Geological Hazard Investigation Combined with Mathematical Modeling in Flood Risk Assessment: A Case Study of Hoang Long River, Ninh Binh Province, Vietnam

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Abstract

The primary function of the river dike system is to safeguard lives and property from flood hazards. However, due to aging infrastructure and various geological or anthropogenic factors, certain vulnerable sections of the dike system can emerge as the water level in the river increases. Flood maps are one tool that presents vital information for authorities and residents in the flood risk mitigation. This study's primary goal is to provide a flood map under the dike break condition using the estimated fracture size parameters from a geo-radar survey and the MIKE FLOOD model. This approach addresses the observed research gap by utilizing a survey database instead of relying on empirical models which are capable to produce the conservative estimates of the dike breach outflow. A case study is conducted on the Hoang Long River dike system in Ninh Binh Province, Vietnam.

Keywords: *flood risk assessment, dike break, dike failure, geo-radar, breach outflow, MIKE FLOOD*

1. Introduction

The dike system plays a vital role in protecting individuals, assets, and the environment from the risk of rising river water levels. Under the impact of climate change, the flow conditions have become more severe (Zagonjolli M., 2007). Meanwhile, river dikes, constructed long ago, often suffered from damages caused by geological hazards (such as earthquakes and subsidence) (Dat T.T. và nnk, 2019) as well as pressure from human activities (such as using dikes systems as traffic routes) (Hue N.H. và nnk, 2019). The condition of these dike system raises concerns for the residents living in the vicinity. The damage caused by the dike breaks depends on many factors, including the inundation water depth, flow velocity, breach outflow, population density, property distribution, and the adaptive capacity of residents in the affected area (Nguyen M.T. và nnk, 2021). Among these factors, determining the fracture size of the dike breach is the first essential technical steps in dike break simulation (Froehlich D.C., 2008) which the output of this modeling holds significant value for society. The dam breach parameters are usually estimated using the empirical formula related to geometrical properties: the dam's height, the slope, and the reservoir capacity (Dat T.T. và nnk, 2019; Froehlich D.C., 2008). Although it might not be effective, the simplicity of this empirical approach can be explained for the widespread use of empirical models in practical application.

Various studies have used numerical models to investigate dike failure's impact, for example, HEC-RAS (Brunner G.W., và nnkand CEIWR-HEC., 2016), MIKE FLOOD (DHI Water and Environment., 2014), NWS-DAMBRK (Fread D.L., 1991), or NARX (Bomers A., 2021) neural network. Ansori et al (2021) used HEC-RAS to simulate the dam failure of Way Apu reservoir in Malaysia with different design frequency discharge. In the work of Dat et al. (2019), MIKE FLOOD was used to simulate various dam break scenarios for the DakDrinh reservoir in Viet Nam and define the affected area. Anouk Bomers (2021) (2021) combined the HEC-RAS hydraulic model and the NARX artificial neural networks model to reduce the computer's weight processor when evaluating the fracture flow.

It is generally acknowledged that breach parameters are the most significant uncertainty in dam break studies spite the model used (ASCE/EWRI, 2011) (Wu W., 2011). This work tries to fill the lack of studies observed, using an extensive database instead of empirical approaches, or hypothetical values. Therefore, the main objective of this study is to exploring the dam breach parameters at critical locations using the geo-radar observation and to simulate flooding due to dike break using MIKE FLOOD model.

2. Material and methods

2.1 Description of study site

Hoang Long River is a tributary of the Day River, the largest river in Ninh Binh province. The upstream of the Hoang Long River is called the Boi River. The Hoang Long River has a length of about 125km, and the basin area is 1550 km^2. Hoang Long River flows through a lowlands area with only a 2–4m elevation. These terrain conditions cause severe flooding quickly after heavy rain. Hoang Long River has a complex hydrological regime; in the flood season, the river is affected by the Boi River upstream, and the downstream is greatly affected by floods from the Red River.

