High performance computing based distributed multi-layered city-scale transportation network tool

PEER Transportation Systems Research Program

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Background

Urban resilience under natural disasters relies on the cooperation of multiple critical infrastructure networks. However, it is not well understood how these complex networks impact and interact with each other during and after disasters (Figure 1). For cities to be prepared against disasters more effectively, an efficient tool is needed to take these cross-network interactions into consideration.

Figure 1. (a) Christchurch, 2011 (Eidinger & Tang, 2014); (b) Syke Creek bridge during Irma (John Campbell/USAC).

Methodology

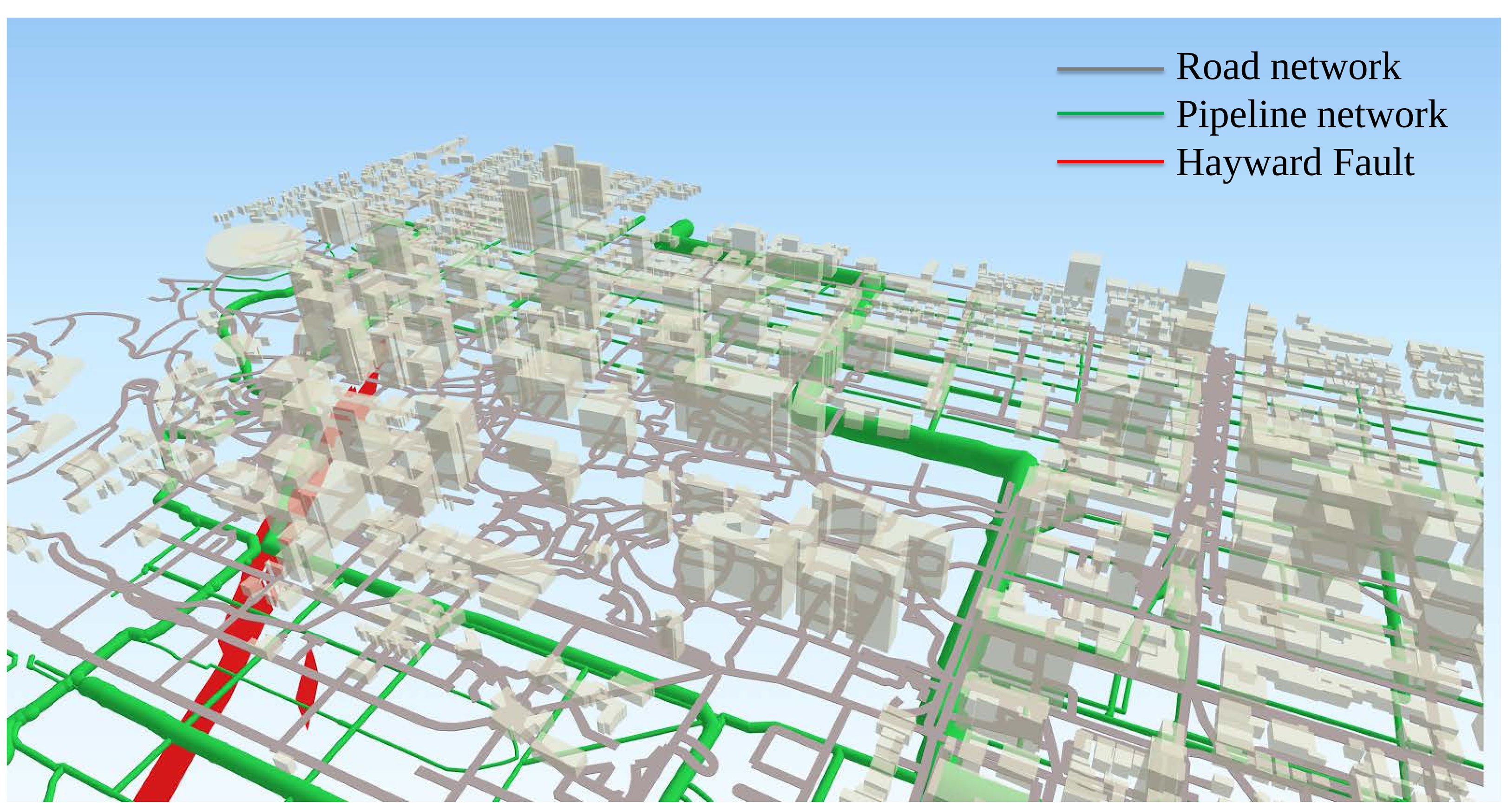

Figure 2. Road network, pipeline network and Hayward Fault at UC Berkeley (part of the study area).

