Holistic Assessment of Critical Infrastructure Resilience during Disasters (HACIRD)

- A case study of the 2023 Kahramanmaraş earthquakes

Erik Kimblad

Division of Risk Management and Societal Safety

LTH | Lund university

Holistic Assessment of Critical Infrastructure Resilience during Disasters (HACIRD):

A Case Study of the 2023 Kahramanmaraş Earthquakes

Erik Kimblad

Lund 2024

Resilience Assessment of Critical Infrastructures during Disasters:
A Case Study of the 2023 Kahramanmaraş Earthquakes

Erik Kimblad

Number of pages: 84
Illustrations: 25

Keywords
Critical infrastructure, Lifeline, Resilience, Interdependencies, Earthquake, Natural hazards, Turkey, Holistic, Disaster, Framework, Assessment, Empirical, Case study

Abstract
On February 6, 2023, two earthquakes (7.8MW and 7.7MW) struck Turkey within nine hours, resulting in over 50,000 fatalities and significant damage to critical infrastructures (CI) which provide services essential for the functioning of society. This thesis aims to holistically assess the impact this earthquake had on critical infrastructures for providing vital societal services through the development and application of a generic resilience framework. The framework for holistic assessment of critical infrastructures during disasters (HACIRD) combines methods from past assessments, to assess quantitative and qualitative aspects of resilience for CIs both individually and holistically, which was lacking in the literature. The framework was then applied to the 2023 earthquakes, which revealed needs for: 1) Managing dependencies on electricity, 2) Managing dependencies on telecommunication, 3) Overall greater consideration of resilience in industries, 4) Addressing bottlenecks in railway system, 5) Better managing interdependencies through cross-sectoral forums. The framework application encountered challenges. Data quality was low due to biases and only limited direct contact with CI representatives. The assessment itself encountered challenges regarding complex interactions, subjectivity, and comparability. Despite challenges, the framework, in its current state, revealed to be very useful and applicable for attaining a holistic critical infrastructure interdependency assessment of the 2023 Turkish earthquake, providing many valuable insights for improved critical infrastructure and disaster risk management. To further validate and enhance the framework and its application, it can be applied in more cases, a more standardized methodology developed and operator incentives for assessments and cross-sectoral collaborations examined.

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

http://www.risk.lth.se

Telefon: 046 - 222 73 60

Division of Risk Management and Societal Safety
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.risk.lth.se

Telephone: +46 46 222 73 60

Abstract

On February 6, 2023, two earthquakes (7.8MW and 7.7MW) struck Turkey within nine hours, resulting in over 50,000 fatalities and significant damage to critical infrastructures (CI) which provide services essential for the functioning of society. This thesis aims to holistically assess the impact this earthquake had on critical infrastructures for providing vital societal services through the development and application of a generic resilience framework. The framework for holistic assessment of critical infrastructures during disasters (HACIRD) combines methods from past assessments, to assess quantitative and qualitative aspects of resilience for CIs both individually and holistically, which was lacking in the literature. The framework was then applied to the 2023 earthquakes, which revealed needs for: 1) Managing dependencies on electricity, 2) Managing dependencies on telecommunication, 3) Overall greater consideration of resilience in industries, 4) Addressing bottlenecks in railway system, 5) Better managing interdependencies through cross-sectoral forums. The framework application encountered challenges. Data quality was low due to biases and only limited direct contact with CI representatives. The assessment itself encountered challenges regarding complex interactions, subjectivity, and comparability. Despite challenges, the framework, in its current state, revealed to be very useful and applicable for attaining a holistic critical infrastructure interdependency assessment of the 2023 Turkish earthquake, providing many valuable insights for improved critical infrastructure and disaster risk management. To further validate and enhance the framework and its application, it can be applied in more cases, a more standardized methodology developed and operator incentives for assessments and cross-sectoral collaborations examined.

Preface

I started this project with the goal of providing an in-depth analysis of the impact the 2023 Kahramanmaraş earthquakes had on critical infrastructures, and the resilience and interdependencies which could be observed for the infrastructures. I had originally planned to conduct an on-site visit to one of the affected areas, where I would conduct interviews with local infrastructure managers or operators. I even received funding for the site visit in the form of a student travel grant from Brandforsk. However, it became clear early on that our contact network in the affected area was not as strong as I had hoped, which resulted in me having to do the contact seeking myself from Sweden, with little success in engaging interest from stakeholders. Nonetheless, the amount of information and data that could be obtained through the internet was greater than I expected. This was especially true after using Google Translate extensively to translate queries into Turkish and translate the results back to English. The project became a journey of navigating through a labyrinth of institutional and operator websites for reports and databases. Ultimately, I was able to obtain better data than I had originally thought, and was able to apply my suggested framework for assessment.

I would like to express my sincere gratitude to Jonas Johansson, associate professor at the Division of Risk Management and Societal Safety at Lund University, for his excellent supervision of my thesis. His insights and ideas during our meetings helped me to stay on track and improve my thesis in many ways. I would also like to thank Serdar Selamet, associate professor at Bogazici University in Istanbul, for his help and guidance in obtaining relevant literature and offer to bridge in the contact seeking for interviews. I would also like to thank Margaret McNamee, professor at the Division of Fire Safety Engineering at Lund University. Our initial discussions sparked the idea of writing about the 2023 earthquakes, and she was the one who initiated the contact with Serdar. I am also grateful to Brandforsk for providing me with travel funding, even though I never had a chance to use it. Lastly, I would like to thank my daughter Livia, whose arrival provided me with breaks of joy and sense of purposefulness during this otherwise difficult and sometimes frustrating thesis writing process. I would also like to thank my girlfriend Imelda for being a supporting and loving partner and co-parent.

List of Abbreviations

AFAD	The Disaster and Emergency Management Presidency *(Afet ve Acil Durum Yönetimi Başkanlığı)*
CI	Critical infrastructure
EÜAŞ	The Electricity Generation Company (*Elektrik Üretim A.Ş)*
KGM	The General Directorate of Highways *(Karayolları Genel Müdürlüğü)*
NATO	North Atlantic Treaty Organization
OECD	Organisation for Economic Co-operation and Development
HACIRD	Holistic Assessment of Critical Infrastructure Resilience during Disasters
TCDD	The State Railways of the Republic of Turkey *(Türkiye Cumhuriyeti Devlet Demiryolları)*
TEİAŞ	Turkish Electricity Transmission Corporation *(Türkiye Elektrik İletim A. Ş)*

Table of Contents

1. Introduction ... 1
1.1. Background ... 1
1.2. Aim and purpose ... 2
1.3. Research Questions ... 2
1.4. Delimitations and limitations ... 2
2. Theoretical background ... 5
2.1. Critical infrastructure ... 5
2.2. Resilience ... 7
2.3. Interdependencies and cascading effects ... 9
2.4. Policies and Directives ... 11
3. Literature review ... 15
3.1. Methodology ... 15
3.2. Key findings ... 18
4. HACIRD Framework ... 23
4.1. Individual CI Resilience Assessment ... 26
4.2. Interdependency assessment ... 29
4.3. Holistic resilience assessment ... 32
5. Case Study Methodology ... 35
5.1. Data Collection ... 36
5.2. Data Processing ... 36
6. Case Study Assessment ... 39
6.1. Electricity ... 42
6.2. Highway Transportation ... 46
6.3. Railway transportation ... 48
6.4. Port infrastructure ... 50

6.5. Water supply 52
6.6. Industry.. 54
6.7. Telecommunications 57
6.8. Interdependency assessment 60
6.9. Holistic Resilience assessment.. 63
6.10. Case Study reflections... 66
7. Discussion 71
7.1. Framework Opportunities 71
7.2. Data collection issues 75
7.3. Data analysis issues... 77
7.4. Framework application recommendations 79
7.5. Future research and development.. 80
8. Conclusion... 83
9. References 85
9.1. Literature Review 85
9.2. Other Literature 88
9.3. Case study data... 92
Appendix A - Energy 99
Appendix B - Transportation.. 111
Appendix C - Water 125
Appendix D - Industry.. 129
Appendix E - Telecommunication 133
Appendix F - Interdependency.. 139

1. Introduction

1.1. Background

Critical infrastructures (CI) provide services essential for the functioning of society. Disruptions to these services can lead to severe consequences for both the economy and the health and safety of the population. On 6 February 2023, two powerful earthquakes, measuring 7.8 Mw and 7.7 Mw, struck southern Turkey and northern Syria, causing extensive damage to buildings and other infrastructure. This earthquake event, also known as the 2023 Kahramanmaraş earthquakes, stands as Turkeys most costly in decades, resulting in the loss of over 50,000 lives and an estimated $34.2 billion in direct physical damages (The World Bank, 2023).

The earthquakes also significantly impacted CIs, including electricity, drinking water and transportation, with some areas completely cut off from these services, causing additional severe consequences. As of the summer of 2023, there were numerous reports published addressing the physical damages on CIs caused by the earthquakes (Çetin et al., 2023; EERI & GEER, 2023; İTÜ, 2023; Sagbas et al., 2023). However, there was an apparent lack of official reports and academic literature discussing the observed resilience of both individual systems and the overall CI system-of-systems. This lack of comprehensive assessment is not unique to the 2023 Kahramanmaraş earthquakes, as generally there is a scarcity of post-disasters system-of-systems resilience assessments. Previous post-disaster assessments have either focused on the performance of singular CIs, as in studies such as Aghababaei et al. (2021), or on specific CI system factors such as interdependencies, as explored by McDaniels et al. (2007b). To truly understand the societal impacts of disasters, conducting holistic assessments of CI resilience offers a better understanding how the CI system-of-systems were affected. Additionally, it could offer several opportunities, including:

- Providing a clearer basis for proactive decision-making.
- Enhance CI operator and civil defense preparedness.
- Effective emergency relief planning.
- Improved post-disaster sense making.
- Improved understanding of disasters and interdependencies.

1.2. Aim and purpose

This thesis aims to develop a framework for assessing critical infrastructure resilience and interdependencies after a disaster. To demonstrate its practicality, the framework is applied to a real-world case: the 2023 Kahramanmaraş earthquakes in Turkey. The framework aims to be generalizable for assessing the effect various natural hazards, such as earthquakes, have on CIs, and to address aspects such as resilience and interdependencies at both the level of individual CIs and the broader CI system-of-systems level. To accomplish this, the thesis collects and analyzes data from Turkish reports, articles, hearings and databases to provide both quantitative and qualitative descriptions of the resilience of seven CIs and the overall system they constitute during the 2023 Kahramanmaraş earthquakes. Furthermore, by applying this framework to a real-world case, the thesis also hopes to gain valuable insights into the challenges and opportunities that can arise when conducting post-disaster assessments.

1.3. Research Questions

The result of the thesis aims to address the following four research questions:

- Q1. What are important aspects to include in the development of a comprehensive framework to empirically assess the resilience of critical infrastructures during a disaster, both at an individual and a holistic system-of-systems level?
- Q2. By applying such a framework, how did the critical infrastructures in Turkey demonstrate resilience and interdependencies during the 2023 Kahramanmaraş earthquakes?
- Q3. What insight can be gained from the practical application of a framework in a real-life case study, particularly in terms of challenges encountered?
- Q4. What are the potential opportunities of empirical assessments for enhancing resilience in critical infrastructure?

1.4. Delimitations and limitations

Due to time and scope constraints of the thesis and limited data availability, the assessment will focus exclusively on the earthquakes impact on Turkish critical infrastructure. The transparency of data regarding critical infrastructure is notably lower in Syria, and the earthquake affected region in Syria is deeply involved in the ongoing Syrian civil war, resulting in limited access to reconnaissance teams to conduct damage assessments. Additionally, the earthquakes impact was more widespread in Turkey, which could justify its focus in the assessment. Nevertheless, due to the political and economical differences between the two countries it would have been an interesting comparison of the two countries if data were available.

The assessments also did not include all CI:s but focused specifically on technical infrastructures. This was mainly due to data availability and time availability for the scope of the thesis. It was also partly due to that it is less clear how to include resilience measurements for non-technical infrastructures, such as health care and law enforcement, together with measurements for resilience of technical CIs into a system-of-systems assessment of resilience.

2. Theoretical background

2.1. Critical infrastructure

Before delving deeper into the concept of critical infrastructure resilience, it is essential to establish a clear definition of infrastructure itself and determine what makes certain infrastructures classified as critical. One interpretation of the term infrastructure is defining it as:

> “large scale, man-made systems that function interdependently to produce and distribute essential goods” (Zio, 2016)

What constitutes as critical infrastructures can be defined in various ways. One definition commonly used within the European union is:

> “Critical infrastructure is an asset or system which is essential for the maintenance of vital societal functions. The damage to a critical infrastructure, its destruction or disruption by natural disasters, terrorism, criminal activity, or malicious behavior, may have a significant negative impact for the security of the EU and the well-being of its citizens.” (European Commission, 2006)

OECD also conducted surveys by asking experts from various countries to obtain insight in how their different member states would define CIs. According to the surveys, Turkey define CIs as:

> “Whole of networks, assets, systems and structures that would form serious impacts on safety, economy, health of citizens as a result of negative effect on conduct of environment, social order and public service in case it fails to fulfil its function partially or completely” (OECD, 2019, p. 65)

The commonality of above definitions is that it describes CI as an asset or system which functionality is essential for the wellbeing of society and its citizens.

Another term used to some extent synonymously with CI is lifeline systems. Lifelines is often used as a more narrow concept, often specifically referring to energy, water, transport and health infrastructures (Hallegatte et al., 2019). Hence, while all lifelines are CIs, not all CIs, such as government and financial infrastructures, can be classified as lifelines.

What constitute as a CI sector varies between OECD countries (Figure 1). The infrastructure sectors that are defined as critical in Turkey in an OECD-report are marked in red.

	AUS	AUT	BEL	CAN	CHE	CHL	CZE	DEU	ESP	EST	FIN	FRA	GBR	GRC	IRL	ISL	ISR	ITA	KOR	LAT	LUX	MEX	NLD	NOR	NZL	POL	PRT	SVK	SVN	SWE	TUR	USA
Energy	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Nuclear sector				•			•		•			•	•				•		•				•	•								•
ICT	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•
Transportation	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Water	•	•	•	•	•		•	•	•	•	•	•	•				•		•	•	•		•	•	•	•		•				•
Dams & flood defence	•					•	•					•			•	•		•	•	•		•	•	•					•		•	•
Food supply & dist.	•	•		•	•		•	•	•		•	•	•				•				•			•		•				•	•	•
Health	•	•	•	•	•	•	•	•	•	•	•	•	•				•		•	•	•			•		•		•		•	•	•
Finance & banking	•	•	•	•	•		•	•	•	•	•	•	•				•		•	•	•		•	•		•		•		•	•	•
Government		•		•	•		•	•	•			•	•				•		•	•	•			•		•				•		•
Public safety	•	•		•	•		•	•	•				•				•			•	•		•	•						•		•
Law enforcement		•				•		•				•	•				•			•	•		•	•								
Chemical industry	•	•			•				•		•	•	•				•			•	•		•	•		•		•				•
Space sector			•						•			•	•																			
Defence industry	•										•	•	•				•			•												•
Critical manufacturing				•							•	•					•							•							•	•
Other		•	•					•	•	•	•	•	•				•		•	•	•		•	•	•	•				•	•	•

Figure 1. List of critical sectors per OECD countries (OECD, 2019)

A term that has gained increased usage in recent times in an European context is critical entity. It refers to a public or private organization or component whose role is essential for proper functioning of society. The Critical Entity Directive (2022/2557), recently implemented by the EU, establishes criteria for identifying entities that could be deemed critical. This includes critical infrastructure operators but may extend to other operators that may not normally fall under the definition of critical infrastructure. The focus of this thesis will be on technical CIs and the critical entities responsible for operating them.

2.2. Resilience

The concept of resilience has gained popularity in both academic and policy usage over the years. The term was first introduced in the science of mechanics in the mid-1800s to describe the strength and durability of steel beams (Alexander, 2013). It later expanded to fields like ecological science in the mid-1900s, where it was used to describe the ability of a system to absorb change and disturbances while still maintaining the same relationship between population and state variables (Alexander, 2013). Given the varying uses of the term in different academic fields, it is crucial to establish a clear definition of how this masters thesis use the concept of resilience.

Woods (2015) for instance described four perspectives of what makes a system resilient:

1. Resilience as rebound: the ability of a system to bounce back to its normal state after facing a disruption or surprise.
2. Resilience as robustness: the systems ability to absorb the effects from various types of perturbations without exceeding critical thresholds.
3. Resilience as graceful extensibility: the systems capability to handle and adapt to surprises near its boundaries of safe operation without experiencing a catastrophic failure.
4. Resilience as sustained adaptability: the systems ability to maintain its capacity to adapt to future disturbances as conditions evolve.

Traditionally, resilience has been seen as something a system has, i.e. something which is measurable or identifiable. In contrast, Park et al. (2013) sees resilience as something a system does, i.e. as adaptive processes undertaken by the system. These processes can be understood through four components or functions (Becker, 2014; Park et al., 2013):

1. Anticipating and foreseeing potential outcomes based on acquired knowledge.
2. Sensing or recognizing impeding events by monitor incorporated indicators or assessing outcomes of recent occurrences.
3. Adapting the system based on the knowledge gained from anticipation and sensing, which may involve system redesign to prevent or mitigate consequences, as well as prepare for efficient crisis response and recovery.
4. Learning from past experiences by acquiring new knowledge, such as assessing the effectiveness of adaptive actions taken.

Another interpretation of resilience popular within the context of community resilience, CI and disaster risk reductions was characterized by Bruneau et al. (2003) two decades ago and includes four dimensions:

1. Robustness: The systems ability to maintain critical operations and functions in the face of crisis
2. Resourcefulness: The systems ability to skillfully prepare for, respond to and manage a crisis
3. Rapidity: The systems ability to rapidly recovery to normal operations
4. Redundancy: The extent to which elements of the system are substitutional, meaning if one element fail there is another to cover for its loss of functionality.

To illustrate how signs of CI resilience can be measured, Bruneau et al. (2003) proposed a resilience triangle concept. This concept looks at resilience through the loss of functionality of the CI services due to the disruption. The area formed between the functionality curve during normal operation and that during the disruption would thus provide comparable indications of resilience, see Figure 2.

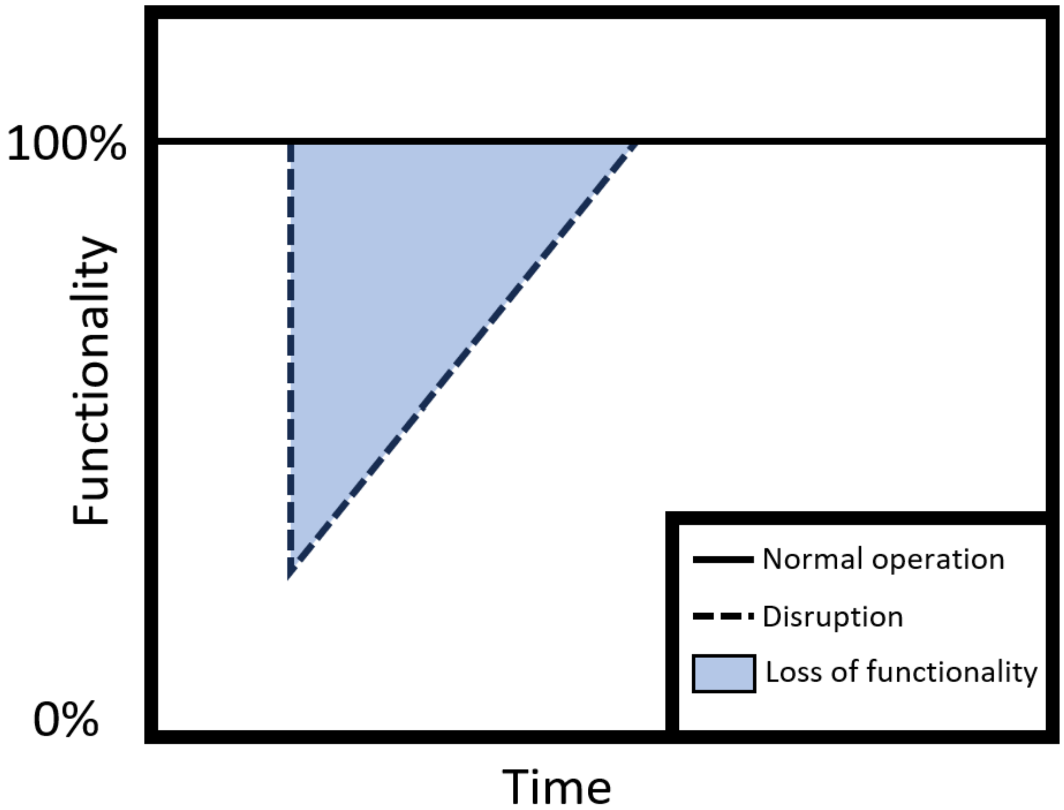


Figure 2. Illustration of the resilience triangle concept

These four dimensions of resilience in the context of CI resilience can be understood through studying four aspects (Bruneau et al., 2003):

- Technical aspects: The physical infrastructure itself, such as its observed redundancy and ability to absorb the hazard and maintain functionality.
- Organizational aspects: The incentives and processes that drive CI operators to engage in resilience-enhancing activities. This includes the organization ability to learn from past events and adapt to be more resilient in the future.
- Social aspects: The social impact of the disruption of the CIs performance on society. This includes physical harm, such as injuries or deaths, as well as other effects.
- Economic aspects: The economic impact as a consequence of the disruption of a CI. This includes the costs to the infrastructure itself such as repairs, lost productivity etc, as well as the cost sustained by the entities that depend on the services provided by the CI.