The Hoang Long River has a primary dike system for flood protection, consisting of the Ta Hoang Long Dike and the Huu Hoang Long Dike. This dike wall height adheres to the flood control level of the approved plan of +5.53 meters

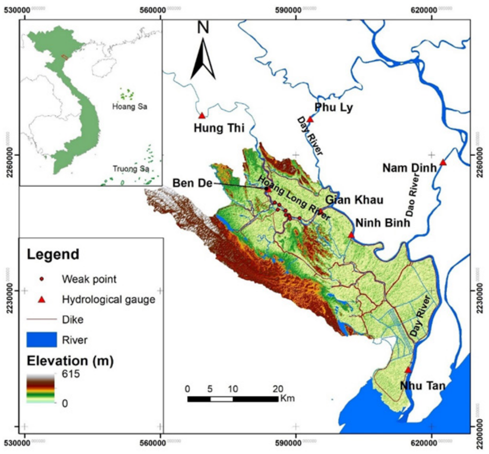

Fig. 1. Area of study

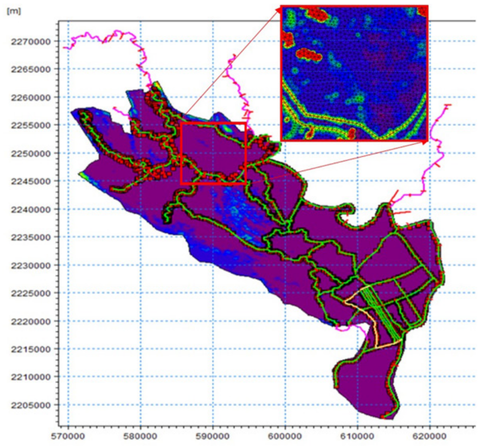

Fig. 2. Hydrologic and hydraulic coupling in MIKE FLOOD

(The Ministry of Agriculture and Rural Development., 2012). However, this dikes network was built over different dike periods. The earth-fill layer is not uniform and is constructed in multiple stages to meet the flood prevention requirements of the potentially endangered areas. These dikes have been renovated recently to serve road traffic for the locality's socio-economic development. This use has increased pressure on the dike system and dike safety (Hue N.H. và nnk, 2019).

2.2 Method and materials

MIKE FLOOD model

The MIKE FLOOD model developed by the Danish Hydraulic Institute was used to simulate inundation caused by dike failure (The Ministry of Agriculture and Rural Development., 2012). The model is integrated with (i) MIKE 11 model with the dike break module (DamBREK) to simulate unidirectional flow in the river and (ii) MIKE 21 model to simulate 2-D flow in flooded areas. Although the MIKE 11 model has outstanding advantages in simulating 1D flow in complex river networks, and MIKE 21 model can simulate the surface flow. However, MIKE 11 alone will be challenging to simulate overflow if flow directions are unknown in advance and can not define the velocity field. Using MIKE 21 to simulate the surface and mainstream flow requires reducing the mesh size to the extent which can show the channel's topography change. As a consequence, the computational time is a dramatic increase. To utilize the advantages of 1-D and 2-D models and overcome their disadvantages, MIKE FLOOD allows the coupling of MIKE 11 and MIKE 21 models in the simulation. This coupling model allows increasing the mesh size of the model. (i.e., reducing computation time), simulating the surface and stream flow. Therefore, the MIKE FLOOD model was employed in this study.

Materials

The hydrometeorological data, riverbed, and floodplains topography are collected for the inundation model. The hourly rainfall data at Ninh Binh meteorological station and seven hydrological stations (Nhu Tan, Ninh Binh, Gian Khau, Ben De, Nam Dinh, Phu Ly, and Hung Thi) were obtained from 2008 to 2020. The flood water level collected at seven hydrological stations is used for the model's boundary conditions and model verification. These data were provided by the National Center for Hydrometeorological Forecasting (NCHMF)(https://nchmf.gov.vn/). Riverbed topographic data collected from multiple sources throughout 2005 and 2019 includes 113 river cross-sections defining the 333km river lengths. Topographic data of floodplain areas are extracted from topographic maps at a scale of 1:10,000 m provided by the Vietnam Ministry of Natural Resource and Environment.

