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Application of Adaptive Time-Stepping in the Resilience Analysis of Interdependent Infrastructure Systems Using an Iterative Optimization-based Simulation Framework

HAMED HAFEZNIA[1,2] and BOŽIDAR STOJADINOVIĆ [1,2]

[1] Institute of Structural Engineering, Department of Civil, Environmental and Geomatic Engineering, ETH Zürich, 8093 Zurich, Switzerland.

[2] Singapore-ETH Centre, Future Resilient Systems, CREATE campus, 1 CREATE Way, #06-01 CREATE Tower, Singapore 138602, Singapore.

E-mail: hamed.hafeznia@sec.ethz.ch

E-mail: stojadinovic@ibk.baug.ethz.ch

Civil Infrastructure Systems (CISs) play a crucial role in the socioeconomic development of communities. CISs are also known as critical infrastructure systems because of providing essential commodities and services. Due to complexity and interdependency, a disruption in the function of CISs may result in cascading failures and malfunction in the performance of other infrastructure systems, such as water and communication. Hence, the resilience of the CISs against natural hazards has taken stakeholders' attention. Improving the resilience of infrastructure systems can reduce the damages to the CISs and economic losses of urban communities. This research introduces an Iterative Optimization-based Simulation (IOS) framework to quantify the resilience of interdependent infrastructure systems to natural disasters. This IOS framework comprises five modules, namely, risk assessment, database, simulation, optimization, and controller.

The role of the risk assessment module is to simulate the hazard and assess its impacts on the functionality of infrastructure networks' components. After evaluating the components' vulnerability, the data regarding the post-disaster status of infrastructure networks is transferred to the database module. Next, this data is called by the simulation module to trace the evolution in the performance of infrastructure networks. The data generated by the simulation module is populated in the database. Then, the simulated data is applied to the optimization model to find the optimal flow of services within the networks. According to the optimal solution stored in the database, the simulation module changes the supply and demand patterns and the same time, models the recovery process and updates the functionality level of the components in the interdependent CISs. In the end, this module simulates the operation of the infrastructure networks to trace the performance evolution for the next step of the recovery. In the meantime, the controller module computes the resilience metric defined for this research. The procedure is iterated between the simulation, database, optimization, and controller modules until the stopping criterion is met.

Most research studies considering an optimization-based framework have applied Equal Time-Stepping (ETS) to the resilience assessment period (e.g., one day). This approach is applicable to small and deterministic case studies. The computational burden for the probabilistic resilience assessment of large-scale interdependent infrastructure networks is a serious challenge, especially in the case of using Equal Time-Stepping (ETS). Since the optimization module of the proposed IOS framework incorporates a Mixed-Integer Linear Programming (MILP) problem to find the optimal service distribution within the infrastructure networks, to reduce the

computational cost, this research proposes deploying an Adaptive Time-Stepping (ATS) approach. The ATS approach changes the size of steps during the resilience assessment period of interdependent CISs.

The interdependent infrastructure networks (power, natural gas, and water) located in Shelby County (TN), USA, are the case study of this research study. The seismic resilience of Shelby County's infrastructure networks was evaluated against the earthquake with a magnitude of 8.2 and an epicenter located at 35.3 N and 90.3 W by using Adaptive Time-Stepping (ATS) and Equal Time-Stepping (ETS) approaches. In the ATS approach, the length of the time steps varies between T, 2T, and 3T (T is equal to one day). Due to the complexity of the problem, the performance evolution of interdependent CISs is not predictable. Hence, the automatic determination of step size is not applicable to the IOS framework for resilience assessment. The interval for each time step size varies by case study since each case study has a particular behavior during the post-disaster recovery. For the case study of this research, the time step size is T for the interval starting from the first day and ending on the 45th day. The IOS framework is implemented with a 2T time step between the 46th and 75th days. After the 75th day, the time step size for the IOS framework is 3T.

The results show that applying ATS to the resilience assessment period reduced the computation time by 35.7 percent (from 133.7 seconds to 86 seconds) compared to the ETS approach in the case of using Gaussian distributed restoration functions. However, using the ATS approach resulted in a 1.6 % error in the computed resilience metric. Therefore, time efficiency improvement using ATS outweighs the computational error, especially for the probabilistic resilience assessment of interdependent CISs. Since the failed components with higher importance are often restored earlier, there are rapid changes in the interdependent CISs' performance evolution in the initial days after the hazard occurrence. As a conclusion, it is recommended that the resilience assessment of the interdependent CISs is carried out using ATS such that in the shortest time step for the initial days (e.g., the first 30-60 days) to closely follow the changes in the CISs' performance evolution. Then the time step size can gradually be lengthened so that the total error of the discretization remains low while increasing the computation speed.

Keywords: Resilience, Adaptive Time-Stepping, Iterative Optimization-based Simulation framework, Interdependent Infrastructure Networks.

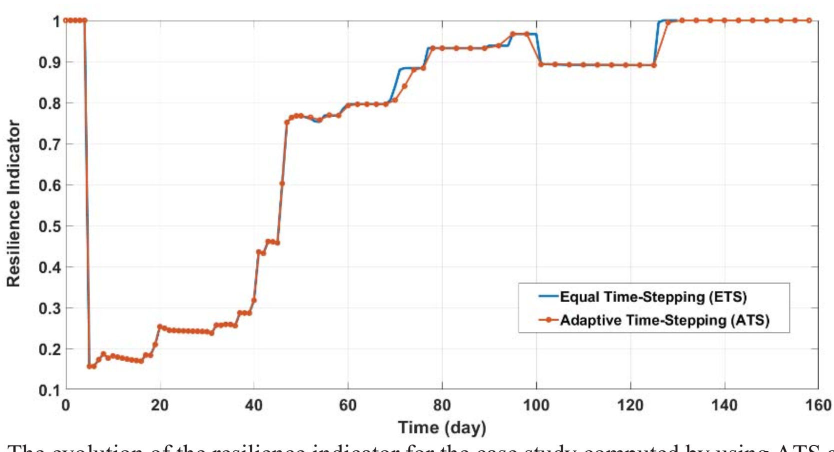

Fig. 1. The evolution of the resilience indicator for the case study computed by using ATS and ETS.