Setting the case in the San Francisco Bay Area, this project aims at modeling the performances and interactions of its water pipeline network and the transportation network under earthquake hazards. The core parts are a *GPU-accelerated hydraulic model* and a *graph-parallel distributed Agent Based Model (ABM) for traffic flows* at city scale.

The study consists of three stages,

(1) water pipeline breakages due to ground motion and the subsequent local flooding;
(2) earthquake induced bridge failures and the changes in route availability and capacity;
(3) component failures and chain effects in a coupled multi-layered water pipeline and transportation system.

Core Modules

(a) Agent-based model for traffic simulation

Agent-based model (ABM) is a powerful tool for simulating complex traffic dynamics: traffic is created by hundreds of thousands of (or even more) agents traversing a road network. Agents can find the quickest route between origins and destinations (Figure 3) and possess “personalities” in time-cost preference.

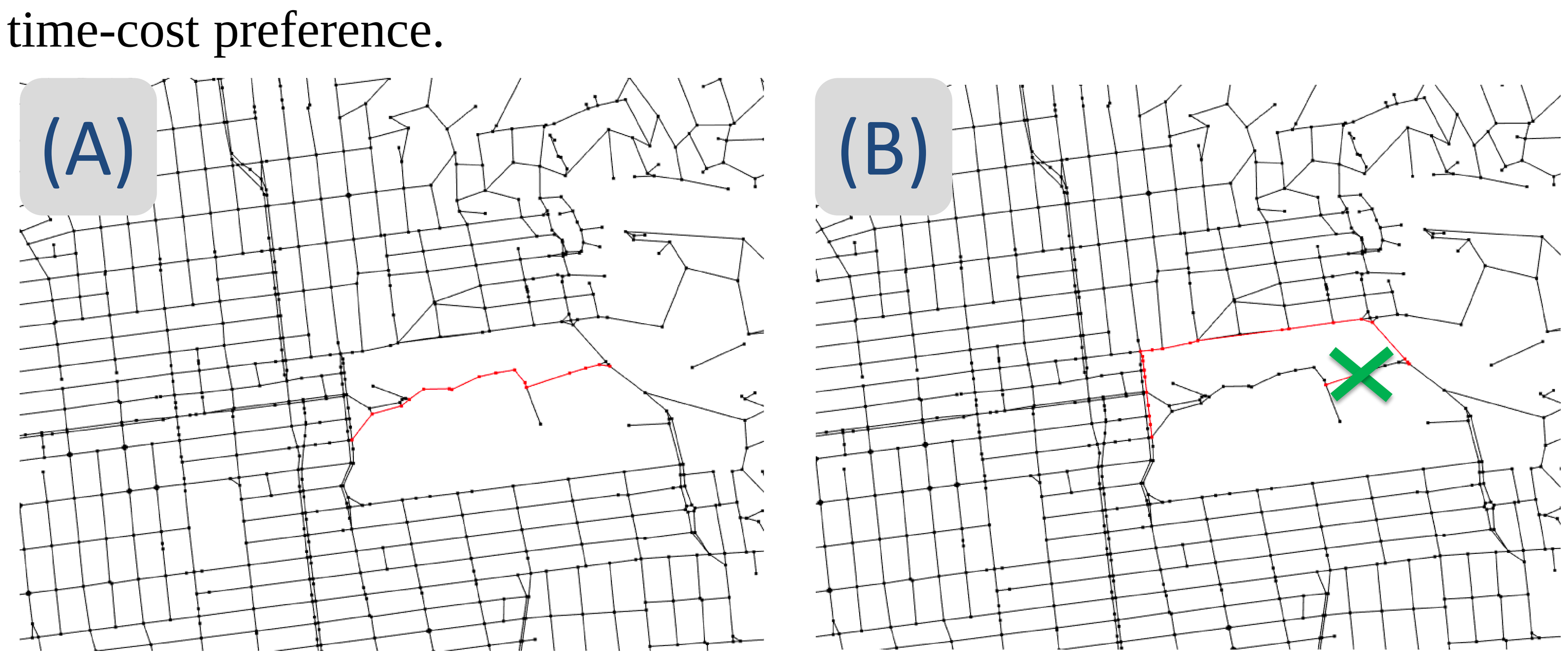

Figure 3. Traffic routes before (A) and after (B) road closure.