Establishing of coupled link 1D-2D in MIKE FLOOD model

a) Establishing network in 1D model

Fig. 3. The location of the levee subsidence on the left bank of the Hoang Long River

Tab. 1. The abnormal points along the Ta Hoang Long and Huu Hoang Long levees

Levee	#	Anomalies	Coordinates		Depth from the surface (m)	Predicted abnormal points
			Longitude	Latitude		
Huu Hoang Long	1	H1	105° 49' 43.23"	20° 19' 20.20"	2.4	Termite voids
	2	H2	105° 49' 55.49"	20° 19' 13.46"	1.8	Termite voids
	3	H3	105° 50' 25.66"	20° 18' 38.82"	3.8	Termite voids
	4	H4	105° 51' 42.48"	20° 18' 03.28"	2.5	Termite voids
Ta Hoang Long	6	T1	105° 49' 13.26"	20° 20' 03.98"	2.0	Termite voids
	7	**T2**	**105° 49' 42.60"**	**20° 19' 48.29"**	**1.0**	**Termite voids**
	8	T3	105° 49' 54.38"	20° 19' 41.35"	5.7	Termite voids
	9	T4	105° 49' 58.99"	20° 19' 38.39"	1.0	Termite voids
	10	T5	105° 50' 05.64"	20° 19' 33.34"	0.9	Termite voids

Tab. 2. The parameters of dike failures

Elevation of dike failure water level (m)	Initial failures		Limitation failures	
	$Z_{Initial}$ (m)	$B_{Initial}$ (m)	Z_{End} (m)	B_{End} (m)
4.3	4.33	10	2.5	110

The hydraulic system includes the Day River, Dao River, Hoang Long River, and inland waterways. The Day River is the longest in this network, stretching 105.5 km (from Phu Ly station to Cua Day), followed by the Hoang Long River at 60.7 km (from Hung Thi station to the Day River confluence) and the Dao River at about 24.5 km (from Nam Dinh station to the Day River confluence). Other rivers have a length in the range from 7 to 24 km. The total simulated length of the rivers is 407.5km with 259 river cross-sections. Figure 2 depicts the location and length of the rivers.

The water level at the Hung Thi, Phu Ly, and Nam Dinh stations define the upper boundaries of the river system. The tidal water level at the Day mouth calculated from the harmonic constant is defined as the lower boundary (Huan N.M., 2015).

b) Establishing computation mesh in 2D, MIKE FLOOD

The study defined the computational domain from the topographic map of the 1:10,000 scale. It includes the entire Ninh Binh province, with an area of 1387 km². The study area is discretized into 30686 elements, with the size varying in a range of 20–250m. The fine mesh is defined for important and complex areas (such as urban and residential areas). The flat area, like a paddy field, is defined with the larger grid cell size. In the MIKE FLOOD model, the 2-D model is connected to the 1-D model through side connections (Figure 2).

c) The location of vulnerable levees using Georadar physical survey (GPR)

The study surveyed various dike sections to determine the locations of vulnerable points along the levee system. The preliminary survey results identified four weak points on the right bank of the Hoang Long River levee and six weak points on the left bank, showing signs of subsidence and surface cracks (Figure 3, Table 1). The research team continued to utilize geo-radar physical survey, also known as Ground Penetrating Radar (GPR), a geophysical exploration method that uses electromagnetic wave propagation through the ground. By emitting radiofrequency electromagnetic waves into the subsurface as pulses, the radar system records the reflections when encountering boundaries or inhomogeneities in the electrical properties of the subsurface, capturing the data with receiving antennas. Using various processing, analysis, and interpretation techniques on the recorded electromagnetic wave field, anomalies-causing objects can be inferred. Ground-penetrating radar method offers several advantages in shallow geological surveys, such as non-destructiveness, ease of mobility, fast data acquisition, high resolution, and accuracy. The results obtained from geo-radar measurements can correlate with other geological and geophysical survey findings to elucidate geological factors, such as boundaries between soil and rock layers, and determine the position, depth, and size of anomalous objects within levee bodies or embankments. This study utilized the GSSI SIR-30 geo-radar system with a 100MHz frequency, antenna model 3207/3207A, and a noise-resistant display to measure continuously over vulnerable sections. Using a frequency filter ranging from 25 to 300MHz allows for a maximum depth penetration of 13 meters from the ground surface.