2.2.1. Definition used in the thesis

While the interpretations of resilience described above differ, likely to be applicable for a specific context, they share several overarching concepts. To consider these concepts, and make them usable for empirical assessments of CI resilience during disasters, this thesis suggest that resilience can be defined as a system's ability for:

1. Anticipation: Measures taken by the system before the event to better anticipate and prepare for it.
2. Robustness: The ability of the system to withstand disturbance and maintain operation of an event. This includes consideration of the systems redundancy and buffering capacity.
3. Recovery: The ability of the system to recover from disturbance during the event. This includes the systems resourcefulness, rapidity and ability for damage assessment.
4. Adaptation: The ability of the system to learn from the event and make improvements to better prepare for future events.

2.3. Interdependencies and cascading effects

Hazards can have the potential to set off a series of reactions that intensify their disruptive effect. Complex interactions between the environment and human-made systems can lead to multi-dimensional effects which evolves and amplifies over time. Consequently, if vulnerabilities in human-made systems go unrecognized, even low-level hazards can sometimes have the potential to set of large chain effects that ultimately lead to disaster, which is commonly termed cascading effects (Johansson et al., 2015b; Pescaroli & Alexander, 2015).

One of the vulnerabilities in human-made systems are the presence of interdependencies between CIs. The interactions between infrastructures can result in cascading effects, where the disruption of one infrastructure can affect the function of another. These dependencies can be categorized as either unidirectional, where infrastructure A relies on infrastructure B but not vice versa, or bidirectional, where both infrastructure A and B depend on each other's services (Johansson & Hassel, 2010). Commonly, the term interdependencies refers to bidirectional dependencies, while unidirectional dependencies are referred to as dependencies. However, because it is possible for unknown complex higher-order dependencies to exist between two seemingly unidirectional dependent infrastructures, in this thesis the term interdependencies will be used to refer to both bidirectional and unidirectional dependencies.

To provide a framework for understanding and analyzing these interdependencies Rinaldi et al. (2001) developed a framework consisting of various dimensions. For example, interdependencies an infrastructure has can vary depending on its state of operation. There may be different interdependencies during normal operation compared to a state of crisis. Additionally, the infrastructure characteristics includes various aspects, such as the spatial and temporal scales at which interdependencies are examined. For instance, interdependencies can exist between infrastructures both at a local and national scale. Additionally, the timescales of infrastructure interdependencies can vary, ranging from immediate effects occurring within seconds, to more gradual impacts that might unfold over several years. The types of interdependencies can overarchingly be divided into three categories: functional, geographical, and logical. [1]

[1] (1) Functional: Refers to the reliance an infrastructure has on a commodity or service produced by another infrastructure, in order to operate effectively. This includes the service of information sharing, which Rinaldi et al. (2001) described as cyber interdependency. An example of functional interdependency is when an infrastructure depends on the functionality of electricity infrastructure to perform its tasks. (2) Geographic: Infrastructures are considered geographically interdependent when a localized environmental event has the potential to affect all of them. For instance, if multiple infrastructures are located in the same geographical area, a natural hazard, like an earthquake, could lead to disruptions in several of these infrastructures simultaneously. (3) Logical: The state of one infrastructure can be logically interdependent by the state of another, primarily due to human decision-making. For instance, if there is a disruption in the railway system, commuters who usually travel by train could choose to use their cars instead, which could cause traffic congestions on highways.

2.4. Policies and Directives

2.4.1. OECD

The Organisation for Economic Co-operation and Development (OECD) is an international organization consisting of 38 member states, including Turkey. One of its purpose is to develop and promote evidence based recommendation for standards and policies related to various social, economic and environmental challenges (OECD, 2023). One of the OECD's initiatives related to critical infrastructure has been conducting surveys across its member states about their resilience work. The findings from these surveys lead to a report about CI issues which provides a toolkit with seven recommended steps for good governance of infrastructure resilience (OECD, 2019). These include:

1. Creating a multi-sector governance structure for critical infrastructure resilience.
2. Understanding complex interdependencies and vulnerabilities across infrastructure systems to prioritize resilience efforts.
3. Establishing trust between government and operators by securing risk-related information sharing.
4. Building partnerships to develop a common vision and agree on achievable resilience objectives.
5. Defining the policy mix to prioritize cost-effective resilience measures across infrastructure lifecycles.
6. Ensuring accountability and monitoring implementation of critical infrastructure resilience policies.
7. Addressing the transboundary dimension of infrastructure systems.

2.4.2. NATO

The North Atlantic Treaty Organization is a military alliance, which Turkey has been a member of since 1952 (NATO, 2023). While NATO's primary focus is on the military capabilities of its allies, the operational effectiveness of military forces relies heavily on civil infrastructure services such as transportation, energy and water. To ensure a high military capability inside the NATO member countries, it was decided during the 2016 Warsaw summit to establish baseline requirements for civil infrastructure and other critical services supporting military operations (NATO, 2019). This means that each member state must continuously prepare and plan to be resilient to withstand and recover from any type of major shock, including those resulting from natural hazards. There are seven baseline requirements for resilience:

1. Assured continuity of government and critical government services

2. Resilient energy supplies
3. Ability to deal effectively with uncontrolled movement of people
4. Resilient food and water resources
5. Ability to deal with mass casualties.
6. Resilient civil communication systems
7. Resilient civil transportation systems

2.4.3. EU

Initiatives to enhance resilience of CI within the European Union (EU) began in 2004 as a response to recent terrorist attacks having occurred in multiple member states. In light of this, the European council requested a comprehensive strategy to safeguard CIs, primarily from future terrorist threats (Karabacak & Ozkan, 2009; Naucodie, 2014). This led to the establishment of the European Programme for Critical Infrastructure Protection (EPCIP) in 2006. Its purpose was to raise awareness, build capacity for effective protection and foster a shared objective for critical infrastructure protection (CIP) within the EU (EUR-Lex, 2006). The program stated that member states were responsible for protecting CIs within their national borders. To facilitate the exchange of information on best practices and to provide timely warnings, a Critical Infrastructure Warning Information Network (CIWIN) was also established.

In 2008, as part of the EPCIP, the EU implemented the directive (2008/114/EC) on *the identification and designation European critical infrastructure and the assessment of the need to improve their protection,* also known as the ECI or CIP Directive. This directive identified transport and energy to be sectors where disruptions could have cross-border impacts, thus designating infrastructures within these two sectors to be European CIs. Member states were then responsible to identify these CIs within their borders and impose requirements on operators in terms of preparedness, planning and reporting. The directive then mandated that the member states used this information to every two years share an assessment to the European commission about the threats and risks encountered in their European CI sectors.

In 2022, the EU approved a new directive (2022/2557) on the resilience of critical entities, also known as the Critical Entities Resilience Directive (CER), replacing the ECI directive. Unlike the previous directive that focused more generally on protecting infrastructures, the CER directive emphasized the protection and resilience of the entities operating these infrastructures. It promotes system robustness, the ability to withstand stress, and a comprehensive system preparedness, encompassing entities taking actions both before, during and after an incident.

The directive requires member states to identify and regulate critical entities within each CI sector. Certain entities of particular interest to the EU are also subject to oversight by the European Commission. The scope of hazards addressed by the directive was broadened beyond terrorism, encompassing natural hazards, accidents and various antagonistic threats including terrorist attacks, attacks by foreign nations, and sabotage. The directive also broadened the range of CI beyond energy and transportation to include banking, financial markets, health, wastewater, digital infrastructure, public administration, space and food. Additionally, it introduced the need for a greater emphasis on interdependencies among different infrastructures, promoting a systems-of-systems perspective. However, the directive has faced criticism for increasing regulation without adequately addressing how member states can assess and manage the resilience of these critical entities and their interdependencies (Pursiainen & Kytömaa, 2023).

2.4.4. Turkey

In Turkey under the law No.5902 the Disaster and Emergency Management Authority (AFAD) is the responsible agency for the national protection of CI. As of 2014 there were large legal gaps with no regulatory enforcement of the protection of CIs (AFAD, 2014). A survey conducted by OECD in 2016 showed that Turkey then as well lacked a national critical infrastructure protection program, and that little information were shared about vulnerabilities (Figure 3).

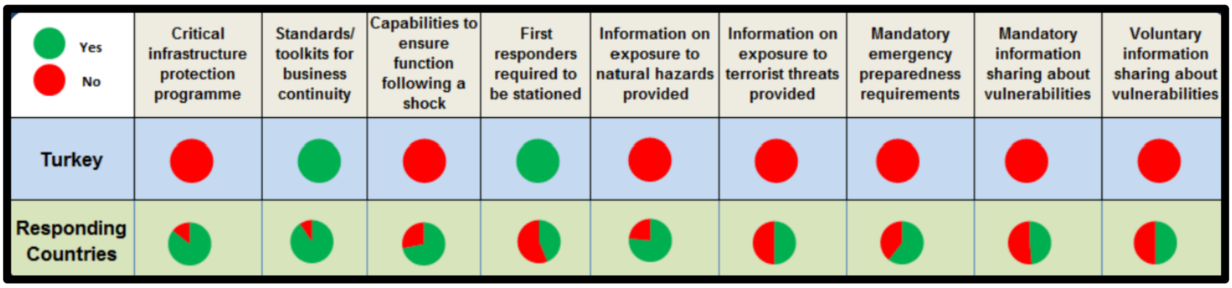


Figure 3. Survey conducted on critical infrastructure protection (OECD, 2017)

The issue of protecting CIs in Turkey gained attention due to increasing national concerns about cyber security and a need to meet EU requirements (Ertem & Velibeyoglu, 2020). In 2014, as part of Turkey´s efforts to comply with EU prerequisites for potential EU membership, the Turkish Disaster and Emergency Management Authority (AFAD) developed a roadmap for how the country could align with EU regulations, including implementation of the ECI directive (AFAD, 2014). This roadmap aimed to identify national CIs, assess their potential cross-border significance, clarify responsibilities of organizations and institutions involved, and provide guidelines for action plans to enhance infrastructure protection by 2023 in accordance with the ECI directive.

A later document, the AFAD strategic plan 2019-2023, discusses the protection of CIs as part of its broader goal to enhance Turkeys resilience to various disasters (AFAD, 2019). While the plan includes activities related to protecting CIs, such as identifying them, conducting risk assessments and strengthen the capabilities of reconstruction of damaged CIs, its primary emphasis seems to be on coordinating disaster management, with CIs, primarily telecommunications, serving a supporting role in disaster management efforts. Consequently, there is no evidence of coordinated cross-sectoral efforts for CI resilience, nor is the identification of interdependencies among CIs addressed.

2.4.5. United Nations

On March 18 2015 the member states of the United Nations came to an agreement on what is important for reducing the risk of disasters in the upcoming 15 years (2030) and adopted the Sendai Framework for disaster risk reduction (2015-2030) as a guide for more efficient national disaster reducing efforts (UN, 2015).

The framework has established seven global targets to be achieved by the year 2030. One of these targets, known as Global target D, specifically focus on CIs, and states to:

> "Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030" (UN, 2015)

3. Literature review

A literature review was conducted to establish the foundation for the thesis framework methodology. Its purpose was to gain knowledge on how CI resilience can be measured and assessed following natural hazards like earthquakes. The review specifically aimed to explore empirical methods for collecting and analyzing data that describe CI interdependencies and resilience.

3.1. Methodology

A review of both academic literature and grey literature, i.e. reports or articles outside academic literature of relevance to the thesis purpose, was conducted. The academic literature review was partly conducted structured and partly unstructured, also including grey literature (Figure 4).

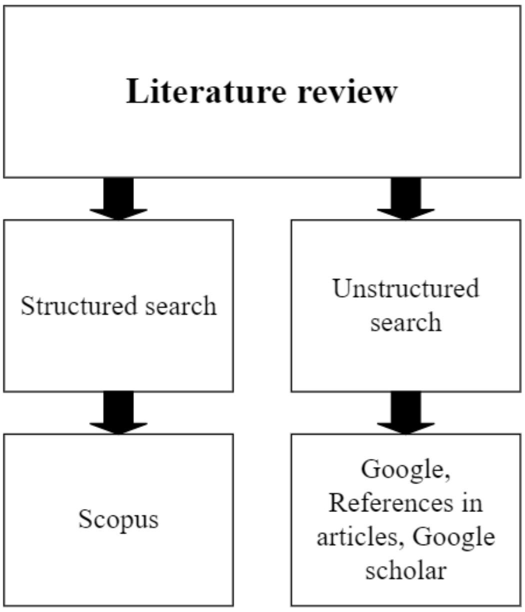


Figure 4. Outline of literature review

3.1.1. Structured search

The structured literature review was conducted using Scopus, one of the world's largest databases for peer-reviewed articles. The review process, see Figure 5, was inspired by the PRISMA flow diagram for systematic reviews, which involved a step-by-step approach of identification, screening, eligibility and ultimately inclusion of papers (Moher et al., 2009). For the structured search, specific search strings were developed and applied for the title, abstract and keywords (TITLE-ABS-KEY). The AND operator ensured the inclusion of each of the different search strings, while the OR operator guaranteed inclusion of at least one word from each search string.

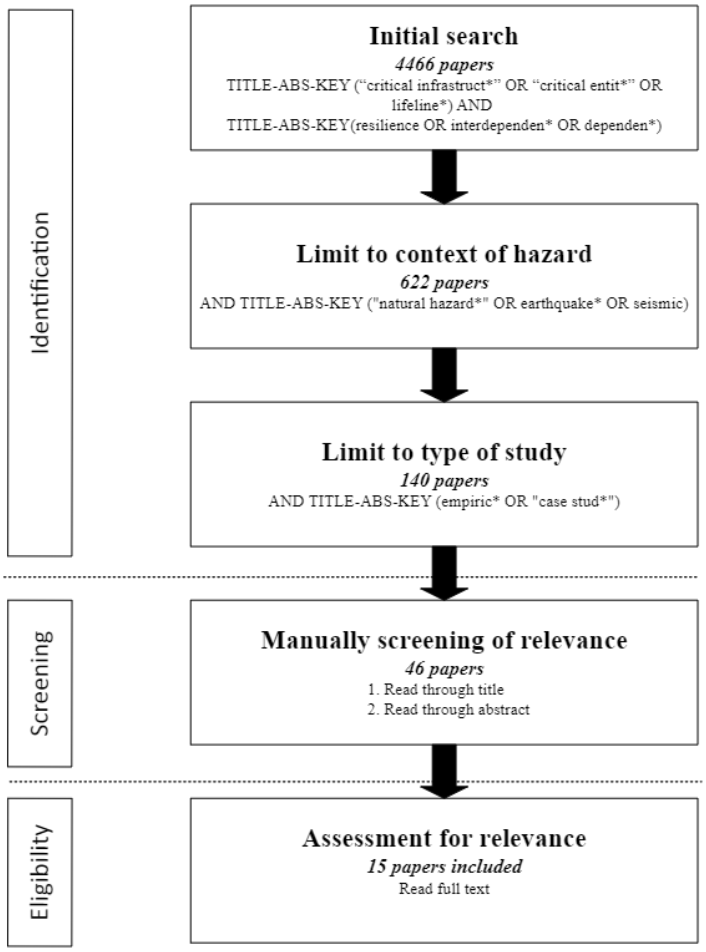


Figure 5. Structured literature search

Initially, a search was performed to identify papers related to CI resilience and interdependencies. Next, the search was narrowed down by considering the specific hazard context and limiting it to specific types of studies, resulting in 140 papers.

Details about the search results shows that the countries with the highest number of publications on the subject are USA, Italy, China, UK and New Zealand (Figure 6). Furthermore, a majority of the papers were written within the past 10 years, indicating a growing interest in the field of research.

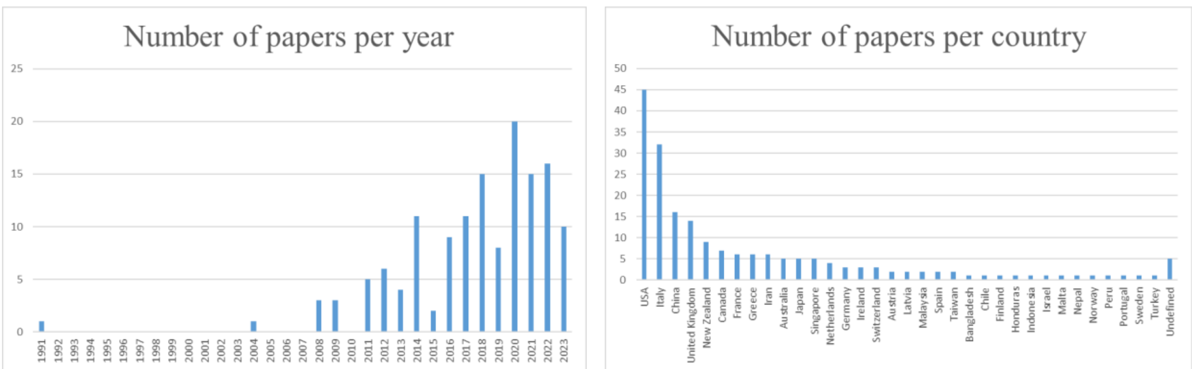


Figure 6. Data on papers found in literature search.

To reduce the number of papers to review, an initial screening was conducted, assessing the relevance of the title and abstract. Papers were excluded if they did not focus on empirical assessments of resilience or interdependencies during real-life events. It was observed that many papers focused on probabilistic assessments of future events, and a few of these papers were included for further review to see if they provided relevant knowledge for the method development in this thesis. The resulting 46 papers were then thoroughly reviewed by reading the full text. This resulted in 15 papers that were deemed eligible for providing relevant knowledge for the thesis and were included in the key findings of the literature review.

3.1.2. Unstructured search

The unstructured search involved using the Google search engine and Google scholar to find reports, articles, and other relevant literature. Search queries such as “assessing critical infrastructure resilience after disaster” and “data gathering for critical infrastructure resilience” were used. Additionally, the supervisor provided suggestion for further relevant literature and relevant articles were also identified through “snowballing” (Wohlin, 2014), which involved scanning through the reference lists of identified relevant papers during the review process in an effort to find additional articles of interest and minimize the risk of omitting relevant literature. After the unstructured search process, 9 articles were considered relevant and were included in the key findings of the literature review.

3.2. Key findings

The key findings from the literature search were categorized into three topics, see Table 1.

Table 1. Findings from articles obtained from the unstructured and structured search, categorized into four topics. Article details is found in Section 9.1

Topic	Unstructured search	Structured search
Assessing Resilience: Simulations and probabilistic methods	(Almaleh, 2023) (Johansson & Hassel, 2010)	(Kammouh et al., 2018) (Kong et al., 2021) (Ma et al., 2023) (Mühlhofer et al., 2023) (Osei-Kyei et al., 2022) (Shafieezadeh & Ivey Burden, 2014) (Aghababaei et al., 2021)
Assessing Resilience: Empirical methods	(Sarkissian et al., 2022) (Johansson et al., 2018)	(Aghababaei et al., 2021) (Alberto et al., 2022) (Cimellaro et al., 2016) (Cimellaro et al., 2014) (Qiang & Xu, 2020)
Assessing Interdependency	(van Eeten et al., 2011) (Luiijf et al., 2009) (McDaniels et al., 2007b) (McDaniels et al., 2007a) (Johansson et al., 2015a)	(Cimellaro et al., 2014) (Lam & Shimizu, 2021) (Ouyang, 2014) (Shubandrio et al., 2022) (Zorn & Shamseldin, 2016)

3.2.1. Assessing Resilience: Simulations and Probabilistic methods

Many researchers in the field of CI resilience are primarily interested in protecting CIs against future disruptions. Thus, much of the literature focuses on exploring uncertainties to predict how CIs will behave during future events. These studies tend to approach resilience from either a vulnerability or a risk perspective, considering various potential events, the resulting consequences, and/or in case of a risk perspective, also their probabilities. Due to the majority of studies of critical infrastructure resilience involve simulation and probabilistic studies, only a handful was selected to be included in the literature review.