(b) Head loss simulation for pipeline network

Hydraulic simulations can obtain the flow rates in each pipe and the unknown heads at each node (Figure 4), usually by solving the equation system representing conservation of mass at nodes and conservation of energy at links [1]:

$$H_i - H_j = \Phi(Q_k)$$

$$\sum_{k=1}^{n_i} Q_{k_{i,j}} + q_i = 0$$

where H_i and H_j are water heads at two ends of pipe k; $\Phi(Q_k)$ is the head loss as a function of flow rate; $Q_{k_{i,j}}$ is the flow in pipe $k_{i,j}$ connected to node i; q_i is the known discharge at node i. Using an efficient GPU-accelerated *conjugate gradient* algorithm, a network consisting of 300,000 nodes can be solved in 5 seconds!

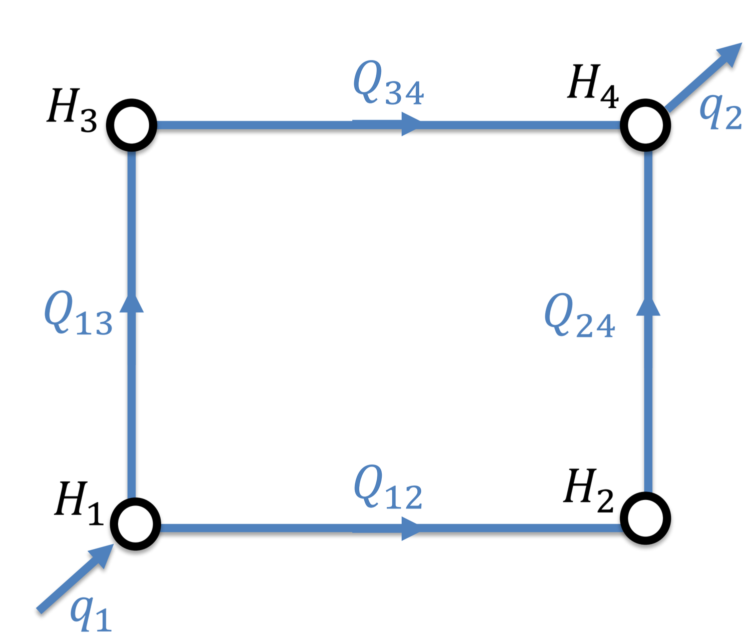

Figure 4. Pipeline network example.

Summary and Future Plan

So far, the transport network and the pipeline network for the study area have been collected. Conversions of these networks to model compatible formats are in progress. In the next steps, seismic related damage scenarios will be obtained from collaborators. Hydraulic simulations of the Bay Area pipe network under earthquake damages will be conducted, followed by traffic simulations under damaged bridges. The final stage will see the coupling of these two simulation models and the creation of a “layered” urban infrastructure system, based on which the performance and resilience of the system will be evaluated.

Acknowledgement

The Pacific Earthquake Engineering Research (PEER), East Bay Municipal Utility District (EBMUD), the Co-PIs Professor Joan Walker, Professor Alexandre Bayen, Professor Jack Baker and CE299 students Hanxiao Deng, Carlin Liao and Haoran Su.

References

[1] E. Todini and L. A. Rossman, “Unified framework for deriving simultaneous equation algorithms for water distribution networks,” *Journal of Hydraulic Engineering*, vol. 139, no. 5, pp. 511-526, 2012.

