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. During Hurricane Irma, a structurally damaged bridge carrying a water main threatened the water supply to a whole community; while in the 2011 Christchurch earthquake, the break of a pipe beneath road pavement disrupted local traffic. An efficient tool is needed to take these cross-network interactions into consideration, so that cities can be prepared against disasters more effectively.

Methodology

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. Both models are designed to run on the High Performance Computers (HPC), enabling efficient real-time or probabilistic analyses, system interaction visualisations and fast disaster relief optimizations.

The study consists of three stages, with evolving focus from individual networks to an interdependent infrastructure system subjected to ground motion scenarios:

(1) water pipeline breakages due to ground motion or liquefaction and the impacts of the subsequent local flooding;

(2) earthquake induced bridge failures and the following 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. Unlike traditional traffic models that are interested in macroscopic descriptions of traffic (flow, speed and density), in ABM traffic is created by hundreds of thousands of (or even more) agents traversing a road network. Agents have similar functionalities in finding the quickest route between origins and destinations. But also, they possess "personalities" in time-cost preference [1]. Figure 1 shows an ABM simulation for London that successfully captures the change in traffic distributions after a hypothesized bridge closure.

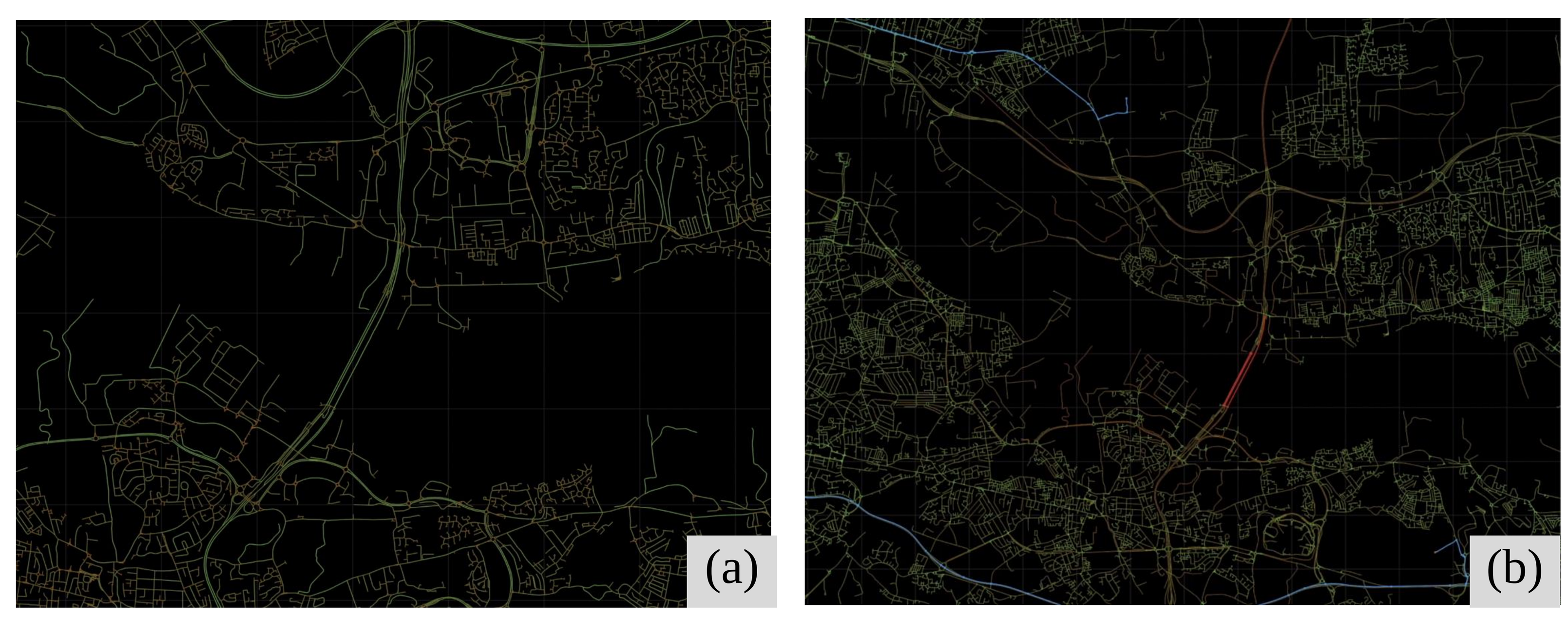

Figure 1. Simulated traffic distributions before (a) and after (b) bridge closure.

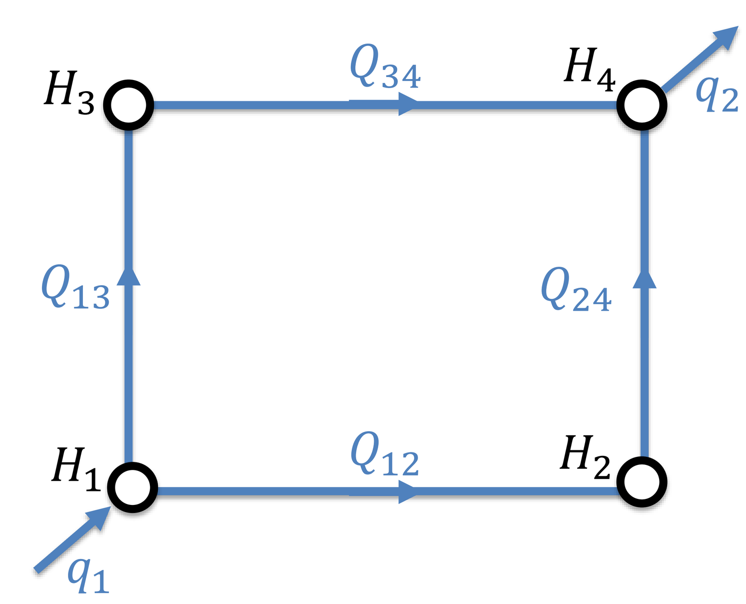

Figure 2. Pipeline network example.

(b) Head loss simulation for pipeline network

Hydraulic simulations aim at obtaining the flow rates in each pipe and the unknown heads at each nodes (e.g., Figure 2), usually by solving the basic equations representing conservation of mass at nodes and conservation of energy at links [2]:

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

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

where H_i and H_j are water heads at two ends of pipe k; $\Phi(Q_k)$ is the head loss due to friction 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.

In a water distribution network, the above equations are written for all nodes and pipes as a system of (nonlinear) equations. In this project, a previously developed highly efficient GPU-accelerated *conjugate gradient* algorithm will be applied to the hydraulic simulations. For a pipeline network that contains 300,000 nodes, it is estimated to take less than 5 seconds for solving one scenario, leading to thousands of pipe break scenarios to be finished in less than an hour!

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

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References

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[2] 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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