Probabilistic studies use previous empirical data to predict the performance of future disruptions (Kammouh et al., 2018; Shafieezadeh & Ivey Burden, 2014). For instance, Kammouh et al. (2018) estimated the downtime of CIs following earthquakes by analyzing data from previous earthquakes around the world to describe restoration as a probability distribution over time. This approach allows for determining with a certain level of confidence whether the recovery of an infrastructure will exceed a certain timeframe given a specific type of hazard. It also enables comparisons of resilience between different types of infrastructure, and between contextual factors such as whether the infrastructure is in a developed or developing country.

To analyze future potential events some studies use simulation models to represent the infrastructures and their interdependencies (Aghababaei et al., 2021; Kong et al., 2021; Ma et al., 2023; Mühlhofer et al., 2023). A prevalent method involves modelling the infrastructure based on network theory, and in some cases also including more functional aspects and salient properties of the infrastructure (Johansson & Hassel, 2010). In these models infrastructure components, like transformers, are represented as nodes and connections such as transmission lines are represented as edges. In the more simplified models, only the topological properties are accounted for, while in more advanced models various degrees of the functionality of the infrastructures are also incorporated. The purpose of such simulations could be to identify how disruptions could cascade through the network when the interdependencies are known and to identify which components or geographical areas could be most vulnerable in the system-of-system (Johansson & Hassel, 2010). However, these simulations require high resolution data of factors including the interactions between infrastructure components, cross-infrastructure interdependencies within the affected regions, as well as the state of components during the disaster, which is difficult to obtain.

3.2.2. Assessing Resilience: Empirical methods

When examining resilience for past real disruptions, empirical methods are preferred because the variables from actual events are either known or can be known. Most studies in literature draw inspiration from Bruneau et al. (2003) which view resilience as a function of the system's robustness, redundancy, resourcefulness and rapidity during a disruption. How they build on this conceptualization is what sets them apart.

Many papers use functionality curves to quantitatively describe the system robustness and rapidity (Alberto et al., 2022; Cimellaro et al., 2016). Robustness is often expressed as the minimum level to which the system performance will decline as a consequence of the disruption. Rapidity is used to describe the time it takes for the system to return to a previous or new, normal state after a disruption occurs.

Some studies also aim to quantitatively describe the redundancy and resourcefulness (Kong et al., 2021; Sarkissian et al., 2022). Redundancy is then often assessed as the average rate of system performance declines after the disastrous event to its lowest point. Similarly, resourcefulness is assessed as the average rate of system recovery from the start of the restoration efforts until it either returns to its normal state or a new state.

Some studies also include calculations of a general resilience value (Ma et al., 2023; Qiang & Xu, 2020; Shen et al., 2020). One commonly used method is to determine the general resilience as the ratio between the area under the actual performance level curve, see Figure 2, and the area under a target performance level curve, which often is considered to be static at 100%, from a specific starting and ending time.

An empirical study by Johansson et al. (2018), collected interruption data for various Swedish CI sectors across many different events. This was used to calculate and compare mean values of resilience across different years and sectors, as well as comparing the distribution of duration and functionality loss for the collected service interruptions.

The literature proposes various methods of assessing a system-of-systems resilience (Cimellaro et al., 2016; Kong et al., 2021; Sarkissian et al., 2022). For instance Sarkissian et al. (2022) assessed CI resilience on a Caribbean island during Hurricane Irma, using a system-of-system approach. They used a centrality measurement based on the observed strengths of dependencies among different CIs to calculate weights, indicating the significance of CIs within the system. These specific weights were then applied to each CI sectors recovery curve during the disaster to calculate a comprehensive system-of-systems recovery curve.

3.2.3. Assessing Interdependency

One way to gather empirical data for interdependency is by analyzing open reports and news articles on the internet (Johansson et al., 2015a; Lam & Shimizu, 2021; McDaniels et al., 2007a; van Eeten et al., 2011). For instance, this was used by Johansson et al. (2015a) in their study focused on the understanding of cascading effects within the system-of-systems of CI. Their study involved categorizing and quantifying interdependencies and cascading effects observed during 40 distinct large-scale disasters which had significant impacts on CIs. They codified cascading effects as originating from one infrastructure (O) and cascading to a dependent infrastructure (D), creating an OD pair. This was presented in a matrix to demonstrate the observed frequency of cascading effects between each different OD pair across the 40 events. Additionally, they analyzed how often each infrastructure acted as an O and D during these events, where the power supply infrastructure was shown to be the most common originator of cascading effects.

McDaniels et al. (2007a) highlighted three advantages of using print media for interdependency studies: its accessibility, its focus on impacts and consequences, and the comprehensiveness of the accounts. However, they acknowledge that relying solely on this type of data might not be ideal for assessing a specific single event due to potential personal biases of reporters, whom for example may choose include what is more newsworthy, while excluding less sensational impacts. To address these limitations, they supplemented their study with more formal official reports and academic literature.

Another way to assess interdependencies involves studying cross-correlations between the performance of different infrastructures (Cimellaro et al., 2014; Ouyang, 2014; Zorn & Shamseldin, 2016). In their study of the 2011 Christchurch earthquake, Zorn and Shamseldin (2016) used statistical correlation equations to quantify the strength of correlation between the recovery curves of different infrastructures and to estimate the most likely lag-time for the interdependent effect between two infrastructures. While this analysis provides insights into interdependencies and its lag-times, a key challenge is its need for precise data of the infrastructure functionality during the event. Furthermore, a high correlation between two infrastructures doesn’t necessarily have to mean a causation, as this can result from other hidden confounding variables.

4. HACIRD Framework

In Section 2, resilience was defined as a system's ability for anticipation, robustness, recovery, and adaptation during a disaster. A deeper analysis was made for the studies in the literature review focused on empirical assessing CI resilience and interdependencies during disasters, to identify whether these studies included a holistic approach, and to what degree they considered interdependencies and/or the four resilience aspects, see Table 2.

Most of the studies focused on quantitatively assessing system performance, often the robustness, recovery or other quantitative resilience measurements. However, they generally overlooked qualitative aspects, such as the system preparedness and anticipation of events, as well as its ability to learn and adapt. This finding is consistent with previous research by Rød and Johansson (2023), which noted a relative limited emphasis on anticipation and adaptation in resilience assessments compared to the more prominent focus on robustness and recovery.

Furthermore, most studies assessed the resilience of specific individual CIs. Only two studies adopted a holistic system-of-systems approach, which also involved assessing interdependencies. However, academic literature focusing on assessing interdependencies during disasters was more frequently found. Nevertheless, these did not include an assessment of resilience and either focused on the system's dependencies towards a particular service, like electricity, during a specific event, or the system-of-systems interdependencies across many different events. Consequently, there was a notable absence of interdependency assessments having a more holistic resilience approach during a specific event.

In summary, the literature review revealed a general lack of post-disaster CI resilience assessments. Among the assessments conducted there was a shortage in comprehensively considering both qualitative and quantitative aspects of resilience as well considering interdependencies between infrastructures. Integrating all these aspects into an assessment framework would allow for a more comprehensive understanding of the impact a specific disastrous event had on the overall CI system-of-systems.

Table 2. Subjects covered in studies assessing CIs empirically after a disaster (●: Covered; -: Not covered).

Studies	Holistic approach	Interdependencies	Anticipation	Robustness	Recovery	Adaptation
(Aghababaei et al., 2021)	-	-	-	●	●	-
(Alberto et al., 2022)	-	-	-	●	●	●
(Cimellaro et al., 2016)	-	●	-	-	●	-
(Cimellaro et al., 2014)	●	●	-	-	●	-
(Qiang & Xu, 2020)	-	-	-	●	●	-
(Sarkissian et al., 2022)	●	●	-	●	●	-
(Johansson et al., 2018)	●	-	-	●	●	-
(van Eeten et al., 2011)	●	●	-	-	-	-
(McDaniels et al., 2007a)	●	●	-	-	-	-
(Johansson et al., 2015a)	●	●	-	-	-	-
(Lam & Shimizu, 2021)	●	●	-	-	-	-
(Shubandrio et al., 2022)	-	●	-	●	-	-
(Zorn & Shamseldin, 2016)	●	●	-	-	●	-
HACIRD-framework	●	●	●	●	●	●

To enable a holistic approach for assessing all four dimensions of resilience and system-of-system interdependencies, a framework was developed for *Holistic Assessment of Critical Infrastructure Resilience during Disasters* (**HACIRD**). The framework combines theories and methods from previous research to better assess the effects of disasters on CIs both individually and holistically, see Figure 7. The framework offers flexibility and scalability, making it applicable at various types of disasters and scales, ranging from a local to national level focus.

The framework purposefully separates the concept of interdependencies with that of resilience, underscoring that rather than being an intrinsic part of infrastructure resilience, interdependencies is a system-of-systems property acting as forces on each infrastructures resilience. Integrating assessments of interdependencies with assessments of the individual CIs resilience enables a more holistic assessment of the entire CI system-of-systems. Although the framework, in its current state, primarily focus on technical and organizational aspects, it can also be used to explore economic and social aspects of resilience. The contributions and opportunities the framework provides are discussed in Section 7.

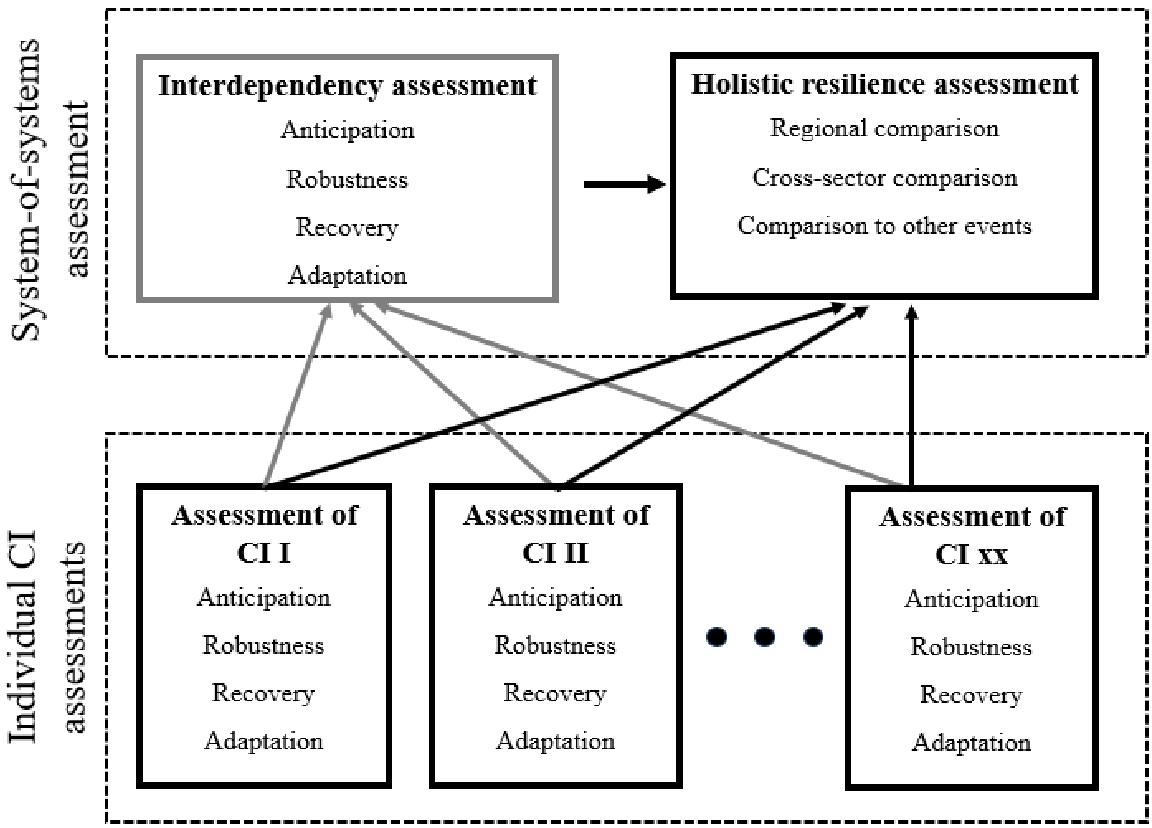


Figure 7. Framework for Holistic Assessment of Critical Infrastructure Resilience during Disasters (HACIRD)

4.1. Individual CI Resilience Assessment

The framework assesses the individual CIs ability for anticipation, robustness, recovery and adaptation during the disaster, as shown in Figure 8. These assessments cover both quantitative and qualitative aspects, offering opportunities for different types of comparisons. Each of the resilience components and important aspects of the framework is outlined below.

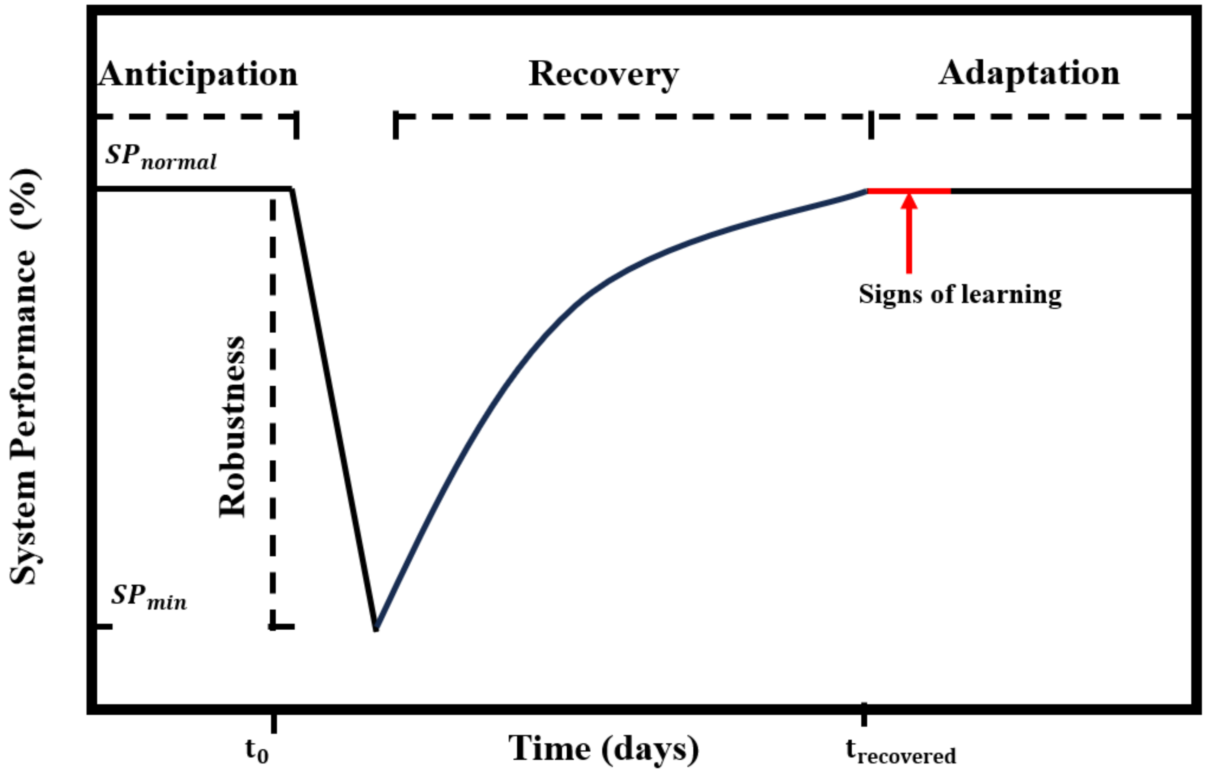


Figure 8. Resilience metrics for system performance curve

4.1.1. System performance

As the goal of assessing quantitative aspects is to provide foundation for comparisons, it is important that the system performance has a similar meaning regardless of what CI is being assessed. The HACIRD framework defines system performance as the percentage of the infrastructure provided service over the disruptive event in relation to the intended service during normal operation.

4.1.2. Anticipation

The anticipatory capabilities of the CI are assessed qualitatively by examining its actions prior to the event which are aimed at reducing the impact of potential hazardous events and enabling suitable responses. This includes:

- Conducted risk and vulnerability assessments.
- Engaged in preparatory activities, such as planning, preparatory exercises etc.

- Financed and implemented initiatives to enhance the infrastructures resilience.

4.1.3. Robustness

The robustness of CIs is assessed by studying how it was affected by the disaster. This includes qualitatively assessing:

- The extent of damage sustained.
- How damage affected ability to maintain its functionality after the disaster.
- Redundancy in system.
- Dependency on services from other CIs or other.

The robustness is also assessed quantitatively based on the minimum level of system performance the infrastructure experienced as a consequence of the disaster, as e.g. done in Kong et al. (2021) , see equation 1.

$$Robustness = \min\,(SP) \tag{1}$$

4.1.4. Recovery

The recovery is assessed qualitatively by analyzing the actions carried out by the CI operators during and after the disaster, in response to changing conditions and emerging needs to restore the system performance, including:

- Ability to mobilize personnel.
- Ability to streamline and coordinate restoration efforts.
- Ability to allocate resources timely.
- Ability to implement temporary solutions.
- Observed dependencies affecting recovery.

The recovery is assessed quantitatively as the time taken to restore the system performance completely to previous levels or stabilize on a new normal level after the disaster, as done in Kong et al. (2021), see equation 2.

$$Recovery = t_{recovered} - t_0 \tag{2}$$

4.1.5. Adaptation

Adaptation refers to how the infrastructure learned from the event and adapted its system so to be better prepared for the future, including measures to build back better damaged CIs. Assessing adaptation can be challenging as implementing measures can take time and may not yet be in place when the assessment is conducted. Thus, in the more direct aftermath of a disaster, mainly signs of learning can be assessed.

The signs of learning of the CI is assessed qualitatively by examining whether the CI operators engaged in learning activities, including:

- Identifying and recognizing strengths and vulnerabilities in the system
- Identifying interdependencies
- Outlining opportunities for improvement

4.2. Interdependency assessment

The framework also specifically address the systems ability to anticipate, learn and adapt to interdependencies and their impact on system robustness and recovery. In the current version, the framework primarily focuses on assessing functional interdependencies.

The framework regards interdependencies as properties of the larger CI system-of-systems rather than being considered as integrated part of the individual CIs resilience. Interdependencies in system-of-systems resilience perspective, function as external forces, acting for or against the individual CI systems inherent resilience. Inherent resilience means that each infrastructure, theoretically, in the absence of any interdependencies would exhibit a certain level of system performance. However, interdependencies introduce forces, putting additional strain to the system performance, affecting either the system robustness ($I_{Robustness}$) or ability to recover ($I_{Recovery}$) during a disaster, see Figure 9.

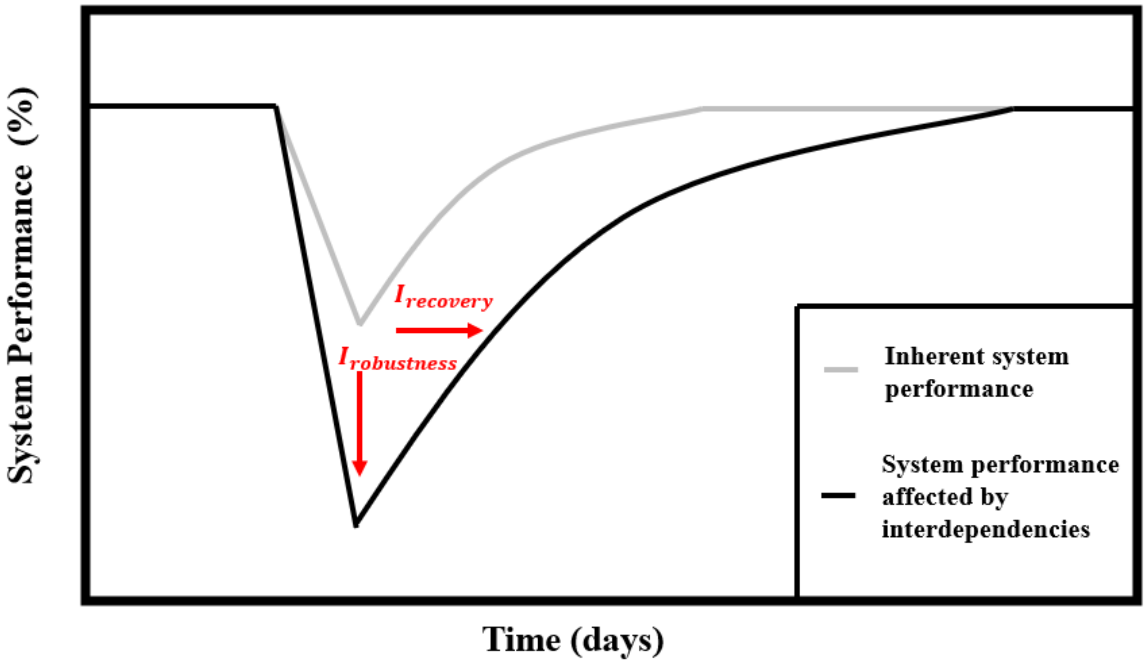


Figure 9. System performance over time. Gray line illustrates the inherent system performance, and black line illustrates the inherent system performance strained by interdependent robustness-affecting and recovery affecting forces.

