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Coupling simulation of overland flooding and underground network drainage in a coastal nuclear power plant

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ABSTRACT

Modelling the flooding inundation in coastal nuclear plants under external hazards is critical for risk assessments associated with nuclear safety. In this paper, a coupled model is developed to simulate the flood process in a coastal nuclear power plant under the combined action of extreme rainfall, wave overtopping, and tidal flow, based on the storm water management model, SWMM and the overland flooding model, TELEMAC-2D. Discharge exchange between the overland flow and the drainage network flow is calculated by a weir equation and an orifice equation, if the water level of a node in the underground network is lower than the elevation of ground surface corresponding to the node, while it is calculated by SWMM through a water level boundary condition. An experiment is performed to observe flow patterns between the drainage network and ground surface and to test the reliability of the numerical model. Three typical flow patterns, i.e. pressure flow, spiral flow and weir flow, are observed, and the computed flow discharge is in good agreement with experimental results. The mathematical model is then applied to a scenario analysis of flooding inundation in a nuclear power plant under the combination of wave overtopping, tidal flow and an extreme rainfall. Results show that the most dangerous scenario near nuclear power units occurs when the rainfall peak arises later than the peak of wave and tide; the wave wall, revetments and pipe system play an important role on weakening the accumulated water depth. The coupled model developed in this paper is likely to supply a useful tool for nuclear power risk assessments associated with flooding inundation, and further work should examine the validation and reliability of the model with field data.

1. Introduction

Flood inundation in coastal nuclear power plants (CNPPs) caused by external hazards, possibly leading to large casualties and property losses (Nuclear Emergency Response Headquaters, 2011), has received increasing attention especially after the Fukushima Daiichi nuclear disaster, due to its great threats to nuclear safety. Numerical simulation has become an important way to predict and assess flood inundation, due to its various advantages in terms of low economical costs, high efficiency in parameter determination, free site restriction, no scale effects, etc. (Chen et al., 2005; Gilles and Moore, 2010; Smith et al., 2006; Vojinovic and Tutulic, 2009; Zoppou, 2001).

Regarding the numerical simulation of flooding inundation, there have been various hydrological and hydraulic models. The hydrological models normally employ the water stage-volume curve to determine the water depth in catchments due to the rainfall and runoff. Hydraulic models, including one-dimensional (1D) model, two-dimensional (2D) model, and 1D-2D coupled model, have been widely used to simulate the overland flooding. 1D model is mainly used to predict the flow through rivers, streets, and ditches (Bates and De Roo, 2000; Mark et al., 2004), while 2D model is generally employed to simulate the flooding in floodplains, estuaries, lakes, and urban areas (Mignot et al., 2006; Gilles and Moore, 2010). Various commercial software and open source codes, such as Delft 3D FLOW (Deltares, 2014), TELEMAC-2D (EDF, 2010), MIKE21 (DHI, 2007), and EFDC (Hamrick, 1996), have been developed based on 2D model. Some coupling models associated with the hydrological model, 1D model, as well as 2D model are developed (Chen et al., 2012; Leandro, 2008; Leandro et al., 2009; Leandro and Martins, 2016; Lin et al., 2006; Vojinovic and Tutulic, 2009) to balance the resolution and computational efficiency.

The flooding inundation in CNPPs is frequently related to the overland flooding and underground network drainage. With regard to the coupling simulation of the overland flow and pipe flow, many efforts have been made (for example, Schmitt et al., 2004). Various 1D-2D (1D sewer model and the 2D overland flooding model) models have also been developed, such as MIKE FLOOD, MIKE URBAN, XP-SWMM, InfoWorks CS, coupling models based on SWMM and 2D model (Leandro and Martins, 2016), etc. The 1D-2D coupling is mainly

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achieved by specifying discharge exchange at some special linkages, such as manholes, inlets, etc. When the bidirectional exchange between inflow from overland and backflow from the underground network is not strong, unidirectional exchange is usually considered (Pathirana et al., 2011; Adeogun et al., 2012). However, bidirectional coupling is necessary for a strong bidirectional flow, and corresponding exchange discharge is normally calculated according to the flow patterns, such as the weir flow and the orifice flow, which are dependent on the relationship of the hydraulic head at the linkage, water level at the surface, and the ground surface elevation (Chen et al., 2007; Leandro and Martins, 2016; Lin et al., 2006; Seyoum et al., 2012; Vojinovic and Tutulic, 2009). Different from the flooding in the urban areas, waves overtopping and tidal flow would be expected to be important for the temporal and spatial distribution of accumulated water in CNPPs, besides the extreme rainfall. Therefore, it is necessary to develop a coupled model to predict the flooding inundation in CNPPs under the combined action of the overtopping, tidal flow and an extreme rainfall.

This work is to develop a coupled model for predicting flooding inundation in CNPPs under the combined action of extreme rainfall, wave overtopping, and sea level variation, based on TELEMAC-2D and SWMM. The specific objects are: (1) to couple the SWMM and TELEMAC-2D; (2) to observe the flow patterns occurring at junctions and validate the coupled model by a laboratory experiment, and (3) to simulate and analyze the flooding inundation in a CNPP.

