Digital Twin Monitoring of Real-Time Levee Operation

Physics-Based and Data-Enabled Digital Twin Modeling and Evaluation of Flood-Induced Levee Damage/Collapse

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Background

The Great Flood of 1993 was one of the most devastating in the US history, causing $12–16 billion in damages. The Mississippi River reached a record high of 49.58 feet at St. Louis on August 1, 1993. The most recent flooding event in Summer 2024 caused damage across multiple states. Large debris and flooding can cause damage to infrastructures, making travel impossible. Power and communication lines can also be taken out by flash floods. In addition, flooding can cause water contamination and impact water supplies. Due to the rapid climate change, the frequency of flooding is increasing nationwide. Hence, there is an urgent need for predicting and evaluating flood-induced levee damage and collapse, and their impact on flooding and water supplies.

This proposal aims at exploring the digital twin technology for mitigating natural disasters, with a focus on flood-induced levee damage and collapse. Federal agencies have realized the great potential of digital twins in transforming scientific research, industrial practices, and many aspects of daily life, as shown in the newly published report: Foundational Research Gaps and Future Directions for Digital Twins | The National Academies Press.

Challenges in modeling solid-fluid interactions

Fluid-solid interactions (FSI) play a key role in flood-induced levee damage and collapse. Several kinds of commercial software such as ANSYS Fluent and FLOW3D-HYDRO employ the finite element method or finite volume method, which have limited capability in simulating multi-phase (solid-liquid-gas) interactions involving failure evolution due to large deformations and non-objective interfacial treatments. We are developing the material point method (MPM) for objective evaluation of multi-phase interactions involving multi-physics and failure evolution (from continuum to fragmentation). However, there is still a lack of understanding about the size effect on failure evolution and fragmentation, as can be seen in the open literature.

Physics-based and data-enabled analyses

Synergizing physics-based and data-enabled approaches could take advantage of their respective strengths in identifying and quantifying the parameters governing the FSI. Since field experiments for mitigating human-made and/or natural disasters are time-intensive and cost-prohibitive, it is required that computational capabilities be developed to generate the required data set that can be utilized to produce simplified design tools. Funded by the federal agencies, we have developed a computer testbed for predicting and evaluating explosion-induced damage to important buildings under multi-phase interactions, as demonstrated in Fig. 1. With the digital testbed, the key system parameters could be identified in a physics-based and data-enabled hypersurface with artificial neural network (ANN) to predict and evaluate the effects of peak pressure, impulse, time of arrival and time of duration of blast loads on the buildings as protected by different types of barrier walls. The optimized sensor network could then be installed on selected control points to signal and mitigate the blast responses.