4.2.1. Anticipation

Anticipation is assessed by examining how interdependencies were addressed at a system-of-systems level before the event. This includes both interdependencies that exist during normal operation and those that could emerge in disastrous events. It assesses operators' engagement in interdependency management activities and governmental efforts to facilitate cross-sector interdependency identification and coordination.

4.2.2. Robustness and recovery

Interdependencies can affect robustness, as the operation of one CI depends on the service provided by another. For instance, a telecommunication network depends on electricity supply to function, and if there is a disruption in the electricity infrastructure in the disaster, it affects the ability for the dependent telecommunication to maintain its system performance and can hence exacerbate the initial disaster impact on the network. These interdependency effects can be visualized as a vertical force ($I_{Robustness}$), decreasing the overall system robustness of the dependent CI, see Figure 9.

Interdependencies can also affect recovery, as the restorative efforts of one infrastructure can depend on the functionality of another. For instance, the condition of road networks can affect the time it takes to restore another infrastructure that needs road access for their recovery efforts. This interdependency can be visualized as a horizontal force ($I_{Recovery}$), prolonging the system recovery of the dependent CI, see Figure 9.

Interdependencies are qualitatively and quantitatively assessed based on their impact on the dependent CIs robustness and recovery. The latter is done on a scale 1 to 5, where 1 is a minor effect, and 5 a significant effect, see Table 3. A rating of 0 indicates the absence of observed or assumed interdependencies, although this does not necessarily mean there are no interdependencies, as they might simply be unknown. The results are then presented in a matrix format, as in Johansson et al. (2015a), with originating CIs (O) on one axis and dependent CIs (D) on the other, forming a grid for each OD pair, allowing for a system-of-systems assessment of interdependency effects across the studied CIs, see an example in Figure 10.

Table 3. Interdependency assessment of origin-dependent infrastructure pairs

Dependent infrastructure	**Originating infrastructure**	**Interdependency description**	$I_{Robustness}$	$I_{Recovery}$
Infrastructure which are affected by the state of the originating infrastructure	Infrastructure whose disruption causes cascading effects to the dependent infrastructure	A description of how the interdependent effects cascade from the originating infrastructure to the dependent infrastructure	The magnitude of the interdependency effect on the dependent infrastructures robustness and recovery on a scale 1 to 5.	

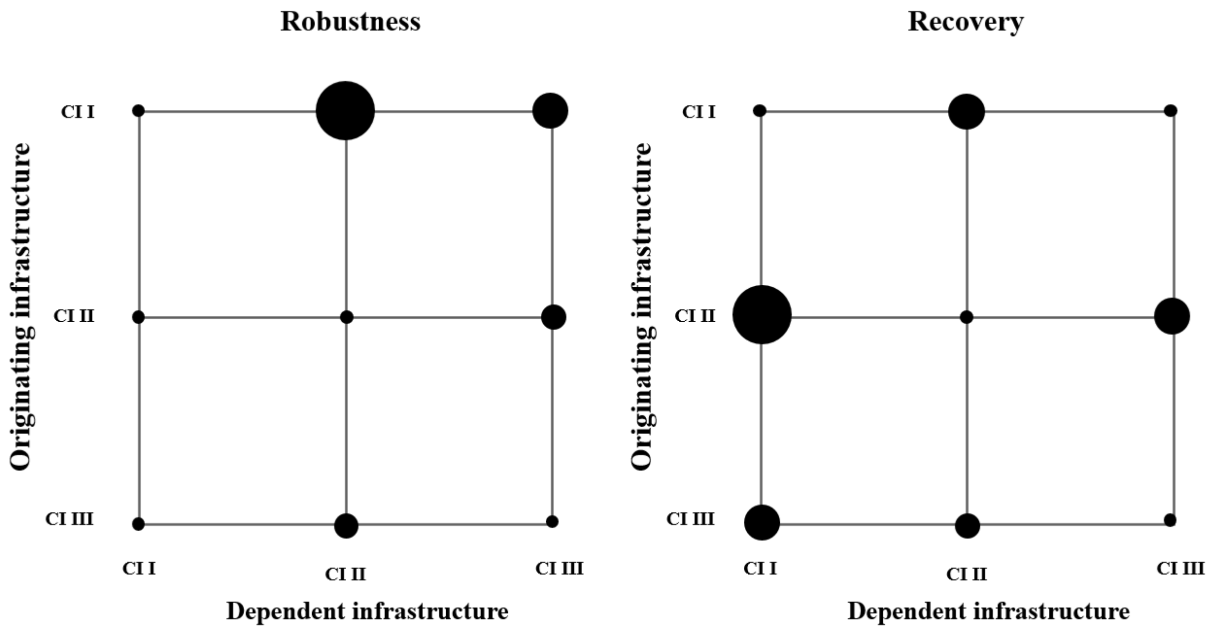


Figure 10. System-of-systems assessment of interdependencies

4.2.3. Adaptation

The adaptation is assessed based on post-event insights into interdependencies. It primarily emphasizes identified signs of learning, including initiatives for improving the coordination and management of interdependencies.

4.3. Holistic resilience assessment

Based on the assessments of all individual CIs assessments and the interdependency assessment, a holistic resilience assessment is conducted. Depending on the specific areas of interest and the data available from the individual assessments, this holistic assessment can include three types of comparative analysis.

4.3.1. Cross-sectorial comparison

A cross-sectorial comparison assesses the relative performance of different CIs within a delimited geographical area during the event. The assessment considers both quantitative and qualitative aspects to study differences between CIs anticipation, robustness, recovery and adaptation. Quantitative aspects include comparing the performance of different CIs during the event, as shown in Figure 11, and analyzing the calculated robustness and recovery. Qualitative aspects include:

- **Anticipation:** Similarities and differences in the precautions taken before the disaster to prepare for disruptions. Did certain CIs demonstrate a greater commitment to strengthen their resilience through proactive measures?
- **Robustness:** Similarities and differences in infrastructure redundancy and ability to absorb the hazard between the CIs and how the CIs managed interdependencies which affected its robustness.
- **Recovery:** Similarities and differences in recovery efforts between the CIs, and how different CIs managed interdependencies which affected their recovery.
- **Adaptation:** Similarities and differences observed in how CIs displayed their ability to identify weaknesses and interdependencies in their infrastructure after the event, as well as their interest and commitment in adapting their system for future events, including interdependencies issues.

To facilitate an easier quantitative comparison across CIs, a resilience ratio (RR) is calculated. The area under the observed system performance (SP) from the time of occurrence of the disaster until the performance is either restored completely to previous normal or stabilized on a new normal, is divided by the normal system performance (SP_{normal}) to attain a ratio. This ratio can be visualized as the proportion of the system performance which was lost due to the disaster.

$$RR = \frac{\int_{t_{earthquake}}^{t_{restored}} SP(t)dt}{SP_{normal} * (t_{restored} - t_{earthquake})} \qquad (4)$$

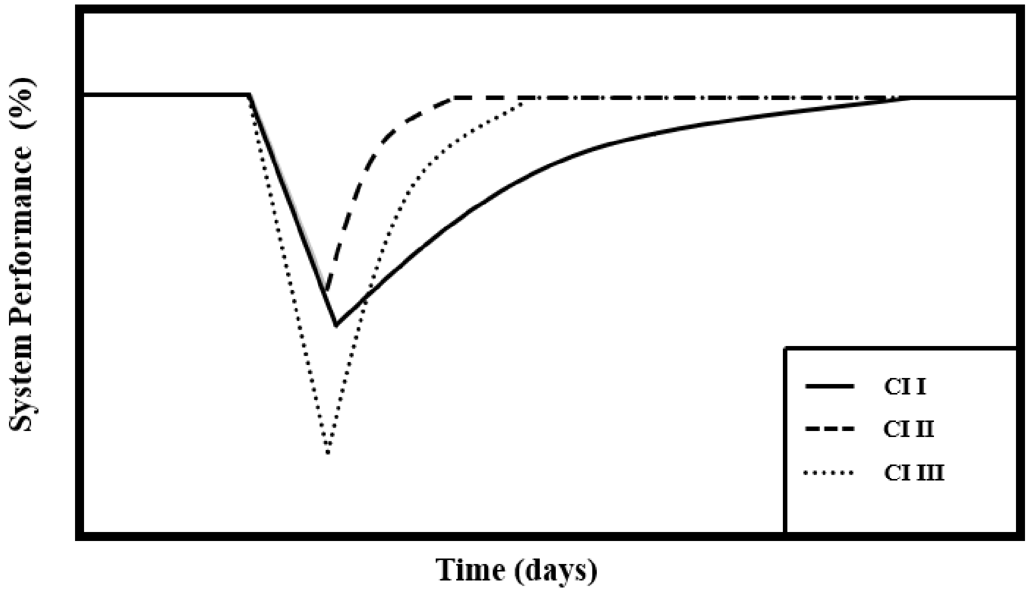


Figure 11. Comparison of resilience between different CIs

4.3.2. Spatial comparison

If detailed data is available for each individual CI across different spatial areas (such as geographical/administrative regions), comparisons can help to understand variations in CIs resilience during the event. For example, regions exposed to higher hazard levels typically experience more severe impacts. However, there may be cases where regions experiencing lower levels of hazard still suffer significant disruptions in CI system performance compared to other areas. The reasons behind these differences are then analyzed considering factors such as whether some regions had fewer backup systems in place or more bottlenecks in the CI system design.

4.3.3. Comparison with previous events

If assessments have previously been conducted on past events using approaches similar to the HACIRD framework, comparisons can be made with the findings of the current assessment to study differences and similarities across various:

- **Contextual factors**: Comparing events with similar hazards occurring in different contexts. For example, comparing hurricanes in the global north with the global south. This can provide valuable insights into factors which might have a great impact on the CIs resilience.
- **Types of hazards**: Comparing events with different types of hazards occurring in similar contexts. For instance, comparing the effects of an earthquake to one of flooding in the same area to understand what sets them apart in terms of consequences on CIs, their resilience, and their interdependent behavior.

5. Case Study Methodology

To use the HACIRD-framework for analyzing the 2023 Kahramanmaraş earthquakes, data had to be collected and processed to fit the framework's structure. The methodology of collecting and processing this data the follows the sequential steps outlined in Figure 12, and is discussed in detail below. This method is specific for this case study but can offer insights for the construction of appropriate methods for utilizing the framework in other case studies.

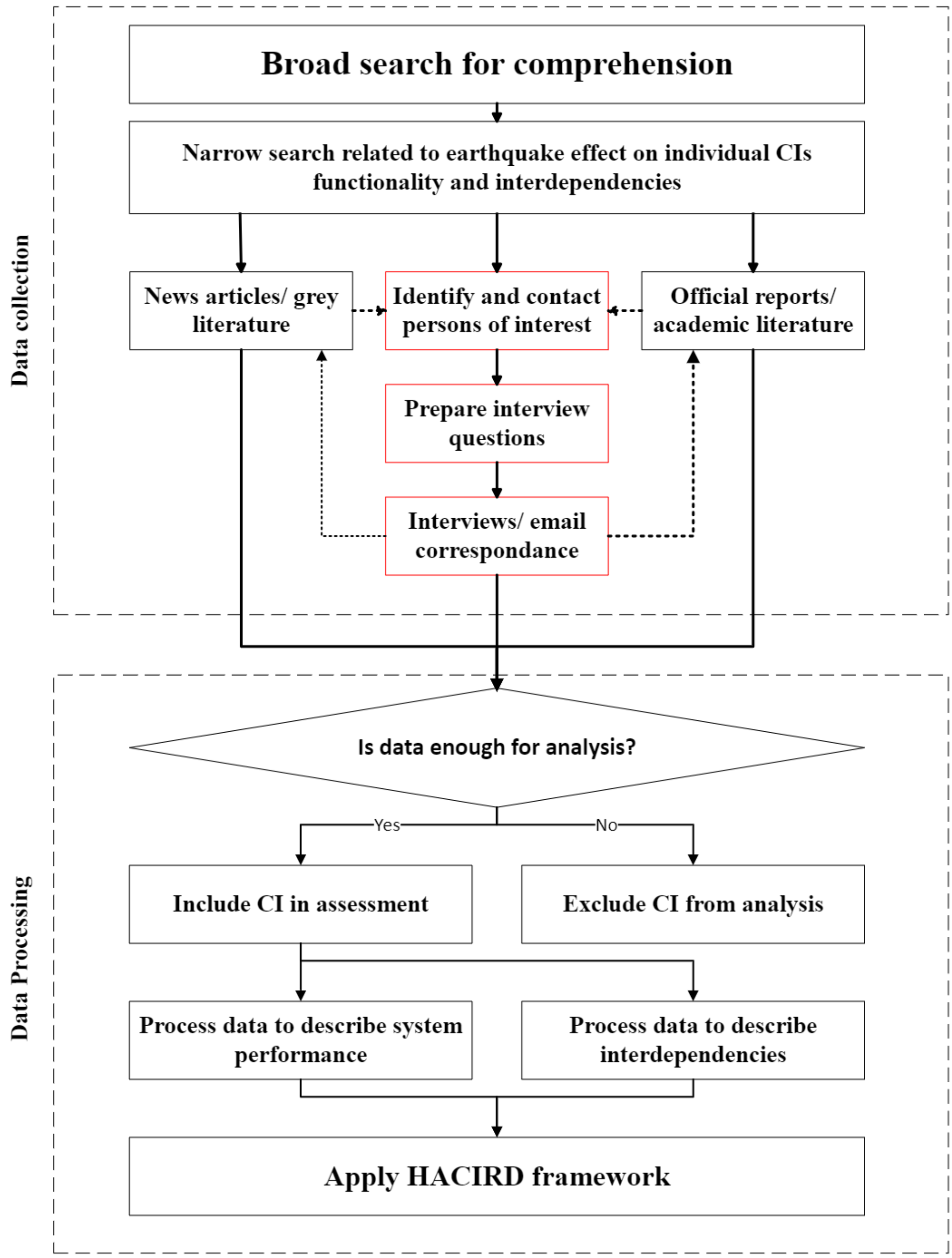


Figure 12. Flowchart of case study methodology

5.1. Data Collection

The first step of the case study was to acquire a comprehensive understanding of CIs within the Turkish context, particularly focusing on the earthquake affected regions. This was done through broad google searches to gather insight into various aspects such as responsible CI operators and functional details including the extent of service delivery on both national and local scales.

The next step involved a focused search on how individual CIs were affected by the earthquakes. This search included a review of numerous sources, including articles, social media posts, academic papers and official reports covering the damages sustained by the infrastructures and the response efforts. Due to a substantial amount of data being in Turkish, Google Translate was used extensively in translating search queries from English to Turkish and subsequently translating the content of the data back into English.

The project initially aimed to conduct interviews with various CI operators. However, it became evident early on that our network of contacts in the affected regions was limited. Consequently, alternative methods had to be employed to connect with relevant individuals for interviews. This involved reaching out to authors of previous articles related to the topic and gathering email addresses from the websites of different CI operators. However, this yielded a low response, although a few contacts did share relevant articles and data.

5.2. Data Processing

Screenings were conducted based on availability of data for each CI. This was used to determine whether the HACIRD-framework could be fully applied to the CI, including both qualitative and quantitative aspects. If the available data was insufficient for any type of assessment, the CI had to be excluded from the assessment.

The collected data needed preprocessing to be assessed with the HACIRD-framework. For certain infrastructures real-time data was accessible online from operators, while for others data was collected from secondary sources. Consequently, there was a wide variation in data resolution and quality, requiring different levels of assumptions during treatment.

The data available for assessing system performance varied among the CIs. In some cases, data was obtained as a specific unit over time which was converted into system performance by dividing the data points over an estimated baseline operational value. This baseline was calculated as the median value over some months before the earthquakes. For other CIs, only limited data on the extent of disruptions were obtained, requiring heavy assumptions to assess system performance.

The interdependency assessment considered both observed and assumed dependencies. Some dependencies for CIs were assumed when a similar specific dependency was observed for other CIs during the earthquakes or had been observed during previous events. The strength of the dependency was subjectively evaluated by the assessor.

6. Case Study Assessment

On 6th of February 2023, the southeastern part of Turkey experienced two consecutive earthquakes along the East Anatolian fault, see Figure 13. The first earthquake struck at 04:17 local time, measuring a magnitude of 7.8 Mw, followed by a 7.5 Mw earthquake at 13:24 (USGS, 2023a). These earthquakes are referred to as the 2023 Kahramanmaraş earthquakes, as they were centered around the Kahramanmaraş province. However, the earthquakes also affected other provinces, including Kilis, Gazientiep, Osmaniye, Adana, Hatay, Adiyaman, Malatya, Şanlıurfa, Diyarbakır and Elazığ (Figure 14).

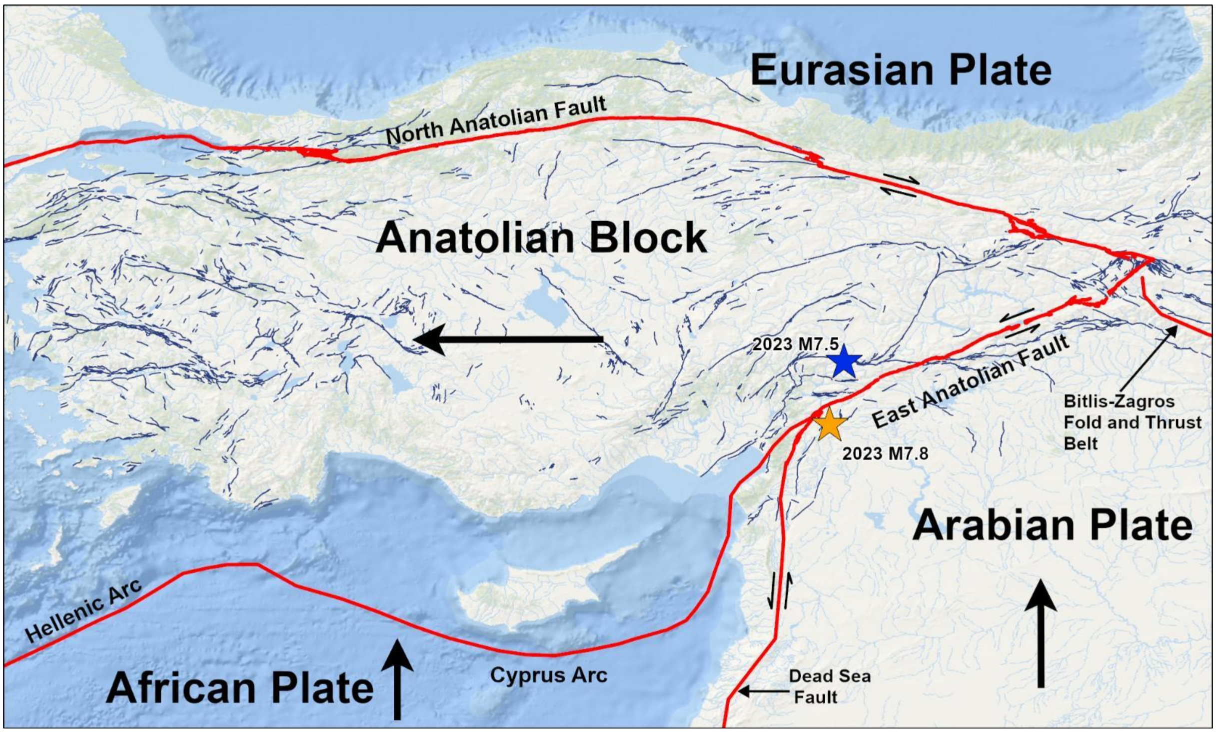


Figure 13. Map over the continental fault lines in Turkey. The yellow star shows the epicenter of the first earthquake 04:17. The blue star shows the epicenter of the 13:24 earthquake (USGS, 2023b)

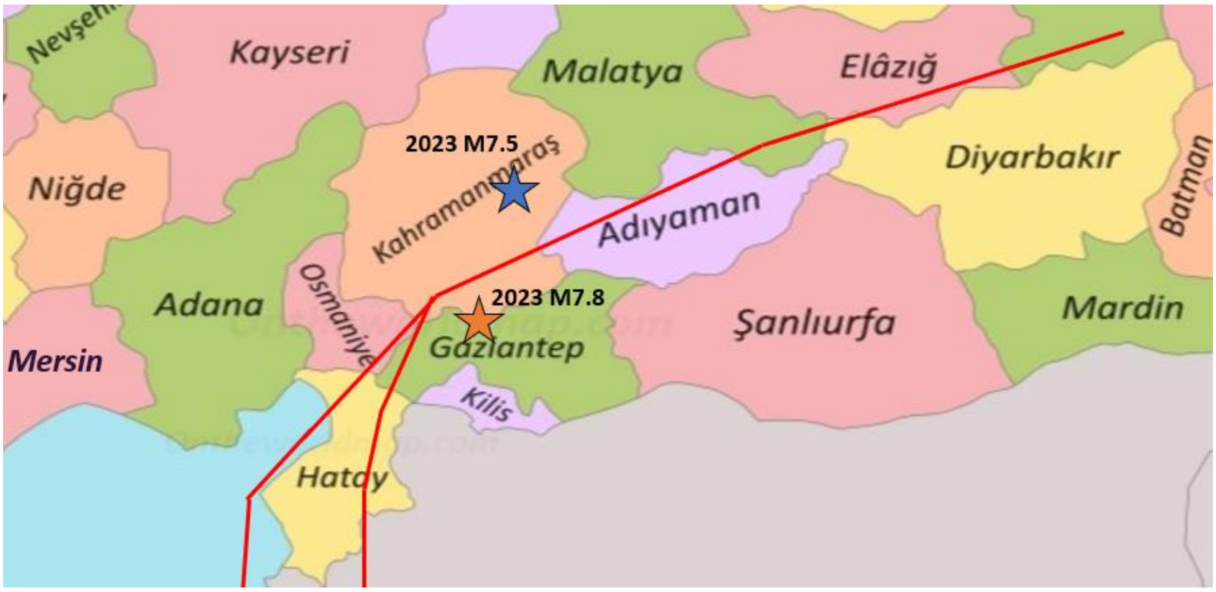


Figure 14. Provinces of the affected area. (OnTheWorldMap, 2023). Fault lines and epicenters are overlayed from image by (EERI & GEER, 2023). The yellow star shows the epicenter of the first earthquake at 04:17. The blue star shows the epicenter of the following earthquake by 13:24.