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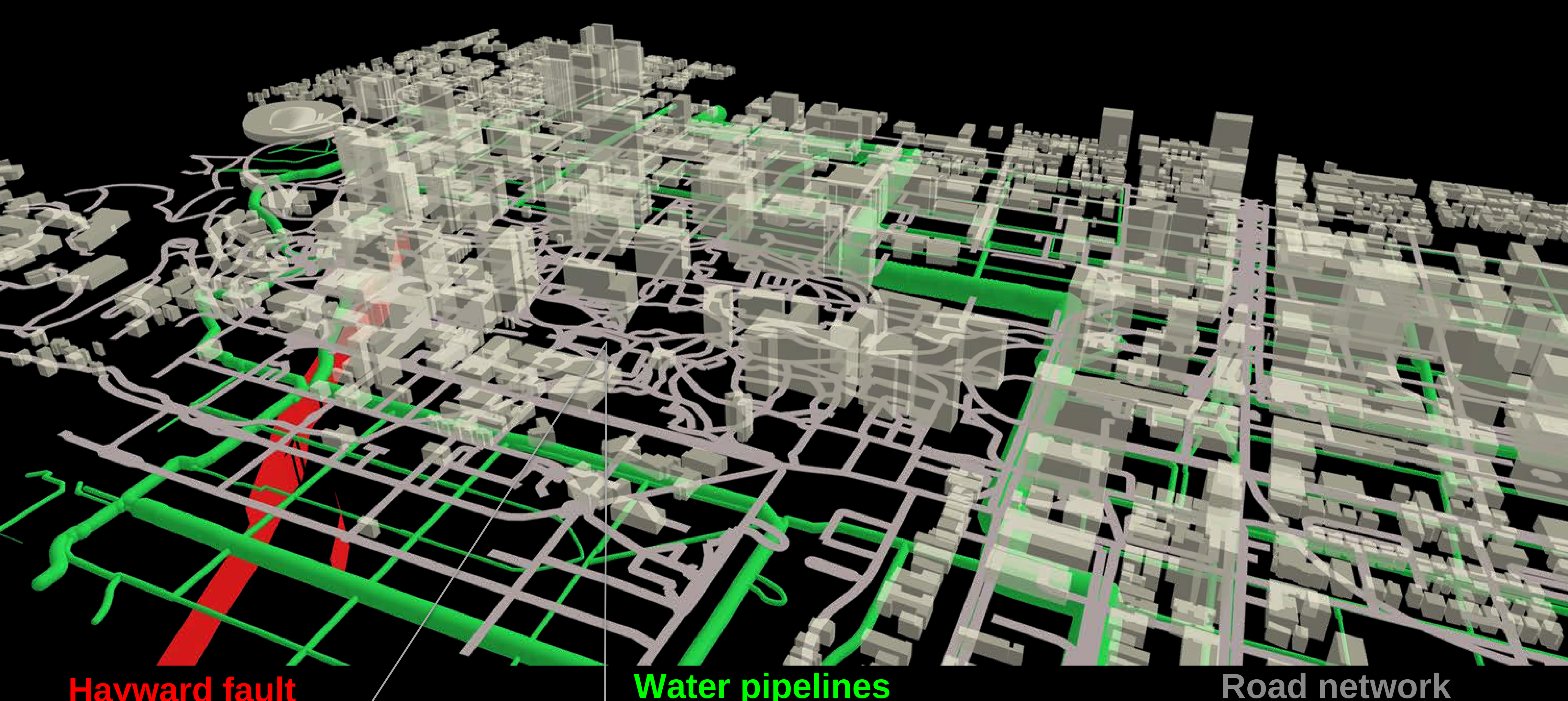
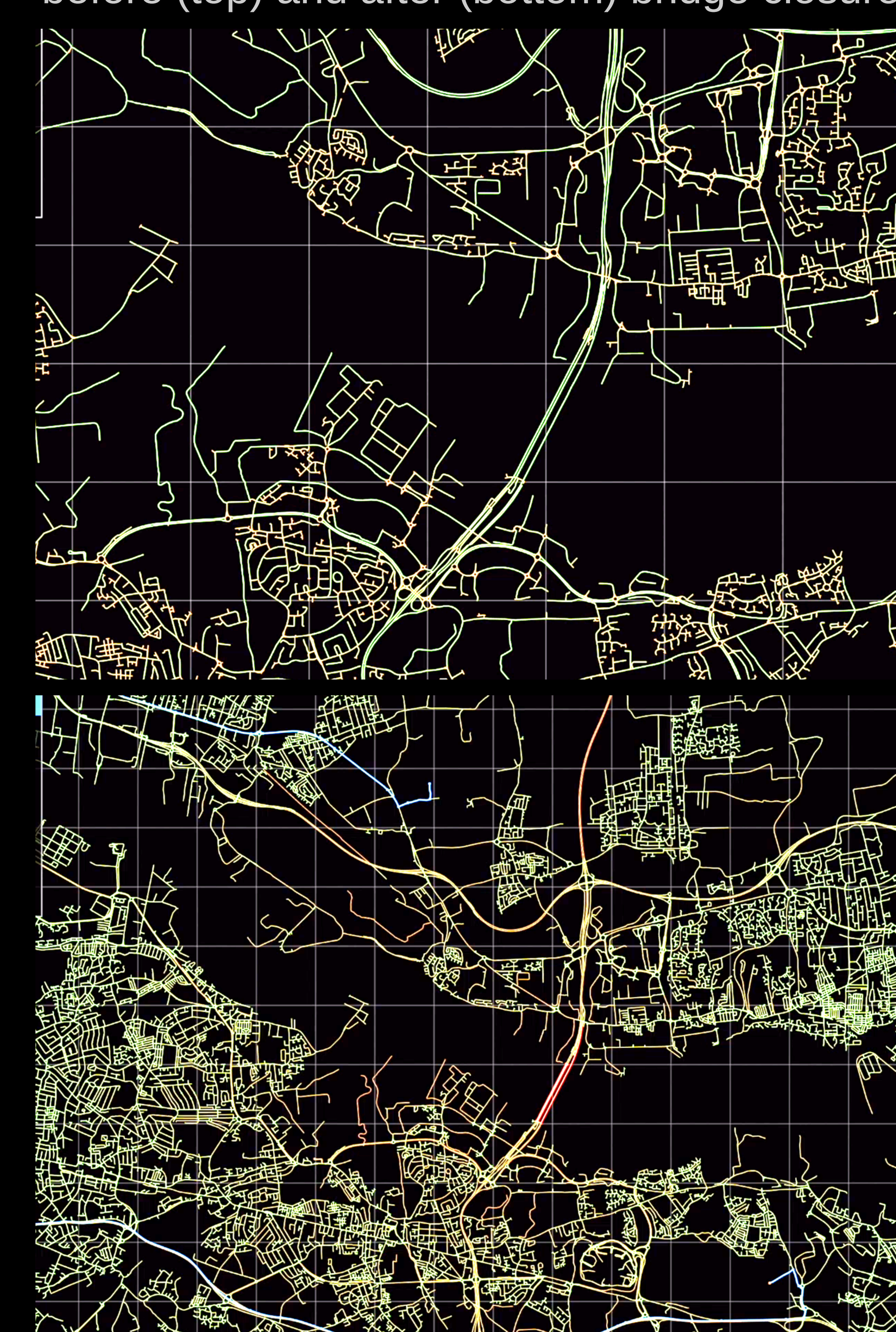
Introduction