The geo-radar measurement of the dike anomalies objects allows for the finding of the geological characteristics of the dike. The main components of the dike consist of loose materials, including clay and clay-sand mixtures. The structure of these geo-radar anomalies suggests that they may indicate the development of termite voids within the dike. If left undetected and untreated, these termite voids within the levee can grow, expand, cause seepage, and potentially lead to subsidence, slope failure, and destruction and pose hidden risks of levee failure (Figure 4). Among the weak points, the survey team observed significant anomalies at location T2 on the left bank of the Hoang Long River levee, making it the most vulnerable point in this area. Based on the measured signals, the survey team estimated the size of the weak section, as shown in Table 2.

3. Results and discussion

3.1 Calibration and validation

The calibration and verification are to determine the appropriate parameters for the study area and to simulate the

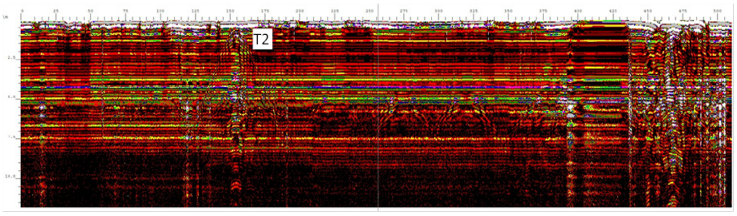

Fig. 4. Abnormal points detected by georadar (T2) on Ta Hoang Long levee

Tab. 3. Model's performance evaluation indicators

	Station	Nash	R^2	Peak flood errors (cm)
Calibration	Ben De	0.91	0.95	26
	Gian Khau	0.81	0.94	21
	Ninh Binh	0.88	0.93	17
Validation	Ben De	0.93	0.95	15
	Gian Khau	0.96	0.96	22
	Ninh Binh	0.96	0.95	21

Tab. 4. Comparison between simulated and measured flood marks

#	Coordinate		Year of 2008 Flood event			Year of 2017 Flood event		
	Longitude X	Latitude Y	Observed (m)	Simulated (m)	Error (m)	Observed (m)	Simulated (m)	Error (m)
1	106.076	20.103	1.1	1.09	0.01	1.05	1.09	-0.04
2	106.071	20.104	1.09	0.93	0.16	1.05	1.08	-0.03
3	106.085	20.084	1.1	1.06	0.04	1.04	1.08	-0.04
4	106.081	20.093	1.11	1.05	0.06	1.05	1.11	-0.06
5	106.089	20.083	1.09	1.05	0.04	1.04	1.04	0
6	106.086	20.091	1.09	1.05	0.04	1.05	1.1	-0.05
7	106.078	20.105	1.12	1.02	0.1	1.07	1.1	-0.03
8	106.079	20.084	1.1	1.06	0.04	1.05	1.04	0.01
9	106.090	20.063	1.1	1.08	0.02	1.05	1.1	-0.05
10	106.079	20.095	1.09	1.03	0.06	1.06	1.09	-0.03
11	106.081	20.101	1.11	1.1	0.01	1.05	1.09	-0.04

dike break scenario later. The large floods in the study area were used for this purpose. The first flooding occurred from October 29, 2008, to November 4, 2008, with the observed rainfall reach 327mm at Ninh Binh station. The water level on the Day river reached 332 cm at Ninh Binh station, causing severe inundation for the river basin. The second flooding occurred from October 3, 2017, to October 13, 2017 making the water level on the Day river reaching 394 cm (at Ninh Binh station). These events are considered as the historical flood events, resulting the severe inundation for the area. Nash-Sutcliffe (Nash J.E., 1970), flood peak error, and coefficient of determination (R2) are used to evaluation the model performance at three hydrological stations.

The comparison between simulated and measured water levels show a good agreement regarding phase and values (Figure 5–10). The Nash-Sutcliffe values range from 0.81 to 0.96 at all three stations during calibration and validation periods. The R2 values range from 0.93 to 0.95 for calibration and validation. The peak flood errors for all stations range from 25 to 26 cm (Table 3).