The earthquakes resulted in over 50,000 deaths and more than 100,000 people were seriously injured, with more than 1.5 million people evacuating cities due collapsed or at-risk homes (International Medical Corps, 2023). The region experienced multiple additional aftershocks, including one more severe centered in Hatay province on February 20th , measuring 6.4 Mw (Michaelson, 2023). Furthermore, the earthquakes damaged CIs leading to additional severe societal consequences.

The resilience of the CIs is assessed using the HACIRD framework. Detailed descriptions of the earthquakes impact, calculations, interdependencies, and references for data for each assessed CI is respectively provided in appendixes, see Table 4. The specific infrastructures chosen for assessment was based on 1) what Turkey considers critical infrastructures, 2) data availability, and 3) the limitations in scope of the thesis and allowed space to report the findings. Excluded infrastructures which were observed to have been affected include for example fuel infrastructure, energy pipeline infrastructure, airports, hospitals.

Table 4. List of appendixes detailing respective CI sector.

CI sector	Detailed description
Electricity	Appendix A
Highway	Appendix B.1
Railway	Appendix B.2
Ports	Appendix B.3
Water supply	Appendix C
Industry	Appendix D
Telecommunication	Appendix E
Interdependencies	***Appendix F***

The assessment includes both a provincial and regional perspective. At the regional level it focuses on the overall resilience in all the affected provinces. At the provincial level it specifically focuses on the observed resilience in Hatay. Despite Hatay being located far away from the epicenter of the earthquakes, the geological conditions, including its alluvial soil and position on the direction of the fault, see Figure 14, led to very high peak ground acceleration values during the earthquakes (Sagbas et al., 2023). This intensity caused significant damage in Hatay, particularly in the city of Antakya, where almost half of the total casualties occurred (≈20,000), and where an estimated 80% of the buildings would need to be demolished (Abraham et al., 2023)

6.1. Electricity

6.1.1. System performance

For electricity infrastructure, system performance is defined as its ability to supply electricity to customers in relation to its normal intended level. This is estimated using analysis of streetlight intensity measured for different cities before and after the earthquakes, see Figure 15.

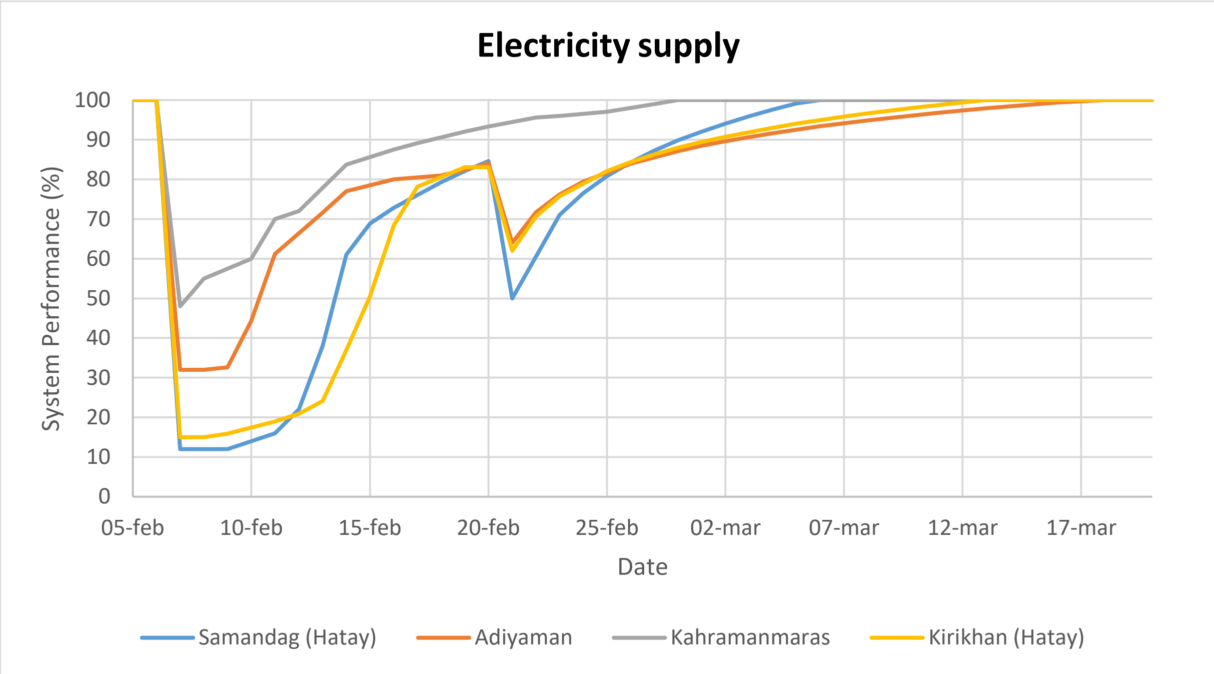


Figure 15. System performance of electricity supply during the February 6 earthquakes

6.1.2. Anticipation

Preceding the earthquakes, TEIAS in collaboration with Middle East Technical University had developed a framework to screen all types of transmission facilities against a variety of risks, including earthquakes. The purpose was to identify vulnerable areas where resources should be allocated to strengthen the system. As of March 29, they had screened 2.23% of the facilities nationwide, with a target of finishing the screening by March 2024.

6.1.3. Robustness

The earthquakes caused severe damage to all aspects of the electricity infrastructure, including the generation facilities, the transmission network and distribution networks. Damage includes ruptures in critical system components, such as generation turbines and transformers. Additionally, many substations experienced structural damage to the housing of the electrical components, where either the building collapsed or debris falling onto the electrical components. Furthermore, transmission and distribution lines were damaged, with transmission towers collapsing due to landslides from ground settlement or structures falling onto distribution lines. As seen in Figure 15, Hatay experienced the greatest system performance decline, maintaining only about 14% of its intended level.

The earthquakes had a mostly local impact on electricity generation, causing only a small nationwide reduction in power production. The total available generation quickly stabilized by increasing production in other plants. Additionally, the interconnected grid enabled areas affected by the earthquakes to receive power from plants outside the affected regions, indicating that disruptions in generation were not the primary cause of the significant decline in electricity supply system performance.

Hydroelectric powerplants demonstrated greater operational robustness compared to natural gas or coal power plants, often managing to continue operation even when they suffered some structural damage. Additionally, power generation was more severely affected in Hatay and Kahramanmaraş compared to the other affected provinces.

The earthquakes led to the inoperability of about 20% of the transmission transformer stations in all the affected provinces. When the transmission system was operationally back, the electricity supply also seemed to increase, indicating that the large-scale disruptions of transmission system was likely one of the main causes of the large drop in system performance in these provinces.

However, even after the transmission system was restored, many areas continued to experience reduced power supply. This can primarily be attributed to the extensive damage sustained by the distribution network. Unlike the transmission system, distribution transformers and power cables are often located in urban areas near other built structures, some of which collapsed during the earthquakes, making these extra susceptible to damage. Therefore, it is likely that damage sustained by the distribution network contributed to the large drop of system performance after the earthquakes, particularly considering that the transmission network remained operational in many affected areas which still experienced power outages.

6.1.4. Recovery

According to Figure 15, Adiyaman took the longest to recover its system performance of electricity supply, approximately 38 days, which is 5 days longer than for Hatay. Efforts to restore electricity were coordinated jointly by transmission and distribution companies, AFAD and the Ministry of Energy and Natural Resources. Within an hour after the initial earthquake, they established an emergency crisis center to coordinate efforts. However, there were reported challenges in communicating with one of the distribution companies as their office building collapsed.

Individual electricity generation facilities showed different recovery. Some were able to resume operations as soon the transmission network was back online, while others, six months later, have remained non-operational since the earthquakes.

Transmission and distribution companies demonstrated flexibility by rapidly increasing their workforce. While they had difficulties mobilizing their own personnel, as they were themselves victims of the disaster, distribution companies managed to source additional manpower from unaffected counterparts. For instance, Toroslar EDAS increased its workforce from 350 to 1011 on the first day of the earthquake, and by the fifth day they had further expanded to 2073 active personnel working in the field.

The transmission system recovered near its pre-disaster supply levels in approximately four days. In contrast, the distribution network, which suffered significant damage, had longer recovery periods. One of the major factors impeding the restoration process was the disrupted accessibility to damaged components within cities, primarily caused by damaged roads and collapsed structures. For rural areas there were also reported difficulties restoring the distribution networks due to disrupted telecommunications. Furthermore, the scale of damage on the power systems required extensive replacement. For instance, in Antakya, Hatay, almost half of the distribution systems had to be replaced.

6.1.5. Adaptation

In a hearing, electrical infrastructure managers highlighted their reliance on telecommunication infrastructure for effective recovery. They discussed the challenges of depending on satellite phones during large-scale disasters, including the high costs of calls and the number of satellite phones required for effective communication, and proposed considering adopting alternative communication systems.

They also raised concerns regarding the logistics required to support recovery personnel. The growing workforce requires essential provisions like shelter, food and water over an extended period of time. The difficulties encountered after the earthquakes highlighted the need for better logistical planning in future events.

Furthermore, they emphasized the necessity for AFAD to develop more comprehensive action plans that enhance coordination between AFAD and distribution companies, making information sharing and resource allocation more efficient.

Government officials expressed concerns regarding the need for enhanced testing of actual systems. They proposed updated legislation and regulation that better specify which components should undergo testing and the methods for testing components against seismic forces.

Notes

The electricity distribution providers regularly upload monthly data on disruptions to their websites. However, there was an observed absence of data for the worst affected provinces in the weeks following the earthquake, which was likely a consequence of the extensive impact of the earthquakes on both society and the electricity infrastructure. Additionally, disruptions upstream in transmission network likely further complicated efforts to gather information about disruptions within the electricity distribution. Consequently, to estimate system performance, daily analysis of satellite imagery of the intensity of street lightning was used. However, its correlation with actual electricity supply remains uncertain.

6.2. Highway Transportation

6.2.1. System Performance

For the KGM 5th directorates highway network, system performance is assessed as its ability to maintain lengths of highway operational relative to the total network length, see Figure 16. This is calculated using data on reported closed highways in February month due to earthquakes. For Hatay, a province within the 5th directorate, system performance is assessed as the number of its 5 interconnecting highway sections which was operational.

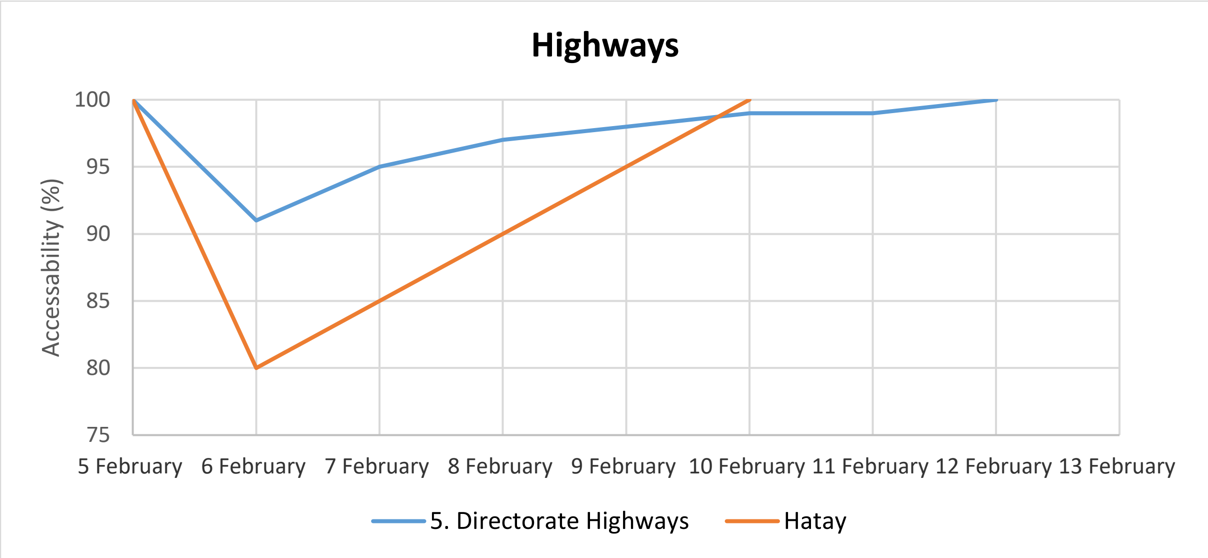


Figure 16. System performance of highways during the earthquakes.

6.2.2. Anticipation

The KGM frequently participates in disaster preparedness exercises organized by AFAD. In 2022 they participated in a national drill that focused on coordinating recovery efforts after an earthquake. During the same year, managers from the directorates in the affected area (5th and 6th) participated in exercises on sandstorms and tornado scenarios. Additionally, the KGM continuously updates regulations of roads, tunnels and bridges against seismic hazards.

6.2.3. Robustness

The earthquakes caused extensive damage to roads and bridges, including structural damage, lateral spreading of roads, and ground settlement beneath highways. Of the highways under the 5th Directorate approximately 91% could remain operational, while the remaining had to be closed for maintenance. In Hatay, the highway connecting the city of Antakya with Reyhanli was out of service due to damage, making the operable highways in the province around 80%. Additionally, highway traffic control stations suffered significant damage, with more than 5 out of the total 29 stations in the affected region becoming unusable, resulting in difficulties for traffic assessments.

6.2.4. Recovery

The KGM quickly mobilized approximately 3 900 personnel and 2 500 machines to assist in the recovery efforts. Within roughly 7 days, the entire 5th directorate roadwork in the affected area was deemed fully functional. In Hatay, the highways were mostly back to normal operation within 5 days. However, certain sections of the highway networks were still severely damaged, and the recovery involved temporary paving either on or beside the highway to get the road back to traffic. The actual reconstruction is likely to have taken much longer time.

6.2.5. Adaptation

The data from KGM did not include information for assessing signs of learning. However, the Presidency of Strategy and Budget proposed to enhance the seismic resistance of traffic control stations by enforcing building codes on these facilities. Additionally, they recommended that KGM perform risk assessments to identify areas in the affected regions where highway earthquake resistance should be improved.

Notes

The data used to assess highway system performance came directly from the highway operator, adding credibility of the results. However, great assumptions were made when assessing. For instance, it was assumed that each section of the highway network was equally critical for traffic flow neglecting the actual traffic conditions in the disrupted sections. Additionally, for Hatay these assumptions were even greater, considering all five highway sections as equally important for the system performance. These oversimplifications introduced significant uncertainties into the results, emphasizing cautious interpretation.

6.3. Railway transportation

6.3.1. System performance

Railway infrastructures system performance is assessed as the percentage of railway sections available for its intended use during the earthquakes. Sections that were open exclusively for emergency purposes were regarded as non-operational. The system performance is estimated using data from news sources and public statements made by the railway managing operator TCDD (Figure 17).

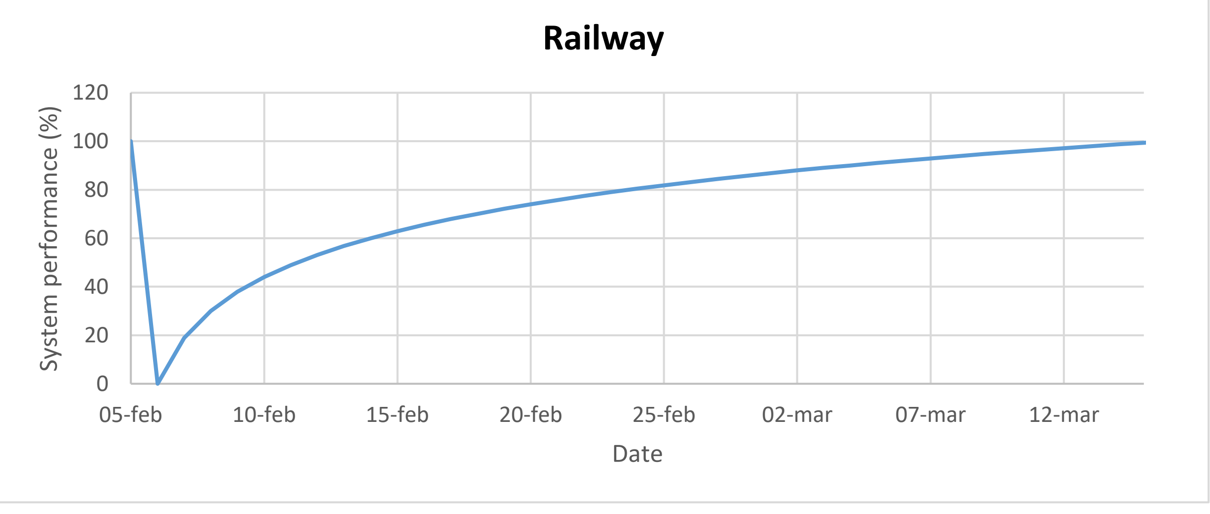


Figure 17. System performance of railways during the earthquakes.

6.3.2. Anticipation

No explicit documentation regarding disaster anticipation for the railway infrastructure was found. However, in their annual report TCDD mention that they engage in systematic risk management processes, with each regional directorate annually conducting risk analysis studies for all their railway lines.

6.3.3. Robustness

The railway suffered significant damage, including structural damage to bridges and tunnels, deformation and cracks in railway tracks, damage to powerlines, and blockages caused by debris and rockfall. Consequently, approximately 1 280 km of railway sections across the 10 affected provinces were inoperable.

The earthquakes caused all railway yards in the provinces of Kahramanmaraş, Gazientep and Malatya to cease operation. This section is a known bottleneck in the Turkish railway system, handling a significant volume of freight transport. Consequently, experts believe that the earthquakes had nationwide impacts on Turkish railway transportation.

In Hatay, most railway sections reopened shortly after the earthquakes, but exclusively for relief efforts, including transporting personnel, food, necessary equipment, temporary “container homes”, and evacuating people in need. For commercial usage, it is reasonable to assume that the system performance of these sections dropped to 0% immediately after the earthquakes.