Urban resilience under natural disasters relies on the cooperation of multiple critical infrastructure networks. However, it is not well understood how these complex networks impact and interact with each other during and after disasters. For cities to be prepared against disasters more effectively, we are proposing an efficient tool to take these cross-network interactions into consideration. The core parts are a *GPU-accelerated hydraulic model* and a *graph-parallel distributed Agent Based Model (ABM) for traffic flows* at city scale.

1. Setting the case in the **San Francisco Bay Area**, this project aims at modeling the performances and interactions of its water pipeline network and the transportation network under earthquake hazards. Here we illustrate the methodology on a 3D map of UC Berkeley in our study area.



Previous case study in London: traffic flow before (top) and after (bottom) bridge closure.



Water pipe breaks. L: Berkeley, 2018. R: Christchurch, 2011 (photo: Eidinger & Tang, 2014).

Traffic simulation: finding shortest path in a damaged network.

2. Hydraulic simulations are used to obtain flow rates/heads at each pipe/node, usually by solving the equation system representing conservations of mass and energy. For a complex network consisting of 300,000 nodes, it only takes **5 seconds** to solve one scenario using our proposed *Conjugate Gradient* algorithm!

3. *Agent-based model (ABM)* is a powerful tool for simulating complex traffic dynamics by having **hundreds of thousands of agents** (or even more) traversing a road network. Agents find the quickest route between origins and destinations and have individual "personalities" in time-cost preference.

Summary

So far, the transport network and the pipeline network for the study area have been collected. Conversions of these networks to model compatible formats are in progress. In the next steps, seismic related damage scenarios will be obtained from collaborators. Hydraulic simulations of the pipe network under earthquake scenarios will be conducted, followed by traffic simulations. The final stage will see the coupling of these two simulation models and the creation of a "layered" urban infrastructure system, based on which the performance and resilience of the system will be evaluated.

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