2. Methods

2.1. The coupled model

The continuity equation and one-dimensional Saint-Venant equation are adopted in SWMM for the flow through a pipe network (Rossman, 2010) as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f + gAh_L = 0, \tag{2}$$

where A is the cross-sectional flow area, t is time, Q is the discharge in the pipe, g is the acceleration of gravity, H is the water level in the pipe, S_f is the friction slope, and h_L is the local resistance loss of unit length expressed as

$$h_L = \frac{KV^2}{2gL}, \tag{3}$$

where K is the a local loss coefficient at location x, and L is the conduit length.

The continuity equation and 2D shallow-water equation are adopted in TELEMAC-2D for the overland flow as (EDF, 2010):

$$\frac{\partial h}{\partial t} + \mathbf{u}\cdot\nabla h + h\nabla\cdot\vec{u} = q_1 + q_2 \tag{4}$$

$$\frac{\partial u}{\partial t} + \mathbf{u}\cdot\nabla u = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}\nabla\cdot(h\nu_t\nabla u) \tag{5}$$

$$\frac{\partial v}{\partial t} + \mathbf{u}\cdot\nabla v = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\nabla\cdot(h\nu_t\nabla v), \tag{6}$$

where h is the water depth, u and v are velocity components of velocity vector $\mathbf{u}$ in the x- and y-directions, respectively, Z is the water level, S_x and S_y are the source terms in the x- and y-directions, respectively, ν_t is the momentum diffusion coefficient, q_1 is the source term to reflect precipitation, and q_2 is the source term to reflect the discharge exchange between the surface flow and pipe flow. The bidirectional coupling between the surface flow and the pipe flow is based on the hydraulic head h_1 at a junction and the ground surface elevation h_f, as shown in Fig. 1.

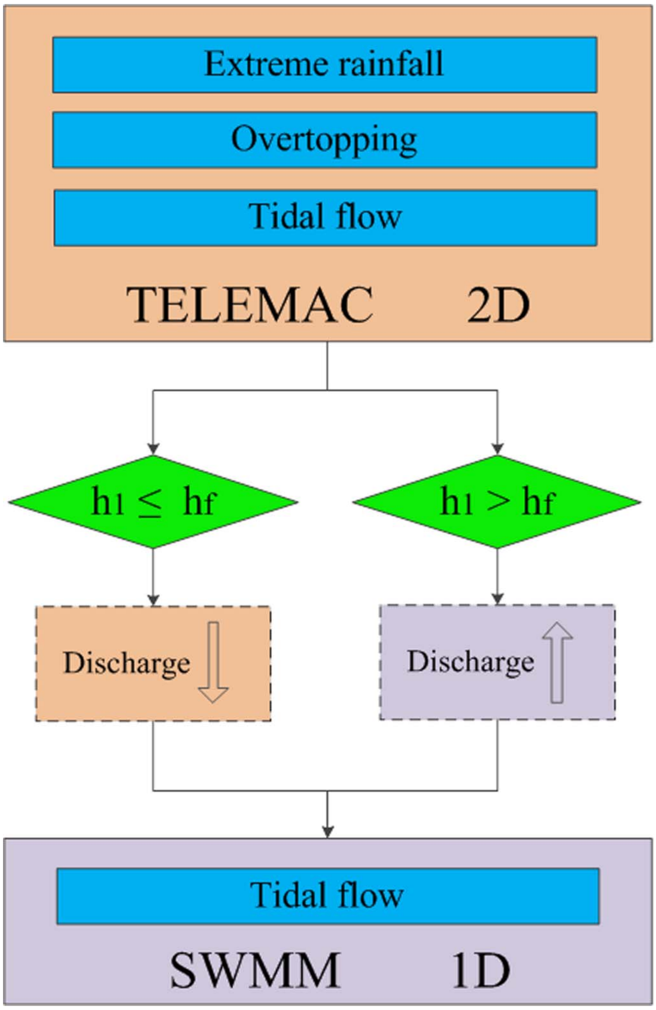

Fig. 1. Schematic diagram of coupling simulation of the surface flow and pipe flow.

For the case of $h_1 > h_f$, q_2 is calculated by SWMM, in SWMM, the water level rather than the flow discharge should be used as data input. For the case of $h_1 \le h_f$, the weir flow equation and the orifice flow equation are used to calculate q_2 (Yao, 2013)

$$q_2 = \min(C_w P_w {H_m}^{1.5}, C_o A\sqrt{2gH_m}), \tag{7}$$

where C_w is the discharge coefficient of weir flow, P_w is the wetted perimeter, H_m is the water depth at manholes, C_o is the discharge coefficient of orifice flow, and A is the cross-sectional area.

The coupling in the present model is different from that in the previous models in calculating the exchange discharge between SWMM and 2D overland flow model. In previous work, the exchange discharge is computed directly by the weir equation and orifice equation, according to the relationship of the hydraulic head at a linkage, water level at the surface, and the ground surface elevation. In the present work, the linkage in the SWMM is considered as a combination of Junction (to which a discharge boundary condition can be applied) and Outfall (to which a water level boundary condition can be applied). The exchange discharge in the present model is calculated directly by a weir equation and an orifice equation when the hydraulic head at the manhole is less than the ground surface elevation, and the exchange discharge is added in the 2D and 1D model as a source term and a discharge boundary condition, respectively. However, the exchange discharge is calculated by SWMM in which a water level boundary condition is specified in SWMM when the hydraulic head at the manhole is equal to or greater than the ground surface elevation, and the exchange discharge for 2D model is given by SWMM.