6.3.4. Recovery

Recovery efforts were immediate, mobilizing personnel, and equipment to remove debris from tracks, restoring broken tracks and overhead lines. After 38 days the railway network is estimated to have been fully operational again.

6.3.5. Adaptation

No reports indicating signs of learning were collected.

Notes

The data gathered was limited, particularly for anticipation and signs of learning. Additionally, there could be arguments regarding the suitability of excluding sections open for emergency usage only, when calculating system performance, especially considering that the focus of the assessment is the infrastructure itself.

6.4. Port infrastructure

6.4.1. System performance

For port infrastructure, the system performance is assessed as the number of ports which were available after the earthquakes compared to its capacity before the event. The earthquake-affected Iskenderun Bay contains 11 ports, 8 of them located in Hatay, each serving different purposes. The system performance is calculated using reports on disruptions of ports and their recovery, and assumed all ports had an equal relative importance (Figure 18).

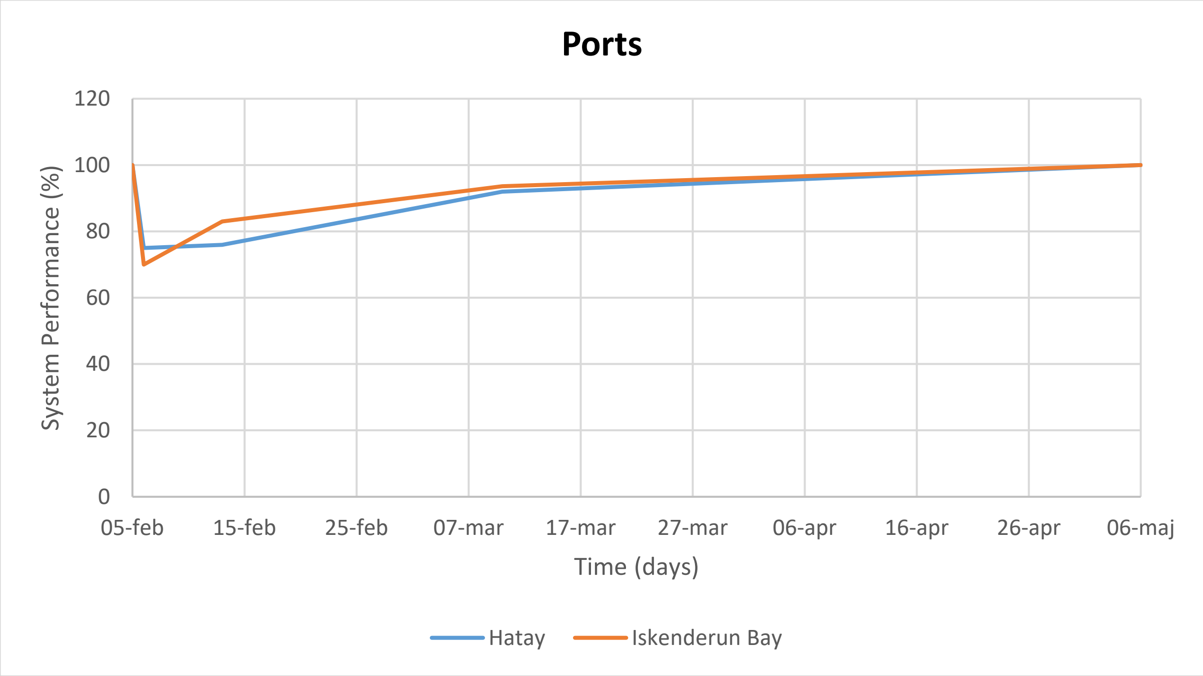


Figure 18. System performance of port infrastructure during the earthquake

6.4.2. Anticipation

No reports of anticipation were found.

6.4.3. Robustness

In Hatay, 75 % of ports were assumed operational following the earthquake. At Iskenderun port, the sole container freight port in Iskenderun Bay, a fire erupted among containers, leading to a complete halt in operations and the destruction of over 1000 containers. Reports suggested that some of these containers stored highly flammable materials, raising concerns about the ports' lack of proper infrastructure and training to safely manage such containers.

Ships originally intended to unload their freight at Iskenderun port were redirected to the port in Mersin. Although Mersin port had the capacity to accommodate additional ships, the large increase in ships required some of them to wait outside Mersin long times before they could dock. This is believed to have had a nationwide impact on industries access to raw materials.

Other ports experienced disruptions as well. For instance, operations at the Ceyhan oil port were halted due to damage sustained by its components during the earthquakes.

6.4.4. Recovery

Efforts to extinguish the fire at Iskenderun port involved isolating containers from the fire, using water cannons on ships, and water bombing using planes and military helicopters. The fire was successfully extinguished after 4 days, and operations gradually resumed. However, some experts estimated it would take up to three months for the port to restore to its normal capacity.

Ceyhan oil port quickly recovered, resuming normal operations in approximately one week.

6.4.5. Adaptation

No reports indicating signs of learning was found.

Notes

The estimation of port infrastructure system performance assumed equal capacity for all ports, despite their actual varying capacity, and handling of different types of goods. Additionally, the calculations were solely based on data from news reports. The estimated three-month recovery time was based on a statement made by an external port expert and not on the actual recovery time. Consequently, the results include high degree of uncertainty, emphasizing a need for cautious assessment.

6.5. Water supply

6.5.1. System performance

For water supply infrastructure, system performance is assessed as its ability to deliver water to customers in relation to its pre-disaster level. Temporary solutions to provide water outside of the regular system, such as through tank trucks, are not considered when calculating the system performance. Data was collected from reports and news sources to estimate the system performance in the province of Hatay (Figure 19).

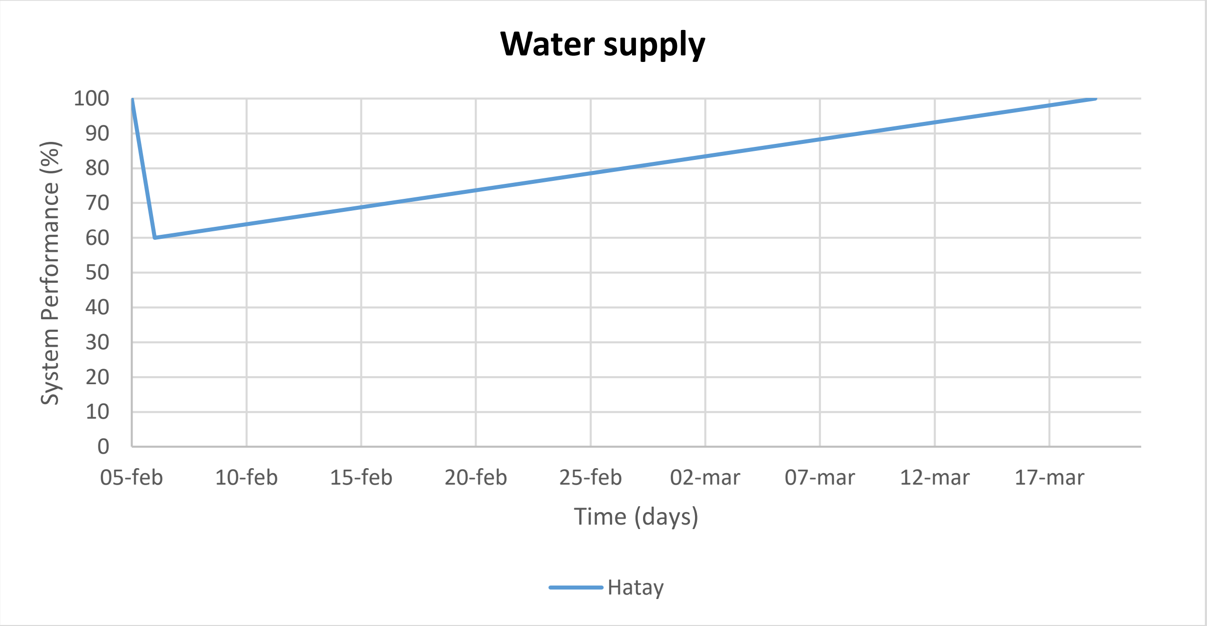


Figure 19. System performance of water supply system during the earthquake

6.5.2. Anticipation

No data on anticipation was found.

6.5.3. Robustness

The earthquakes caused significant damage to water infrastructure. This includes damage to components like piping, with issues such as pullout of unrestraint joints and ruptures causing leakages. Additionally, water sources, wastewater, and freshwater treatment plants, suffered substantial damage to critical parts, including pumps, sedimentation tanks and generators. The power outages made the operation of some pumping stations and treatment facilities dependent on their diesel generators. In Hatay, the earthquakes completely cut off water access for 6 out of its 15 districts, resulting in a system performance of 60%.

6.5.4. Recovery

Mobilizing personnel was challenging after the earthquakes. In Hatay, the water distribution company (HATSU) with over 2 500 personnel, could only mobilize around 200 for restoration efforts as many of the employees themselves were affected. Consequently, during the first two months post-earthquake, HATSU depended on external assistance from other water distribution companies to restore their infrastructure.

Approximately 14 days after the earthquake, by February 20, around 98% of the water supply in the 10 affected provinces had been restored. In Hatay, full restoration was first achieved by March 19, after 41 days. Nevertheless, in certain rural areas of Hatay, it would take several months before full restoration was achieved.

Despite the water supply infrastructure being restored, several water supply operators advised against drinking the water due to the potential risk of contamination from diseases and hazardous chemicals. Drinking water was instead initially provided through tank trucks and bottled water.

6.5.5. Adaptation

No documentation indicating signs of learning was found.

Notes

The data quality was limited as it came mostly from secondary sources such as field reconnaissance studies and news sources. Additionally, it is important to note that the assessment does not reflect the operator’s ability to provide residents with drinking water, as temporary solutions like tank trucks are excluded when calculating system recovery. Instead, it assesses the system’s ability to provide water through its fixed system.

6.6. Industry

6.6.1. System performance

For industries, system performance is assessed as the collective capacity within a specific area to manufacture goods in relation to the pre-disaster manufacturing capacity, see Figure 20. Each industry's contribution to the collective manufacturing was assumed to be equal in the calculations and it was assumed that industries with severe structural damage would remain non-operational until fully repaired. Data for assessment was obtained from a previously conducted field reconnaissance study examining the extent of damage sustained by industries.

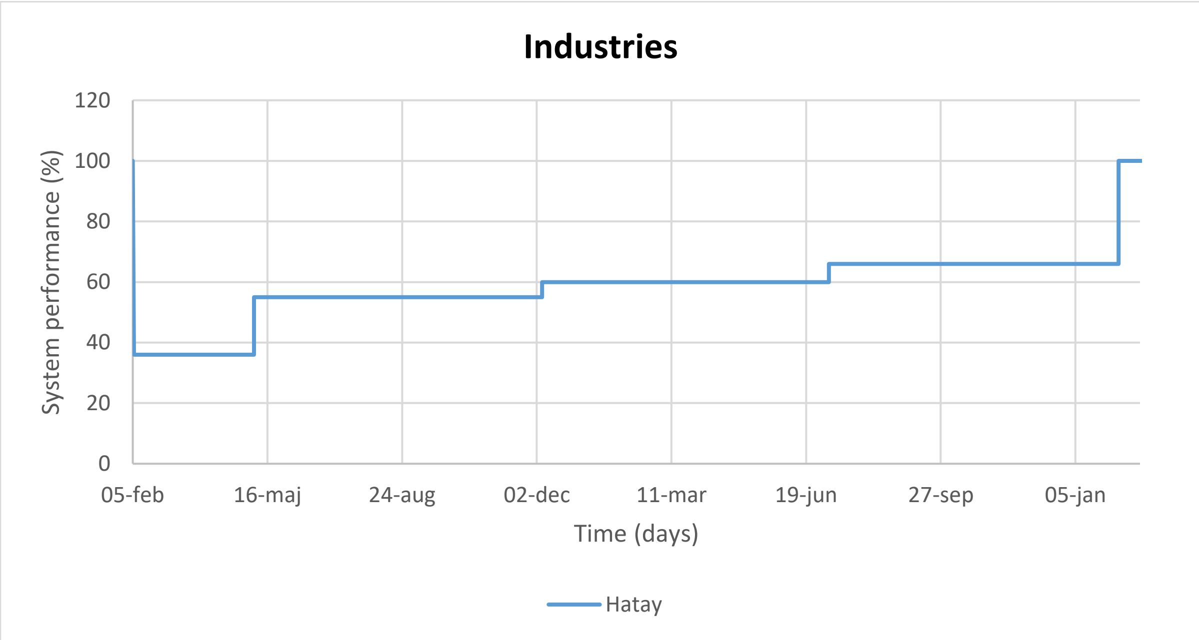


Figure 20. System performance of industries in Hatay

6.6.2. Anticipation

It was reported that some industries had insurance coverage for earthquake-related damage. Additionally, following the 1999 Izmir earthquake Turkey implemented regulations requiring newly constructed industrial facilities to be designed with seismic risks in mind.

6.6.3. Robustness

The earthquakes significantly affected industries, particularly those with inadequate earthquake-resistant building designs. For five of the worst affected provinces, over 33% of industrial facilities either collapsed completely or suffered severe damage. Two weeks after the event, only around 36% of Hatay's industries were still operable.

Many of the heavily affected industries had facilities constructed before 2000 or built later but with poorly reinforced precast concrete. This raises questions about how well recent construction projects have complied to the seismic regulations.

In addition to structural damage, many industries suffered non-structural damage making them inoperable. This includes damage to manufacturing equipment sustained from falling debris or being unsecured and falling over. Furthermore, many industries lacked backup systems, and those not severely damaged from the event could still not operate afterwards due to disruptions in the electricity, natural gas and water supply systems.

6.6.4. Recovery

Industry representatives have indicated that the restoration of damaged facilities could take a long time, with some estimating it could take up to two years to complete. The responsibility for these recovery efforts falls on the industry owners themselves. Given the significant time and expenses involved in the recovery process, coupled with the absence of income during this period, there is a concern that many smaller industries may face bankruptcy. Additionally, some less severely damaged industries faced challenges in resuming operations due to the earthquakes impact on personnel.

6.6.5. Adaptation

There were no direct indications of lessons learned collected from industry managers themselves. However, a field reconnaissance study offered suggestions for improvement, including reassessing buildings constructed before the year 2000, as well as later built precast reinforced concrete structures, to evaluate if further retrofitting is needed. Furthermore, the study noted that many industry owners lacked adequate insurance, highlighting the importance of enhancing business continuity strategies, such as broader insurance coverage, to prepare for a range of potential hazards.

Notes

The calculations of system performance involved several significant assumptions. For instance, it was assumed that all severely damaged industries would take precisely two years to recover sufficiently to resume their operation. This assumption is an oversimplification as it is improbable that all industries would require the same recovery time. Furthermore, some might gradually resume operation as parts of their damaged facilities are restored. that every severe damaged industry would require precisely the same amount of time to recover.

As industries are privately owned, the measures taken for resilience are on their own responsibility. Therefore, it would have been valuable to ask different industry representatives what proactive measures they had taken, what recover efforts they made and what they have learned for future events.

The authors of the reconnaissance study had collected comprehensive data on the severity levels of structural damage to industries in Hatay. Email correspondence was established with these authors, with an agreement that they would share the data later. However, they stopped responding to emails, and no detailed data for Hatay was collected. Consequently, the system performance in Hatay was instead assumed to be the same as the five worst affected provinces combined.

6.7. Telecommunications

6.7.1. System performance

For telecommunications, system performance is assessed as its ability to manage internet and mobile phone traffic, relative to the pre-disaster levels (Figure 21). Calculations relied on data of internet traffic in the regions in the weeks following the earthquakes. It assumes a correlation between changes in internet traffic and the telecommunication operator's ability to provide communication. Exponential functions were used both to extrapolate an estimate recovery time in provinces where data for full traffic recovery was lacking, and to interpolate an estimated the system performance over time for provinces where data for full recovery was collected.

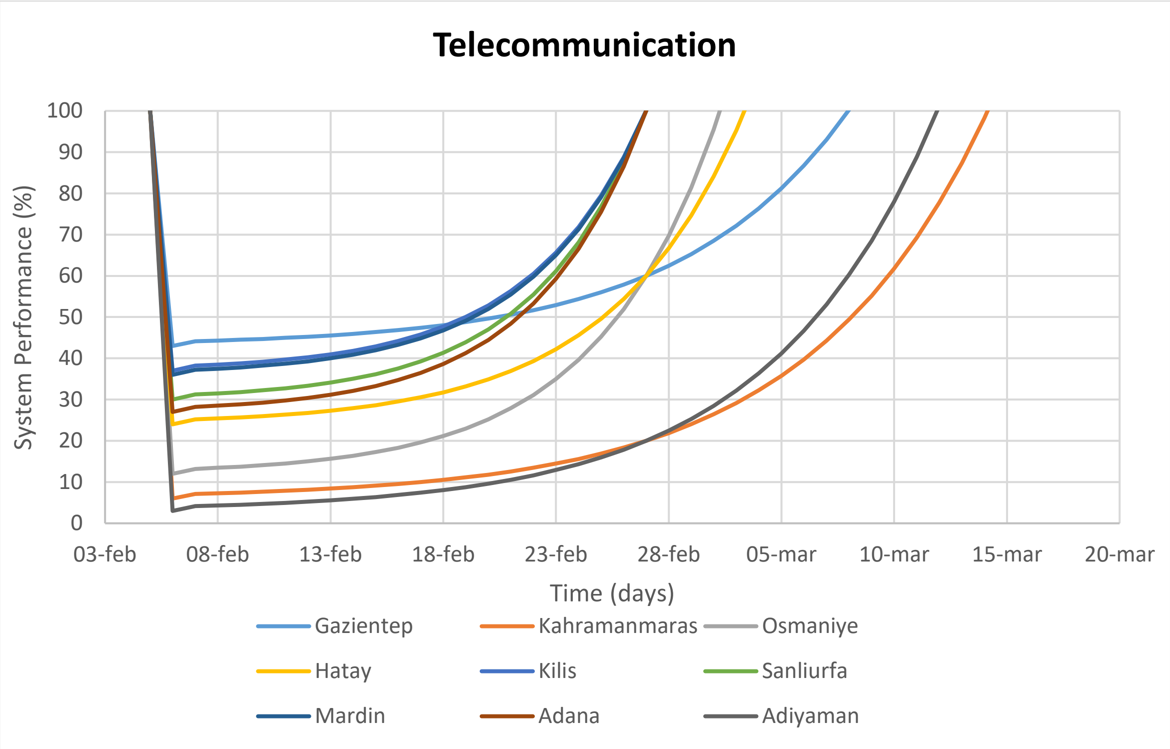


Figure 21. System performance of telecommunications

6.7.2. Anticipation

No data on anticipatory measures was collected.

6.7.3. Robustness

Telecommunications was severely impacted by the earthquakes. A reported 2 451 of the 8 900 telecommunication base stations (28%) located in the 10 affected provinces were disabled after the earthquakes. Many of these were disabled due to power outages, but many also suffered severe damages. For instance, base stations placed on top of buildings were destroyed when the building collapsed. However, the core network services provided by ISPs and MTSOs experienced minimal or no disruptions, allowing them to be operational shortly after the earthquakes.

On the day of the earthquakes, national internet traffic in Turkey dropped to around 80% of its usual levels. The most significant decrease occurred in provinces like Kahramanmaraş, Adiyaman, Hatay and Osmaniye. For instance, internet traffic in Hatay reduced to 24% of its pre-disaster level.

6.7.4. Recovery

To restore the functionality, authorities collaborated with telecom providers and technology companies to install over 400 temporary satellite-connected mobile base stations across the affected regions, with almost half in Hatay. These along with the undamaged stationary base stations, relied on diesel-generators for power. However, the generators could only supply base stations with energy for about 3-4 hours before needing refueling. Due to logistical issues in supplying the generators with fuel, the network experienced unstable connections with frequent disruptions.

Internet traffic in Turkey had mostly returned to normal levels within a week. However, even after three weeks, the system performance in the provinces of Kahramanmaraş, Adiyaman, Hatay and Osmaniye had not yet recovered. Telecommunications in Hatay was mostly restored approximately 27 days after the earthquakes. However, there were reports of extensive disruptions in telecommunications lasting for several months afterwards, particularly in rural areas.

