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DOCTORAL THESIS

Vulnerability of Transportation Networks to Cascading Failure

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TOKYO INSTITUTE OF TECHNOLOGY

Abstract

School of Environment and Society
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Doctor of Engineering

Vulnerability of Transportation Networks to Cascading Failure

by Kashin SUGISHITA

This dissertation, titled *Vulnerability of Transportation Networks to Cascading Failure*, consists of the following six chapters.

Chapter 1 describes the introduction. Complex networked systems sometimes collapse caused by localized errors. Such a phenomenon is called *cascading failure* and it has been studied in complex networks. Most existing studies have discussed blackouts or communication disturbances and there are some successes in engineering applications such as expressing patterns of failure propagation in the Italian blackout in 2003. **?** shows the natures of the systems where cascading failure occur and takes power grids or communication systems as examples. However, not only these systems but also transportation systems should satisfy these natures. Nevertheless, there has been little mentions about transportation systems so far. This situation seems strange, because complex networks should be a study of any complex networked systems in the real world. Two fields have network vulnerability as a research topic in common. Therefore it is expected that both academic fields will develop further by interdisciplinary fusion of concepts in different fields. In order to achieve this great objective, this dissertation aims to objectively and comprehensively clarify the overall picture of the studies on network vulnerability in the two fields, to investigate cascading failure and propose risk management, and to discuss the possibility of interdisciplinary integration of concepts and the future directions.

Chapter 2 proposes a framework for analyzing a citation network with some community structures and applies to the vulnerability studies in the fields of transportation and complex networks. We objectively and comprehensively clarify the overall picture of the studies on network vulnerability in the two fields. First of all, the publication records are obtained from the online academic database *Web of Science*. Then a citation network where nodes and directed links represent the publications and the citation relations respectively is constructed. Next, the giant weakly connected component (GWCC) is extracted and analyzed. As the first step of the analysis of GWCC, the community structure is revealed by applying the Louvain algorithm. Then, the major research development in each community is clarified by applying the main path analysis and papers are reviewed. Finally, the citation patterns among different communities are visualized with a Sankey diagram. We qu-

antitatively reveal the asymmetric citation patterns between the two fields. We also show that there is little citation relationships between communities of cascading failure and transport network vulnerability.

Chapter 3 investigates cascading failure in complex networks. We show the attack tolerance of homo/heterogeneous networks and propose a novel risk management to protect networked systems from cascading failure. The proposed method utilizes an index called collective-influence which has been applicable for identifying influencers or prevention of epidemic diffusion in social networks. Differently from previous studies, we identify *non-influencers* and intentionally remove them right after initial failure to prevent propagation of failures. Comparing the existing strategy proposed by **?**, we show that the proposed strategy can mitigate damage more effectively, especially for heterogeneous networks, with much less computational cost.

Chapter 4 investigates cascading failure in transportation networks. We show gridlock as cascading failure in transportation networks and propose a risk management of intentionally removing links (link closures), which is inspired by the risk management in Chapter 3. Gridlock, a state of zero throughput, corresponds to the eventual state in the process of cascading failure. Namely, when a limited event eventually brings about gridlock, the entire process can be captured as cascading failure. We analyze the influences of route choice behavior, which is considered important in traffic control, on the propagation of failures. The obtained results imply that the slight difference of the network topology has big influences and it sometimes helps to avoid gridlock naturally but it can also accelerate cascading failure and gridlock state can be achieved much faster. Furthermore, we show that the route choice behavior strongly influences the effect of the risk management.

Chapter 5, based on the results obtained in the previous chapters, discusses the interdisciplinary fusion of concepts qualitatively and also discusses the future direction. First of all, with regard to chapter 2, we show that static analysis methods in complex networks have been mainly applied to transportation networks. Also we show that edge betweenness centrality in complex networks has been extended in considering with the dynamic aspects of public transportation networks. Next, based on the results obtained in chapters 3 and 4, it is pointed out that the vulnerability of heterogeneous networks, which are mainly focused on in complex networks, can be strongly dominated by the network topology. This implies that the natures of such heterogeneous networked systems are less likely to be lost even if the model of network flow is simplified. The vulnerability of highly homogeneous networks like road networks has not been studied in complex networks, so it is expected that concept application from transportation field to complex networks can contribute in this respect. Finally, we describe the universality that cascade size distribution of various cascading events follow power-law with similar avalanche exponents and we mention the possibility that such universality governs transportation systems as well.

Chapter 6 concludes this dissertation describing the achievements and related future tasks.