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Resilience-Based Smart Bridge Emergency Management System for Post-Disaster Inspection and Restoration of Highway Bridges

DEPARTMENT OF BUILDING & REAL ESTATE 建築及房地產學系

THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學

Title winning project

A Resilience-Based Smart Bridge Emergency Management System for Post-Disaster Inspection and Restoration of Highway Bridges

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Introduction

Devastating earthquakes are occurring frequently in recent years, inflicting significant casualties and economic losses. In such crisis, highway networks play a vital role in emergency relief, for example, transporting relief supplies and rescuers. Under seismic conditions, bridges are the most vulnerable components of a highway network (Shinozuka, Murachi, Dong, Zhou, & Orlikowski, 2003), and damage states of bridges markedly affect traffic capacities and vehicle passibility of highways. The risk of encountering damaged or impassable bridges during execution of relief operations can significantly affect response time, resulting in further suffering of the affected people.

In order to collect bridge damage information, decision making in determining reliable relief routes is germane. Conventionally, decision makers had to decide the routes for bridge inspection based on their personal experiences. Then, using this subjective decision, inspection teams depart from relief centres by vehicle along the selected routes and inspect bridges one after another until all bridges have been inspected. Although, this method is simple and feasible in inspecting few bridges, it could be inefficient and waste of time with regard to inspecting a great number of bridges on a large highway network.

This is because it is difficult for decision makers to differentiate functions of these bridges in supporting earthquake relief and to settle on scientific inspection routes (Yan, Fan, & Chen, 2016). Moreover, as initial inspection routes are usually generated based on imperfect information received shortly after an earthquake, the routes could be ineffective in the actual situations.
Therefore, **inspection routes should be revised in realtime with accurate and detailed information about disaster areas being gradually revealed and the environment in disaster areas changing frequently.**

After collecting bridge damage information, a rational highway bridge restoration sequencing (HBRS) plan can smooth relief activities and promote recovery of disaster areas. Currently, the most used objective for the optimization of HBRS is maximizing road network resilience during restoration phase. Although it is workable to quantify resilience by employing performance functions of infrastructure systems, assumptions of these functions may conflict with actual situations. First, it is irrational to assume that functionality increases monotonically during recovery phase. For instance, functionality of a highway network may decrease if some bridges are temporarily closed for repair. Furthermore, assuming that at least one accessible road to each city in the network, previous performance functions are unable to be applied to seriously damaged highway networks which contain isolated cities with all external roads being disrupted.

To solve the above-mentioned problems, this project aims at developing a resilience-based smart bridge emergency management system (BEMS) for the optimization of vehicle routing for highway bridge inspection (VR-HBI) and highway bridge restoration sequencing (HBRS).

The resilience-based smart BEMS has three features. First, this system considers both emergency response and recovery phases, and the outputs (actual bridge damage states) generated in response phases that are used as inputs in the recovery phase, enhancing the system's integrity and continuity in emergency management.

Second, this BEMS can adapt to the dynamic working environment: change of workers, resources, traffic patterns, and other conditions.

Third, this system can manage highway bridge inspection and restoration in real time: an initial solution is generated quickly with limited information collected after an earthquake; then with more and more accurate and comprehensive information received, this solution is constantly revised to suit the actual condition, ensuring that emergency response and recovery operations are always carried out efficiently.

This project can further be taken as a foundation of a comprehensive highway bridge emergency management system which consists of different operations in four emergency management phases (i.e. mitigation, preparedness, response, and recovery). Furthermore, the bridge inspection system can combine with other damage detection technologies to efficiently and quickly collect damage information of highway networks after earthquakes.

Objectives

The objectives of this research are clarified as below:

- To develop a novel methodology for measuring highway network resilience which is taken as the benchmark for optimization of HBRS.

  Specifically, a new recovery model that can precisely and practically describe the service performance of the highway network under bridge restoration actions is developed, and a performance indicator of the network is proposed to comprehensively quantify the functionality of the network regardless of if the network contains isolated cities.
- To establish an adaptive real-time bridge emergency management system that contains the optimization of (1) VR-HBI in emergency response phase aiming at giving inspection priority to seriously damaged bridges and important bridges, and (2) HBRS in emergency recovery phase with the aim of maximizing the network resilience.