6.7.5. Adaptation

A manager from one of Turkey´s largest telecommunications provider suggested that future installations in densely populated areas should favor smaller, distributed base stations over centralized tower base stations. While tower structures provide great coverage on rural landscapes, their coverage is less efficient in densely populated areas. Furthermore, the manager proposed better assessments for seismic resistance of buildings when selecting sites for base station placement, addressing the current lack of such information. Finally, they expressed a desire for greater prioritization for telecommunication in terms of fuel and electricity supply during disasters and giving telecommunication vehicles traffic priority similar to emergency rescues vehicles, arguing for its importance in society.

Notes

Obtaining direct data to estimate the system performance of telecommunication was challenging, necessitating uncertain assumptions. For instance, extrapolating internet traffic data using an exponential may not be suitable for modelling recovery, since recovery often follows sigmoid pattern with a prolonged tail for the last percentages of recovery. Additionally, assuming a direct correlation between internet traffic and telecommunication system performance could be misguided, as other factors might explain reduced internet traffic. For instance, temporary closure of businesses in the affected region or earthquake-related changes in people's behavior could have affected the internet usage.

6.8. Interdependency assessment

6.8.1. Anticipation

At the national level, no evidence was found of initiatives to coordinate and facilitate identification and management of cross-sectoral interdependencies. None of the national CI protection initiatives, including the CI Protection Roadmap (AFAD, 2014) and the AFAD Strategic Plan (AFAD, 2019), considered interdependencies in their plans for enhancing resilience. Additionally, at the individual CI level, there was no indications of active engagement in identifying and managing dependencies within the risk management and resilience related documentation obtained.

6.8.2. Robustness

Based on observed and assumed interdependencies, see Figure 22, it became evident that electricity was the originator for most interdependencies affecting the robustness of other CIs. While some CIs had prepared for electricity disruptions by implementing reserve generators, it was evident that these generators were not entirely sufficient. They often had a limited capacity, capable of powering only specific parts of the CIs. Additionally, these were primarily designed for short-term, local disruptions, and fuel was in many cases depleted before electricity from the grid was restored, with significant difficulties in fuel supply for many provinces.

Furthermore, industries were observed to have a high level of dependency on other sectors. In many cases, industries could not operate even when they themselves had sustained minimal damage, due to high dependency and little redundancy built into their operations. The responsibility for managing these interdependencies likely rested with the individual industry management, who may have limited knowledge about these interdependencies. Additionally, implementing redundant measures, such as reserve generators, could be expensive, and as a result might have been deprioritized.

6.8.3. Recovery

It was observed that highway and telecommunication operation was important for the recovery of all other CIs (Figure 23). Functional highways were essential for gaining access to sites requiring restoration, while telecommunication was crucial for communicating damage assessments and coordinating recovery efforts. Additionally, many CIs recovery depended on access to fuel, which was necessary for both the machinery and equipment used in the restoration process and for the reserve generators employed to restore the functionality.

6.8.4. Adaptation

After the earthquakes, commissions appointed by the Grand National Assembly of Turkey conducted sector-specific hearings within various CI sectors to better understand the chain of events. During the hearing for the electricity sector, which included electricity production, transmission and distribution operators, numerous concerns were raised related to the electricity sectors dependencies toward other sectors. However, due to the exclusion of the CI sectors from which these dependencies originated in the hearing, these concerns likely stayed within the specific sector, and responsibilities falls on themselves to manage these for future events. This indicates a need for cross-sectoral forums for managing interdependencies.

Notes

The lack of direct contact with various CI representatives and relying solely on secondary sources made it difficult to confirm the existence of specific interdependencies and their impact and required great assumptions. In contrast, if it had been possible to engage representatives in interviews or surveys, they could have provided detailed accounts of how interdependencies materialized, insights in how perception of dependencies changed and adaption made. Additionally, representatives could have assigned the severity grades themselves, which would have allowed for a more precise assessment of their impact on both robustness and recovery.

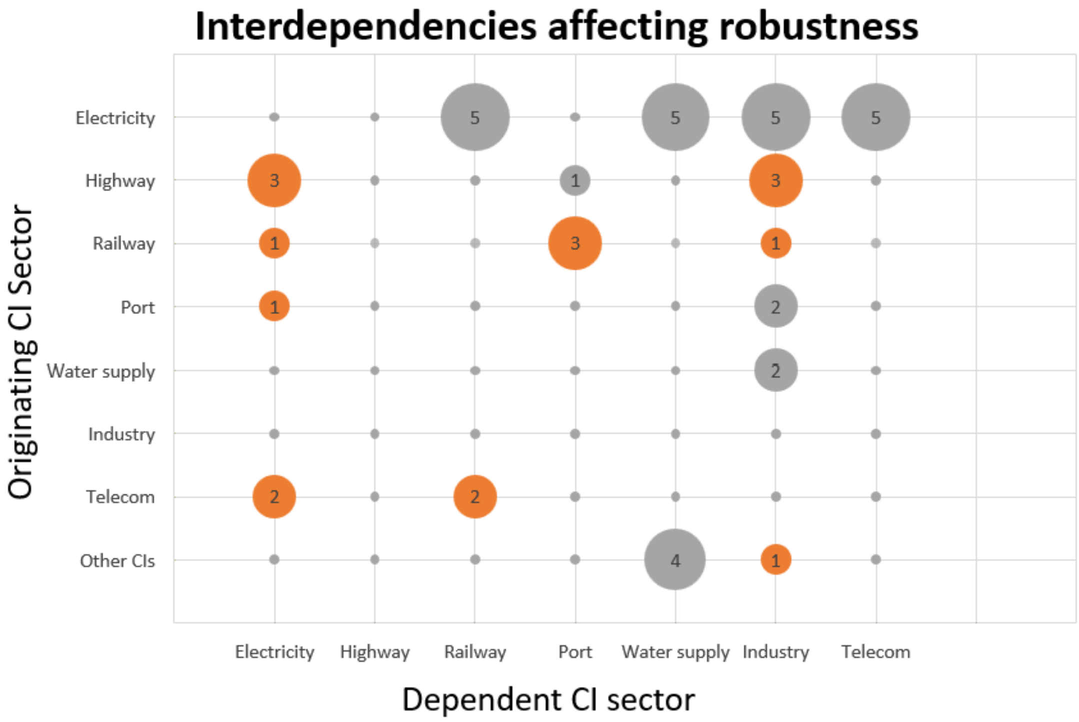


Figure 22. Diagram of interdependencies affecting robustness. The size and number explain the magnitude of interdependencies an a scale 1 to 5. Grey: Interdependencies that were directly observed during the assessment; Orange:Interdependencies not directly observed but observed during previous events and assumed through logical deduction.

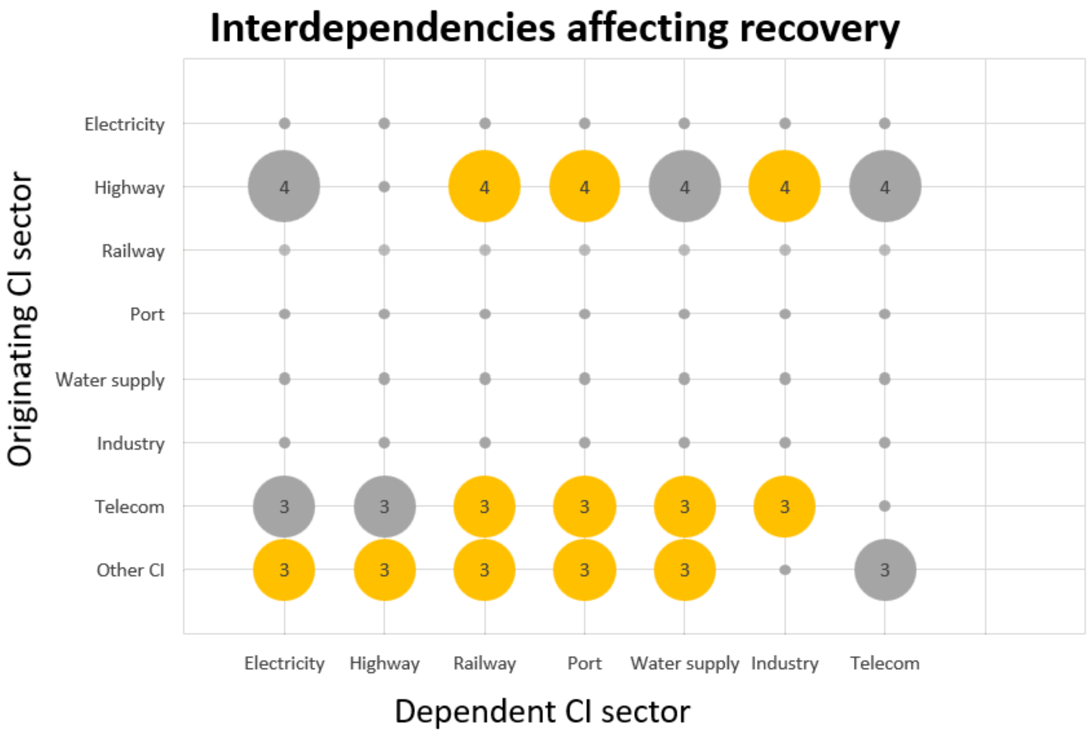


Figure 23. Diagram of interdependencies affecting recovery. The size and number explain the magnitude of these interdependencies an a scale 1 to 5; Grey: Interdependencies that were directly observed during the assessment; Yellow: Interdependencies not directly observed but observed for other CIs during the earthquake, and is assumed through to logical deduction.

6.9. Holistic Resilience assessment

Due to patchy and sometimes limited data from the different provinces, the assessment mainly focused on cross-sector comparisons within the most affected province of Hatay for which also the most comparable data could be collected. The system performance for the respective individual assessments for Hatay are plotted in Figure 24, with calculated values for robustness and recovery in Table 5.

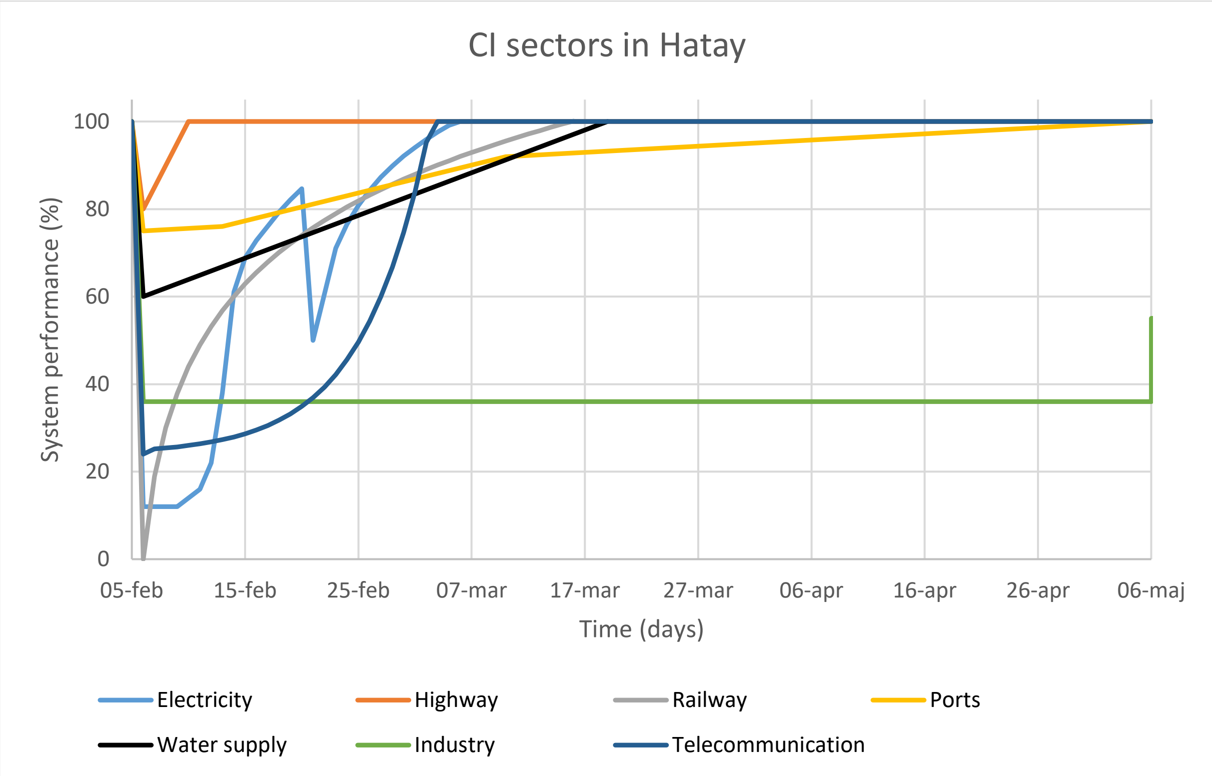


Figure 24. System performance of all CI sectors in Hatay

Table 5 Calculated robustness and recovery for all CI sectors in Hatay; Relative resilience (RR) is calulcated over the first three months after the earhtquake. Green: best; Red: worst.

CI Sector	Robustness	Recovery	RR
Electricity	14%	33 days	88.24%
Highway	80%	5 days	99.44%
Railway	0 %	38 days	89.04%
Ports	75%	89 days (3 months)	90.97%
Water supply	60%	41 days	90.67%
Industry	36%	730 days (2 years)	36.36%
Telecommunication	24%	27 days	83.02%

6.9.1. Anticipation

Due to lack of comprehensive data on anticipation measures, providing a holistic assessment of the overall CI preparedness against disasters is challenging. However, one significant anticipatory measure that cut across various CIs was the implementation of, or lack of, seismic resistance regulations for design of new buildings and retrofitting of existing buildings. It became evident that many CIs buildings did not fully comply with these regulations. This issue of non-compliance was extensively covered in international news media, especially concerning residential buildings and has been cited as a primary reason for the high number of casualties during the event.

6.9.2. Robustness

Table 5 reveals that the railway experienced the most significant sudden loss of functionality after the earthquakes. The railway network has less redundancy, that is alternative routes, compared to the roadway network. Thus, a disruption anywhere on a line between A to B can completely halt operation for the entire line. Additionally, railway transportation is dependent on functioning electricity, not only for powering trains but also for control functions like switches. However, it is noteworthy that the railway lines in Hatay were operational, but for emergency usage only.

The large drop in electricity system performance had a notable observed effect on almost all other CIs. While some CIs had temporary auxiliary power backup solutions, such as reserve generators, they still experienced difficulties in long-term operation until electricity was restored, due to limited personnel for maintenance and restricted access to fuel. This aligns with previous studies (Johansson et al., 2015a; van Eeten et al., 2011), where electricity disruptions has proven to be a dominant initiator of cascading effects in the CI system-of-systems.

6.9.3. Recovery

Road highways were restored relatively quickly as temporary roads could be paved onto or adjacent to damaged sections. In contrast, other CI sectors faced greater challenges in implementing temporary solutions. For instance, the water supply infrastructure had to continuously transport water through tanks, while the telecommunications infrastructure had to establish temporary base stations powered by fuel-driven generators. Table 5 illustrates that nearly all CIs, except for roadway transportation, did not fully recover until electricity was restored. This is unsurprising, given the strong dependency most CIs on electricity for its functionality, with roadway transportation being an exception.

Reports from various CIs highlighted significant difficulties in restoring rural areas following the earthquakes. Issues included disruptions in the rural road network and telecommunication coverage, and a higher priority given to restoring CI functionality in urban areas. This led to slower and less effective recovery efforts in rural areas, leaving some without basic services like water and electricity for months.

All CIs highlighted severe difficulties in mobilizing personnel post-earthquake as a major obstacle to restoring operations. Many personnel lived in severely affected areas, with some losing their lives during the event. Their focus was likely on ensuring the safety of themselves and their families or assisting rescue efforts for neighbors trapped under debris. Furthermore, in Hatay and other severely affected provinces, a significant outmigration occurred, with some estimating upwards of 80% of the population leaving the province due to safety concerns and lack of basic provisions.

The prolonged recovery of industries may significantly impact the societal recovery. Fewer job opportunities may reduce incentives for people who temporarily migrated from cities to return once their homes are deemed safe for living.

6.9.4. Adaptation

As post-event data on operator processes was limited, little was known about the signs of learning and adaptation measures implemented by CI operators. However, the electricity sector emphasized the importance of considering interdependencies to build more redundant systems in the future.

6.10. Case Study reflections

6.10.1. Discussion

The earthquakes had a significant local impact on all CI sectors in the affected provinces, but a relatively limited national-scale impact. Most CIs had returned to their normal operation within a month, which indicates some level of resilience within the system. However, certain sectors, particularly industries, took significantly longer time to recover, potentially years, which could lead to significant societal consequences.

It was evident that disruptions in the electricity supply were the main initiator for cascading events to other infrastructures. Most CIs were in one way or another directly dependent on electricity for their operation. Additionally, disruptions in road transportation and telecommunication disruptions had the most significant impact on the overall system recovery.

6.10.2. Recommendations

Based on the case study findings, there are several measures that could be considered in Turkey to enhance the resilience of CIs at both the individual and the system-of-systems level, including:

1. *Managing dependency on electricity*: Many operators noted a heavy reliance on electricity, and their reserve capacity proved insufficient during prolonged power outages. To address this, they could either add more backup generators, or expand fuel depots for the generators. Additionally, this calls for a higher resource prioritization to build a more robust electricity infrastructure.
2. *Managing dependency on telecommunication*: Operators highlighted dependencies on telecommunication infrastructure for communication and expressed concerns about the need for redundant communication systems. At the individual CI level, this could include adding more satellite telephones within the organization. At a broader systems level, alternative emergency communications systems could be implemented and made readily accessible for CI operators. Additionally, this calls for a higher resource prioritization to build a more robust telecommunication infrastructure.
3. *Overall greater consideration of industries*: As industries were the most affected CI during the earthquakes, and long-term disruptions in this sector could severely affect regional productivity, there is a need to systemically enhance its resilience. This could be achieved by implementing and enforcing seismic resistance regulations more effectively. Additionally, creating better local redundant systems for reserve electricity

generation within organized industrial zones, serving the entire zone rather than placing the responsibility of electricity generation on the individual industry operators.

4. *Addressing bottlenecks in railway system*: The assessment identified a bottleneck within the affected areas railway system, which disruption had national level impact for railway transportation during the earthquakes. Therefore, railway operators should consider whether it is justifiable to have critical bottlenecks situated above fault lines, or if redundancy should be built in the region by creating additional railway connections between cities.
5. *Addressing interdependencies:* The assessment revealed a lack of institutional initiatives for both comprehensively analyzing the event and proactively addressing interdependencies from a CI system-of-systems perspective. It could be beneficial to establish cross-sectoral forums, bringing together stakeholders from various sectors to discuss observed dependencies and collaborate on insights for effective management and planning for interdependencies. Such collaborative system perspective efforts could enable the development of a shared understanding of complex relationships and chain of events during a disaster, including the understanding of cascading effects and higher-order dependencies. Additionally, cross-sectoral forums could help CI operators to clarify their responsibilities during future disasters and what preparatory measures they should undertake. Furthermore, these forums offer insights into which CIs could benefit from stronger partnerships with better cross-sector information-sharing channels, enhancing coordination for future disasters.