The study used flood mark data from the flooding events in November 2008 and October 2017 to evaluate the model's performance in flood-prone areas. The comparison of water levels at the flood marks indicates the discrepancy between the simulated and measured values ranging from 0.1 to 0.3 meters (Table 4). These findings suggest that the model well captures the flood extent in the inundated areas. Flood maps for the 2008 and 2017 flood events are presented in Figures 11 and 12, respectively.

The calibration and validation process of the 1-2D hydrodynamic model in MIKE FLOOD demonstrates a good flow simulation in rivers and over flood-prone areas. The Manning's roughness coefficients in the river range from 0.025 to 0.038 (m^{2}/^{3}/s), while the coefficients over the flooded areas range from 0.03 to 0.056 (m1/3/s). The calibrated and validated model will simulate scenarios involving levee breaches.

Inundation area for dike breach scenarios

The verified model will be used to simulate the dike break scenario. The parameters for the dike breach are determined in Table 2. The study does not consider the influence of rainfall within the study area in evaluating the impact of flooding caused by the dike break. Only the assumption of high water levels in the Hoang Long River leading to the dike break is considered. The simulated results of the dike break scenario using the MIKE FLOOD model are extracted and used to create flood maps using ArcGIS 10.3 software, as shown in Figure 13.

According to the simulation results of the dike break scenario, the flooded area is mainly concentrated in the Gia Vien district, with a commonly observed depth of 2–3 meters covering 3,413 hectares (19.5% of Gia Vien district's total area). The area with an inundation depth of 0.3 to 1.0 meters covers 1,719 hectares (9.8%), while the area with an inundation depth between 1 and 2 meters covers 2,234 hectares (approximately 12.75%) (Figure 13). This information will be crucial for the residents and the authorities to respond to dike break incidents.

4. Conclusions

The safety of dike systems plays a crucial role in protecting human lives and property against the threats posed by river floods. However, levee systems are prone to geological hazards and human-induced damage. Therefore, it is necessary to conduct investigations and surveys to identify vulnerable points in dike systems to implement appropriate response, repair, or improvement measures. In this regard, developing dike breach scenarios is one approach to enhance the capacity to cope with the consequences of dike break. This study conducted a survey to identify weak points in the Hoang Long River dike system in Ninh Binh province. Based on this information, the size, and potential breach locations were determined to simulate the dike breach scenario using the MIKE FLOOD model. The verified model represents well

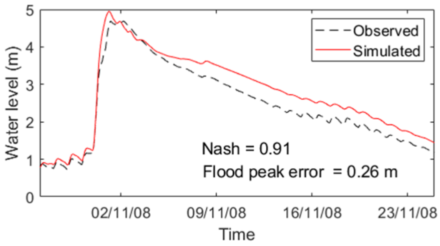

Fig. 5. Simulated and measured water levels at the Ben De station (October 2008 flood event)

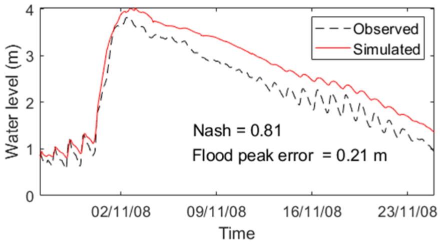

Fig. 6. Simulated and measured water levels at the Gian Khau station (October 2008 flood event)

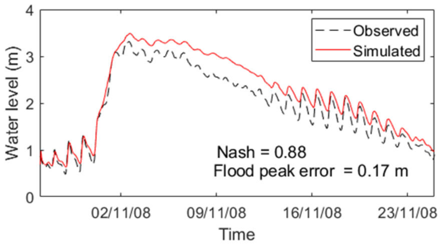

Fig. 7. Simulated and measured water levels at the Ninh Binh station (October 2008 flood event)