  Particularly, this system is able to quickly generate optimum solutions and expediently revise existing solutions according to the diverse information received and collected in continuously changing working environment.
- To develop a Discrete Symbiotic Organism Search (DSOS) algorithm to solve the proposed VR-HBI and HBRS problems.

  Especially, this algorithm should be efficient for solving large-scale problems and be convenient for frequent modifications.

Methodology

The framework of the project is shown in Figure 1. First, **this project proposes a Comprehensive model for qualitative description and quantitative calculation of resilience**. The model can practically and precisely describe the fluctuating functionality of a highway network during the recovery phase after an earthquake. Based on the resilience model, the real-time post-earthquake highway bridge emergency management system is developed. This system consists of two subsystems: the real-time decision making system for bridge inspection and bridge restoration, respectively.

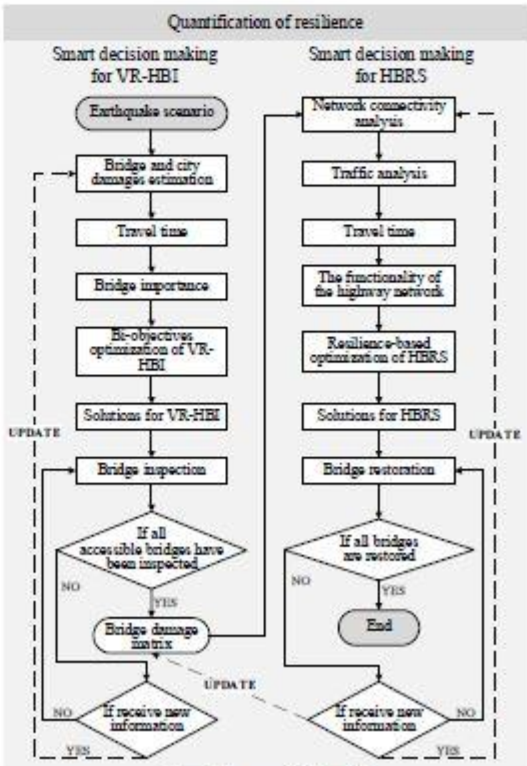

Figure 1 Framework of the project

The first subsystem starts from an earthquake scenario, after which the damages of bridges and cities in a highway network are quickly estimated. Then, the travel time of each road segment is estimated based on the road damage index calculated from the damage indexes of bridges along the road.

Next, a bridge importance index is developed to evaluate the importance of a bridge in relief activities. Aiming at giving priority of inspection to bridges of high probability being in severe damage states and of high importance, a bi-objective DSOS algorithm is developed to generate a set of optimal solutions for VR-HBI. After that decision makers can select one solution based on their preference and instruct workers to inspect bridges according to the selected solution. During the inspection process, if the relief centre receives new information about the affected area, bridge and city damages will be updated as well as other input information, and the solution for VR-HBI will be revised to adapt to the actual situation and changed environment. Finally, if all accessible bridges have been inspected, the real bridge damage matrix (BDM) is generated by gathering all the bridge damage states.

Based on the real BDM, the network connectivity is analysed to check if any cities separate from the network. Then, based on the traffic attributes (including traffic capacity, traffic speed, and length) of each road segment and traffic flows between cities, the traffic analysis is performed to calculate the travel time between cities during emergency recovery phase. Furthermore, the functionality of the highway network can be established, and the DSOS algorithm is used to generate the optimal solution for the HBRS with the objective of maximizing the resilience of the highway network with the constraint condition of recovering the connectivity of isolated cities in shortest time.

After that, bridges are repaired in accordance with the optimal solution. During the restoration process, if relief centre receives new information about the restoration work, the real BDM, the traffic pattern, as well as the functionality of the network will be updated to revise the optimal solution for restoration sequencing of unrepaired bridges. The revision process will repeat until all bridges are restored.

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