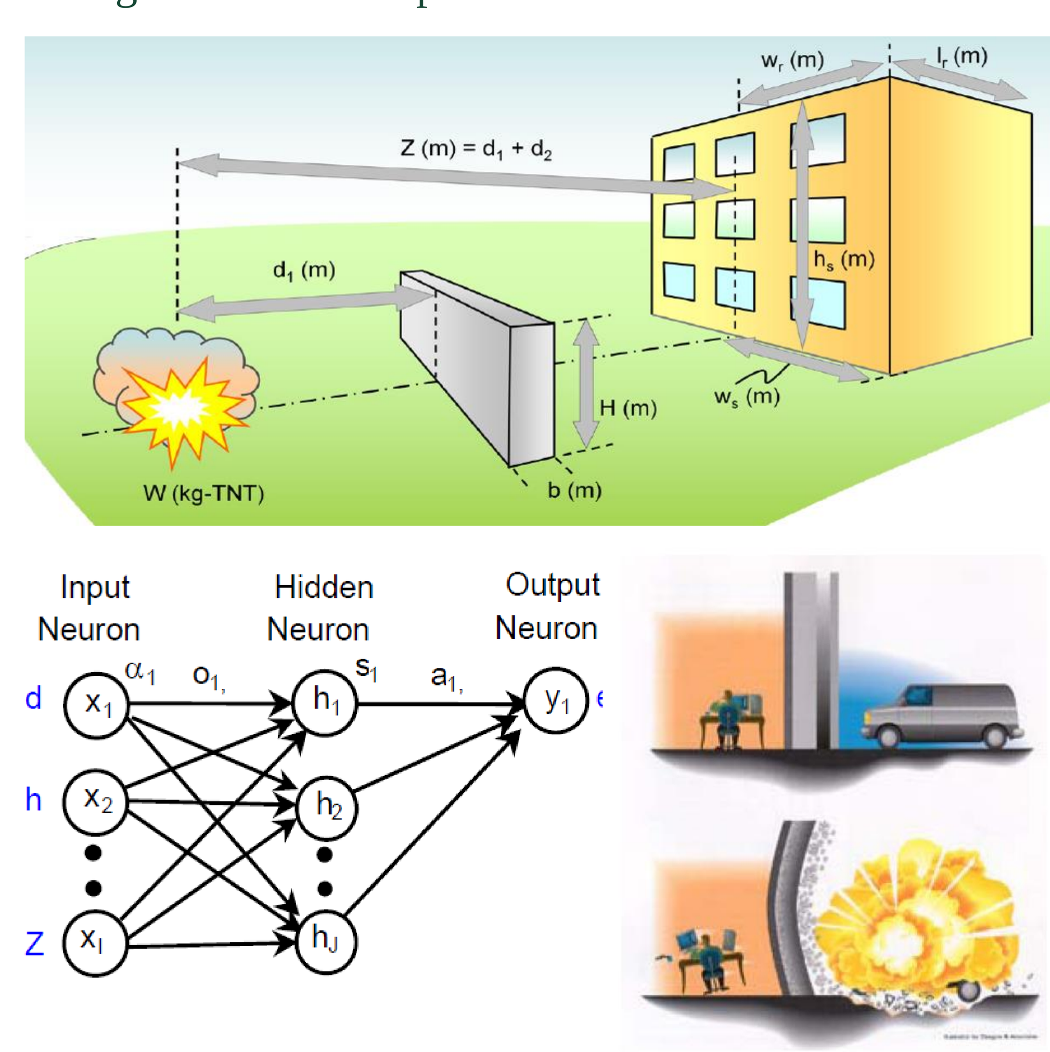

Figure 1. *(a) Using physics-based and data-enabled approaches for predicting and evaluating the performance of blast wall protection of important buildings [Bewick et al., 2011]; and (b) physics-based computer testbed for evaluating explosion-resistant structural designs at University of Missouri (MU) [Chen et al., 2020; Hu and Chen, 2006; Saffarini et al., 2024; among others].*

River modeling

The research team has established a digital river model thorough studies on hydrodynamics using traditional computational fluid dynamics (CFD) method in a selected reach of the Lower Missouri River (Fig. 2). The investigation is an 8-km section of the Lower Missouri River, supported by collaborative research as conducted by the USGS Columbia Environmental Research Center (CERC), providing rich experimental data for model validation.

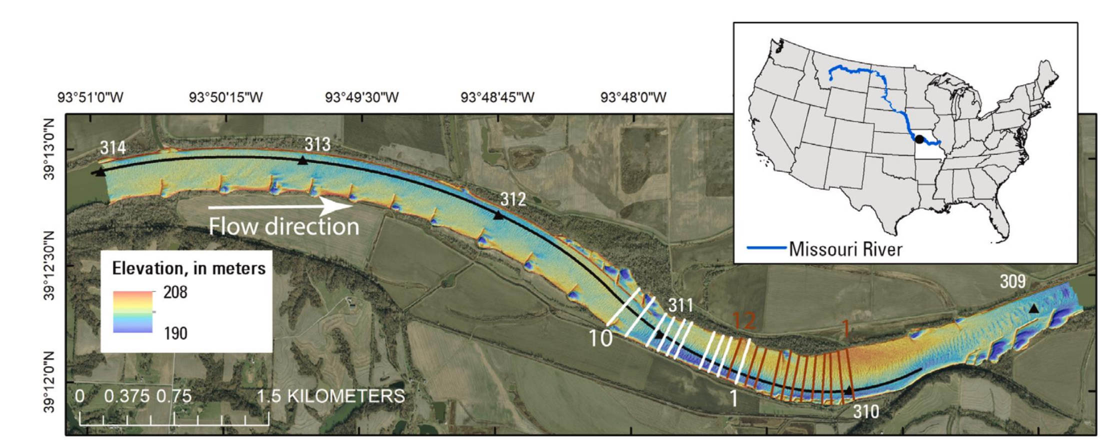

Figure 2*. The selected test site for this project. The colormap shows the bathymetry information. The solid black line is the water surface elevation measurements along the river. White and red lines across the river width are the velocity measurement transects. All data were measured by the USGS CERC. Black triangles show the river miles, which are measured from the confluence with the Mississippi River near St. Louis, Missouri. [Li et al., 2022, Li et al., 2023].*

Our model data show that the turbulence kinetic energy (TKE) vary substantially at 1 m and 5 m below the water surface in the selected study site (Fig. 3). The data points demonstrate different mechanisms of turbulence present in the flow, namely, strong effect of the dikes close to the surface, and strong effect of bedform close to the bottom. The strong dynamic process and the interaction with solid such as dike or levee are not well characterized in traditional CFD model.

