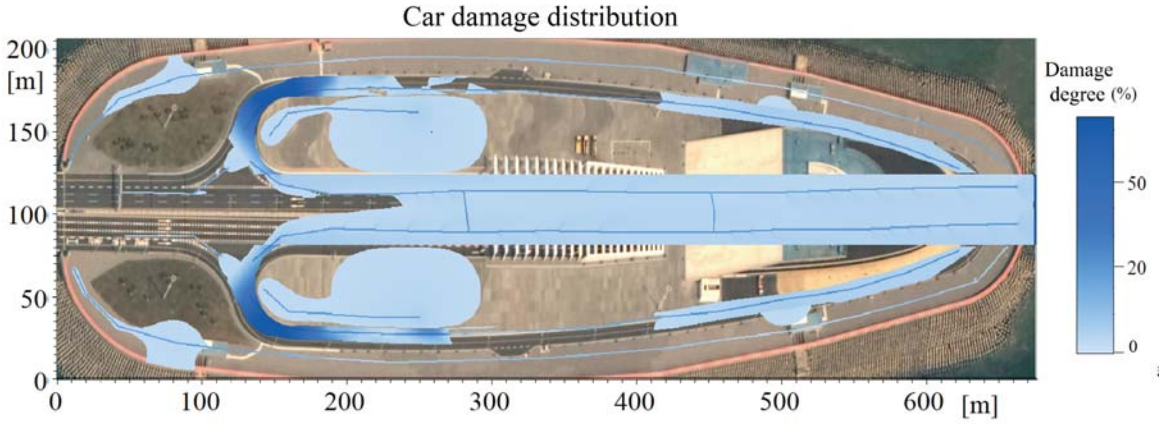

Figure 6. The damage degree distribution of cars on the island for rainfall return periods of 100-year

6 Conclusion

This study is to conduct the flood risk assessment for an artificial island by rainstorm-induced flood disasters. The drainage and the surface flow model are coupled to establish the hydrodynamic model of the artificial island. Flood depth at different locations is obtained for three rainfall return periods on the artificial island. We find that roads on the island are more prone to flooding than other areas under heavy rainfall. Flood at the turns of secondary roads is deepest in all areas and the car damage here is more serious than in other locations.

When a flood disaster occurs, vehicles should avoid dangerous areas on the island and take appropriate precautions. The flood model and damage assessment for rain-induced flood disasters provide support for the flood control of cross-sea transportation infrastructure. However, there are some limitations that need to be improved. The model used the simplified elevation and drainage of the artificial island. The drainage model does not consider the pump on the island. The elevation of the artificial island for the hydrodynamic model needs to be further refined.

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