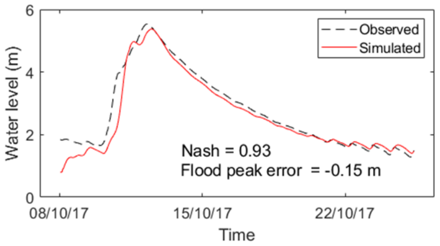

Fig. 8. Simulated and measured water levels at the Ben De station (October 2017 flood event)

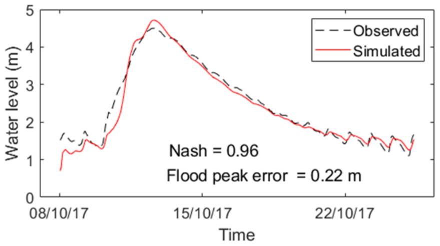

Fig. 9. Simulated and measured water levels at the Gian Khau station (October 2017 flood event)

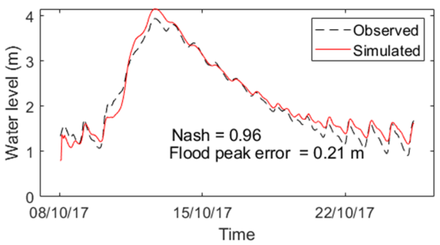

Fig. 10. Simulated and measured water levels at the Ninh Binh station (October 2017 flood event)

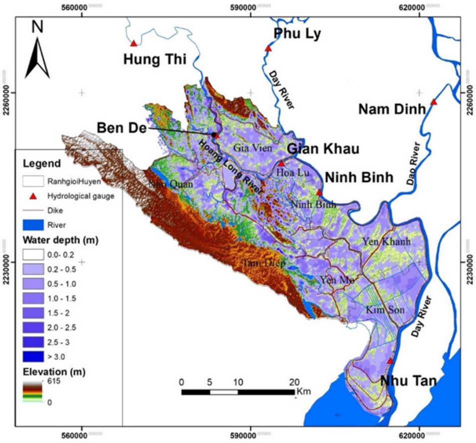

Fig. 11. Flood map of the year of 2008 flood event

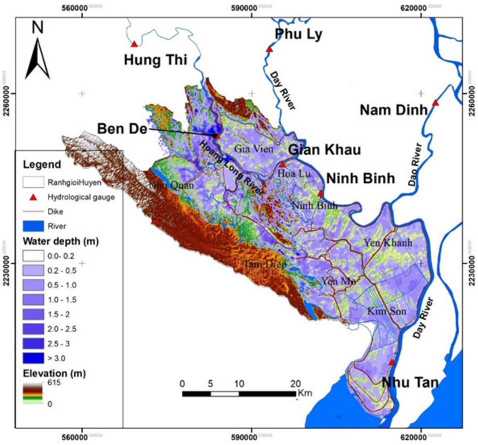

Fig. 12. Flood map of the year of 2017 flood event

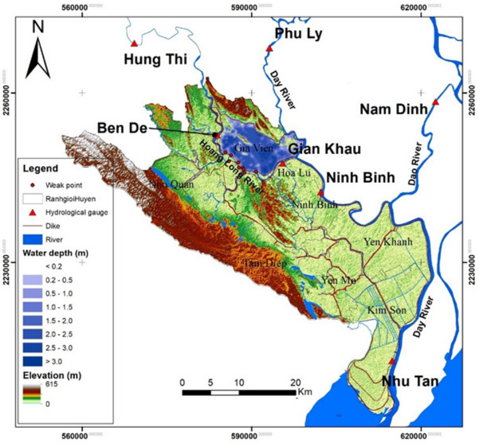

Fig. 13. Flood map according to the dike break scenario.

the historical flood events. The simulation results revealed a Hoang Long dike break's affected area and flood depth. This information will assist managers and residents in developing appropriate strategies to minimize human and property losses during a dike break incident. The results of this approach, overall, tend to be conservative in terms of estimating the fracture size of the dike breach and subsequently, the flood map. The study also demonstrated the potential use of the model for different scenarios or similar regions. Nevertheless, it should be noted that the geo-radar survey method has a depth limitation of 20–30 meters, indicating the need for additional approaches to estimate fracture parameters.

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