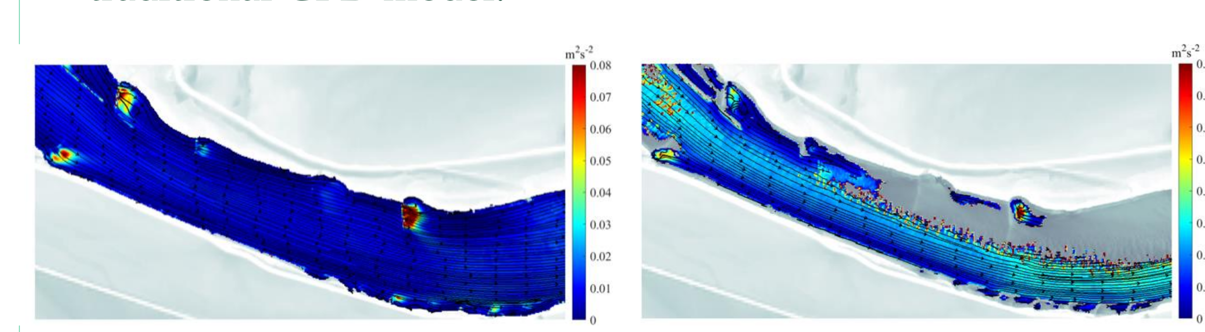

Figure 3. *Turbulence kinetic energy (TKE) at 1 m and 5 m below the water surface [Li et al., 2022].*

Proposed work

We propose a new study to establish physics-based and data-enabled digital systems to monitor and evaluate river flows and the levee safety under extreme weather conditions such as heavy raining and flooding, in combination with selected sensor networks. Addressing the current challenging issues in FSI, this interdisciplinary team effort will identify and quantify the key system parameters governing the real-time FSI (Fig. 4) under different flow velocities and with different geologic media.

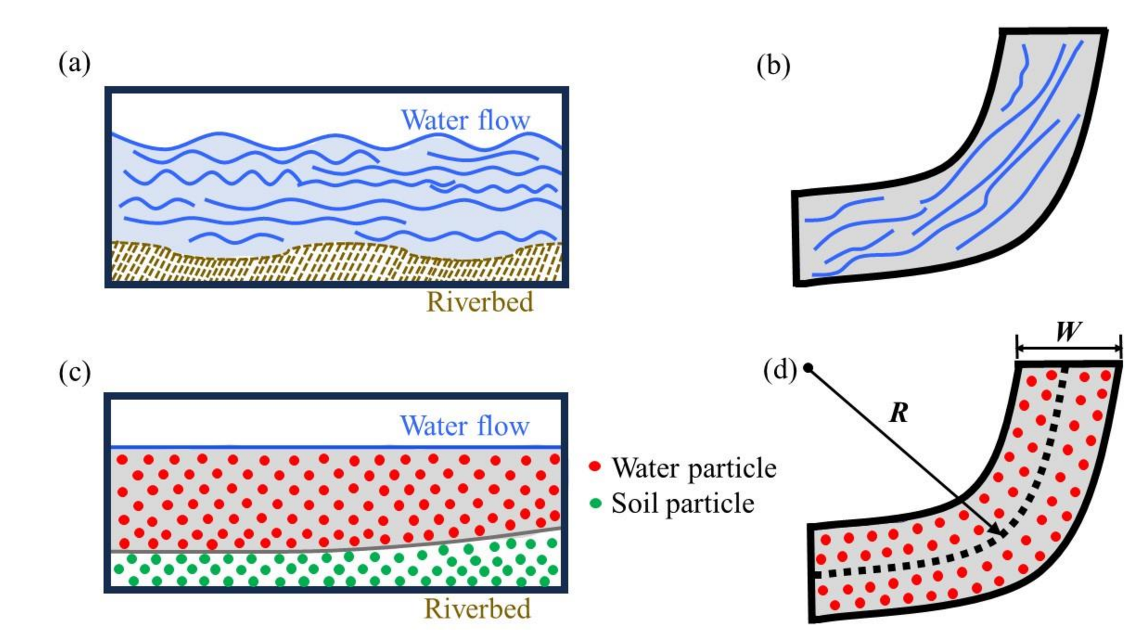

Figure 4*. Representative river segment corresponding to Figure 2: (a) front view of the segment, (b) top view of the segment, (c) front view of the MPM representation of FSI between water and soil particles, and (d) top view of the MPM model where the radius R of curvature and width W are two important system parameters to be considered in physics-based and data-enabled analyses.*

The proposed research topic is challenging because it covers computational mechanics, constitutive modeling, hydrology and hydraulics, and environmental engineering. The scientific driver for the proposed project is to explore the size effect on fragmentation in flood-induced damage and collapse such that physics-based objective solutions could be obtained for data-enabled analyses and digital twin modeling. Hence, an interdisciplinary team is formed for the project, consisting of Chen (computational engineering science), Wang (hydrology and hydraulics) and Deng (water and environmental engineering), with coordinated supervision of their research assistants.