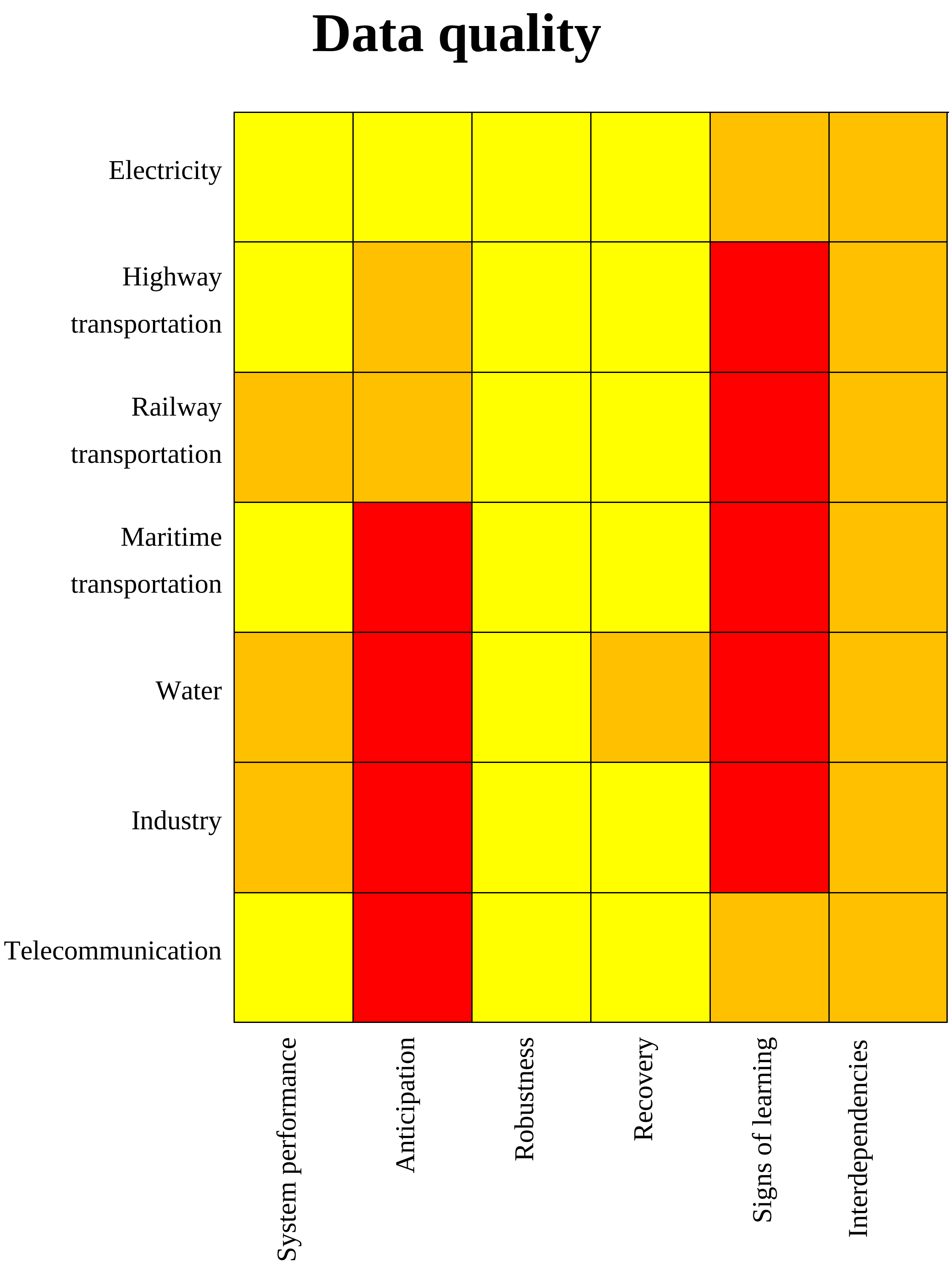
6.10.3. Overall notes on assessment

Conducting the assessment proved challenging due to the limited availability of resilience and interdependency related data from CI operators. The quality of the data used to assess different resilience aspects was evaluated following the criteria detailed in Table 6, and the results for each CIs data quality are presented in Table 7. The results indicate that obtaining adequate data for the aspects of anticipation and adaptation was particularly difficult, resulting in many incomplete assessments. Moreover, none of the collected data could be categorized as high quality, and significant assumptions were required for almost all aspects during the assessment process. Additionally, there were difficulties in acquiring data regarding interdependencies, as this information was not readily available from infrastructures websites, and only briefly mentioned in news articles.

Table 6. Description of different levels of quality on data for assessment

Level	Description
1	• Insufficient or severely lacking data for an assessment. • The assessment results are incomplete or inaccurate.
2	• Data collected is barely sufficient for conducting assessment. • Assessor has to rely heavily on assumptions. • The assessment results can provide indications but are highly uncertain.
3	• Data collected is sufficient for conducting assessment, but its accuracy and reliability are questionable. • Some assumptions had to be made to conduct the assessment. • The assessment results can provide valuable insight but should be approached with careful consideration.
4	• Data collected is highly accurate and reliable and provide a detailed representation of the important aspects used in the HACIRD framework. • Data is collected from firsthand sources or very reliable secondary sources. • Very few and limited assumptions had to be made by the assessor. • Assessment results offer an accurate depiction of the event.

Table 7. Matrix that assess the quality of data obtained for different individual CIs during the assessment. Colors in accordance to Table 6



7. Discussion

The HACIRD-framework enables holistic assessments of the resilience of CI system-of-systems during a disaster, extending prior similar proposed frameworks in the scientific literature. Although its application comes with practical difficulties, the opportunities from using this framework post-disaster make a compelling case for addressing and finding solutions to the practical issues related to data collection and analysis.

7.1. Framework Opportunities

7.1.1. Scientific contributions

The HACIRD framework expands on and integrates previous post-disaster assessment studies. The framework bridges the previous apparent divide of focus on either quantitative or qualitative aspects of CI resilience by encompassing both. For instance, assessments conducted in the more direct aftermath of the disaster (EERI & GEER, 2023; İTÜ, 2023; Sagbas et al., 2023) were primarily qualitative in describing the disasters impact on CIs, lacking extensive quantitative analysis making it challenging to grasp the scale of impact on the system and enabling comparisons across CIs and taking a system-of-system perspective. In contrast, post-disaster resilience assessments conducted much later after the disaster (Cimellaro et al., 2016; Sarkissian et al., 2022) primarily focused on quantitative data to describe the system resilience numerically, lacking in qualitative assessment. By overlooking qualitative aspects, it is difficult to understand how the impact manifested and why the system responded the way it did. By combining both quantitative and qualitative aspects, the HACIRD-framework provides an approach which leaves the crucial qualitative aspects necessary for understanding how the event unfolded, while still producing comparable quantitative results.

Additionally, the conceptualization of resilience as anticipation, robustness, recovery and adaptation provides a clear structure for studying the hazard impact and measures done before, during and after a specific disaster. However, its focus might make it more suitable for assessing specific disasters rather than a continuous long-term resilience processes. While this concept has been explored previously (Rød & Johansson, 2023), its application to a real disaster has not been done before. The case study application demonstrated how this conceptualization makes sense for studying systems during distinct events with great potential for providing valuable insights into the system resilience of CIs during disasters.

The framework combines methodologies for assessing interdependencies from previous studies. For instance, McDaniels et al. (2007a) proposed a methodology to investigate interdependencies during a specific event, but focused specifically on the dependencies of other CIs on electricity. In contrast, van Eeten et al. (2011) and Johansson et al. (2015a) examined interdependencies within the entire CI system-of-systems but not focused on a specific disaster event, rather analyzing the most commonly observed interdependencies across many disruptive events. The HACIRD framework integrates these two approaches to combine a holistic perspective, encompassing all types of interdependencies, with the focus of a specific event.

Additionally, the framework introduces a novel concept, viewing interdependencies as forces impacting other CIs inherent robustness or recovery. This framing aligns with the resilience concept used in the framework, assessing robustness and recovery at both an individual and holistic level, and enables a clearer integration of individual CI assessments with the interdependency assessment. However, it is important to note that this is only a way to conceptualize the impact of interdependencies. Determining the inherent resilience of CIs would require knowledge of the systems performance without the dependencies on other CIs, which is in essence practically impossible.

The HACIRD framework, if applied to multiple disasters, can yield valuable scientific insights. As Ouyang (2014) points out, empirical assessments can provide important insights into how different contexts and types of hazards affect the impact experienced by CIs. For instance, it can highlight how proactive and reactive measures implemented differs between the global north and south, and how it affects CI resilience. Additionally, it could address whether certain types of hazards trigger more cascading effects, and if some hazards have greater impact on system recovery while others have more impact on robustness. Furthermore, it may unveil previously unnoticed interdependencies that become evident during a specific disaster.

7.1.2. Input for predictive tools

The results of assessments with the HACIRD framework valuable insights that can be used to organizations in disaster planning. For instance, data from previous disaster assessments could be used for decision-making tools to identify where investment should be allocated to make the system more resilient (Anderson et al., 2020). Furthermore, it could be used to validate accuracy of results from simulation models of critical infrastructures performance during disaster-scenarios (Johansson & Hassel, 2010). Additionally, it could be used for real-time tools to be applied during a disaster to estimate the magnitude and recovery times of CI service disruptions (Guikema et al., 2014). This could enable relief organizations to plan their logistics more effectively, such as the number of generators or fuel tanks required.

As noted by Anderson et al. (2020), previous empirically based tools have encountered limitations, often overlooking interdependencies and qualitative aspects including anticipatory activities. Additionally, they tend to rely heavily on detailed input information from specific CI operators, making them less generalizable to areas where such data have not been collected. The HACIRD framework has the potential to address these shortcomings by integrating quantitative and qualitative data, interdependencies and having both an individual infrastructure and system-of-system-level focus. When applied to numerous events across different contexts, it could serve as input data for more comprehensive and generalized tools, which could be used even for contexts where not all variables are known.

7.1.3. Input for preparedness exercises

To plan for emergencies, it is common for various entities within society to engage in preparedness exercises. For instance, the highway operator in Turkey engaged in multiple disaster preparedness exercises annually (KGM, 2022a). These exercises serve various purposes, including management training and revision of general preparedness plans or hazard-specific contingency plans.

To effectively conduct preparedness exercises, it is crucial to work with realistic scenarios, which include consideration of dependencies among actors (Abrahamsson et al., 2007). The results obtained through the application of the HACIRD framework can provide valuable input data for creating scenarios that realistically depict what can be expected in terms of performance of different CIs, their interdependencies, and the CI system-of-systems during an event, both quantitatively and qualitatively.

7.1.4. Post-disaster sensemaking

The HACIRD framework can enable better sensemaking of events post-disaster. Through its systematic assessment of anticipation, robustness, recovery and adaptation for individual CIs, their interdependencies and the system-of-systems, the framework can provide better joint understanding of the course of events for all actors involved.

For individual CI operators, the assessments offer insights into interdependency related vulnerabilities affecting their system, which could incentivize collaboration with other CI sectors and adoption of adaptive measures. For instance, the assessment conducted above demonstrated interdependencies between telecommunication and electricity, where telecommunication depended on electricity infrastructure for operation, while electricity depended on telecommunication for recovery. Demonstrating how highly coupled pairs of CI sectors are could encourage them to consider closer collaboration and information-sharing.

Additionally, assessments provide individual CIs with insight into the challenges faced by the CIs they depend on in maintaining system performance during a disaster and their likely behavior in future disasters. Consequently, CI operators may decide to increase their own redundancy for services provided by specific CIs demonstrating vulnerability for different disasters. For instance, CIs dependent on electricity might consider implementing additional reserve generators or stockpile more generator fuel to prepare for even longer power outages.

For governing institutions, post-disaster resilience assessments can provide opportunity of identifying systemic vulnerabilities within and across the system, and recognize areas where legislative, regulatory, and institutional improvements could be necessary. Governance structures related to holistic CI resilience and interdependencies has notoriously often been stuck in deadlocks regarding what institutions should be responsible for the governance, and how to navigate the complexities of coordination with the existing responsibilities of different agencies (European Commission, 2020). Disasters typically create windows of opportunities for change and build back better (der Sarkissian et al., 2021), and implementing the HACIRD framework can help highlight systemic issues. This could promote a prioritization of better governance structures for CI resilience and interdependencies, as for example recommended by OECD (2019).

7.2. Data collection issues

Conducting the assessment revealed a restricted availability of high-quality data. In Turkey, as in many other countries, there is currently no formal incentive for CI operators to gather and provide data for the purpose of being used in a comprehensive system-of-systems analysis. Consequently, the responsibility of collecting and comparing data falls on the assessor themselves, resulting in the following challenges.

7.2.1. Uncomplete data

To accurately conduct cross-sector comparisons, it is crucial to obtain comprehensive data. In the case study, there seemed to be more anticipatory measures in the electricity sector compared to others, suggesting better preparedness. However, this discrepancy might result from incomplete data obtained for the assessment. Nonetheless, an apparent lack of data for an aspect should not be ignored. Instead, it is important to involve CI operators when conducting assessments as they could clarify apparent lack of information, and maybe provide the assessor with missing data.

7.2.2. Access to firsthand sources

To accurately assess CI performance and responses, it is essential to gather data from operators directly. These sources can provide valuable insights and validate the assumptions previously made by the assessor. However, engaging these representatives can be challenging, which became evident early on in this thesis as the author is from Sweden- and the Turkish contact from Istanbul, with limited connections in the affected area. Engaging representatives requires their interest in the assessment purpose and to participate in interviews or supplying data. During this thesis work, many emails were sent to each infrastructure sector asking for data on disruptions, but only KGM replied. Consequently, the quality of the assessments can vary greatly depending on the assessor’s ability to engage relevant stakeholders during the assessment process.

7.2.3. Biased data sources

As mentioned by Ouyang (2014), empirical assessments relying on secondary sources, such as news articles or public statements from operator representatives, can suffer from reporting bias, as certain aspects of resilience or interdependencies might be underreported even though it has a crucial role. These biases could for example stem from the agenda of the reporter or representative. In the case study it was observed that representatives of infrastructure operators often presented an idealized picture of its performance and its response efforts, aimed at portraying a positive image of its organization. In contrast, news outlets with political stances opposing the current Turkish government, such as those with socialist and Kurdish affiliations, frequently reported about states of functionality that contradicted the official accounts. For instance, in Hatay where the official statement claimed that water supply was largely fully operational a few months after the earthquakes, contradictory news reports revealed that many households were still without water more than half a year later.

Another issue is regarding the transparency of operators after a major disaster. Out of fear of being held accountable, or due to attribution biases, operators might tend to overstate their contributions to positive results and shift blame for shortcomings onto other entities (Johnson & Levin, 2009). In Turkey for instance, statements of one Vodafone executive blamed the problems in power, transportation and fuel infrastructure as explanations for its own infrastructures instability and ineffectiveness in response following the earthquakes.

7.3. Data analysis issues

7.3.1. Biased assessor

One weakness of previously conducted empirical assessments of disasters is that no standardized methodology was used (Ouyang, 2014). Due to ambiguities and limited availability of data, the assessors must do several assumptions when processing and analyzing data. For example, for the case study in this thesis, functionality data for internet traffic was only available for the first few weeks, and an exponential function was used to extrapolate the recovery. This assumption of recovery following an exponential function lacks a clear basis, and another assessor would likely do it differently, resulting in another recovery. Thus, when data is scarce, much interpretations and assumptions are left to the assessor, leading to subjective result.

7.3.2. Comparability issues

A challenge in assessment is how to consider geographically different administrative borders for individual CIs in cross-sectoral comparisons. In the case study, some CIs were administratively delimited within provinces, such as municipal water infrastructure or industries, while others stretched over multiple provinces, such as electricity and highway networks. Hence, for example, conducting provincial cross-sectoral comparisons becomes difficult if not all CI sectors have data on their systems response within the specific province of interest.

There are also uncertainties in how to consider differences in types of services provided by CIs for cross-sectoral comparisons. For example, in the case study, the railway lines in Hatay remained operational but only for emergency use. This highlights a need to consider whether it is the ability to provide services through the physical system or the ability to satisfy the customer demand of services as intended that should be measured. Clarifying the measurement from the outset and maintaining consistency throughout the assessment is necessary to yield comparable results.

7.3.3. Complex interactions

Simplifying complex system interactions can result in great analytical sacrifices. For instance, disasters like the 2023 Kahramanmaraş earthquakes, can lead to mass population movement, changing demand for CI services. In heavily affected provinces like Hatay, post-earthquake mobility data indicated a population decline of around 80% (Lewis, 2023), resulting in an increase in demand for neighboring unaffected provinces. Paradoxically, this may indicate lower relative resilience for unaffected compared to affected provinces (Figure 25). However, ignoring shifting demands in the assessment makes it challenging to determine whether poor system performance is due to shifting demands or poor resilience. Furthermore, population movements are likely temporary, and many individuals are expected to return after reconstruction. This raises further questions about how demand changes should be accounted for.

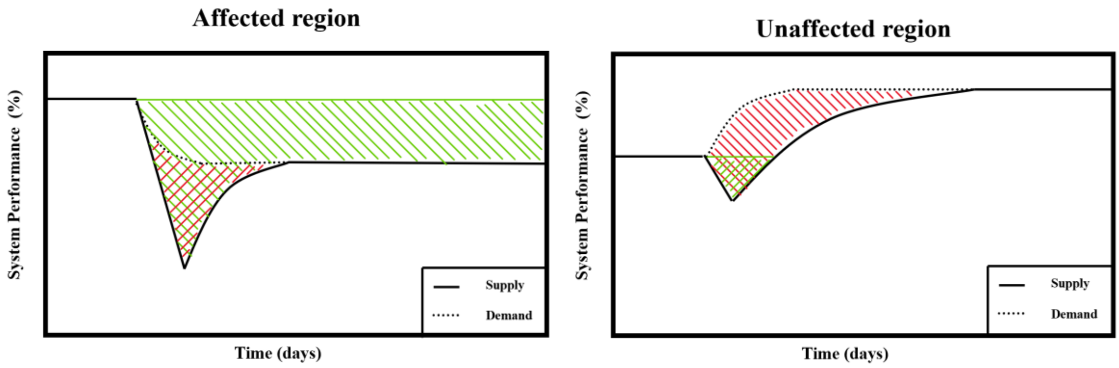


Figure 25. System performance in a situation were residents from an affected region have migrated to an unaffected region. The red area demonstrates the loss of system performance if shifting demands are being considered, and green area demonstrates if they are not taken into account.

Another challenge is deciding how to include temporary restoration efforts in the assessment of system performance. For instance, should the resilience of water infrastructure only be assessed based on its ability to deliver water through its usual fixed infrastructure, or should temporary solutions like tank trucks also be considered? Even though the water distribution were restored rather quickly in some provinces in Turkey, concerns were raised about the safety to drink the water due to risk of contamination. Instead, drinking water was supplied by tank trucks, and neglecting this makes it difficult to assess the system's ability to provide drinking water as intended. However, including solutions outside the fixed infrastructure complicates the quantification of system performance. It becomes challenging to differentiate the contribution made by the water distribution infrastructure from that of other relief organizations to provide inhabitants with water. Collecting data on the quantity of services distributed through the infrastructure is likely to be much simpler than obtaining data on demand met. Furthermore, assessing service availability, rather than the service distribution via the CI system, could portray the CI operator's resilience inaccurately.

7.4. Framework application recommendations

Given the challenges discussed earlier in applying the framework to real events, this section will offer recommendations for its effective application.

7.4.1. When should assessments be conducted?

Before starting the assessment of an event, it is important to consider whether the timing is appropriate. The case study revealed that conducting assessments relatively shortly after an event can be challenging. While CI operators possess valuable information, it often takes them some time to formalize this into comprehensive reports. Many of the operators released annual reports on their websites, outlining their activities over the course of the year. However, at the time of writing, none of them had published their annual report for 2023. Additionally, waiting some time could provide the opportunity of including more adaptive measures that were implemented after the event in the assessment. Furthermore, contacting operator managers shortly after a disaster to participate can be difficult as they are likely occupied with post-disaster activities. However, their recollection of details is likely to be more accurate and less distorted relatively soon after the event. Considering these factors, the ideal assessment timeframe is likely around 1-2 years after the event. This allows for numerous reports to be published, while the memories of the participating CI managers are still fresh and reliable.

7.4.2. Who should perform the assessment?

In practice, individual CI assessments should ideally be conducted by the operators themselves, as they possess better access to detailed data and a deeper contextual understanding of their operations. Additionally, it allows CI operators to gain a better understand of their system during the event and facilitate the development of action plans for improved future preparedness. However, as discussed above, CI operators might provide a somewhat biased recollection of the disaster. These individual assessments could then be used by an external actor, e.g. governmental agencies, for assessing the holistic CI resilience.

If CI operators cannot perform the assessment themselves, it is important for the assessor to be able to establish a good network within the area of interest before conducting the assessment. As shown in the case study, establishing contact with local CI operators without existing connections can be challenging. While certain aspects, like robustness and recovery can somewhat be estimated from online resources, aspects of interdependencies, anticipation and adaptation require direct interaction with CI operators to assess.

7.5. Future research and development

This section explores ideas for future research and further development of the framework.

7.5.1. Application to other events

To validate the HACIRD framework's suitability to assess resilience during disasters, it should be applied to a wider range of events. This broader application would help to determine the framework effectiveness in comparing and contrasting resilience across different contexts and types of disaster scenarios. Additionally, to make the frameworks result valuable for tools, a comprehensive database including data encompassing qualitative and quantitative aspects of resilience for many different events would be necessary.

Applying the framework in multiple disaster scenarios could also address whether the framework is better suited for certain types of events. For example, it may be more suitable for assessing sudden impact events like earthquakes than prolonged events like heat waves. Additionally, it could provide insight into the effectiveness of different data collection strategies, which could help to concretize a methodology.

7.5.2. Concretize the framework into a methodology

Developing a standardized methodology based on the HACIRD framework would ensure that data collection and calculations consistently follow a similar procedure during its application. Here the presented case study could be used as a basis (Section 5). This methodology should be simple and applicable to cases with limited data, while still allowing as much high-quality data as possible into the assessment.

When developing a methodology, the potential for quantifying more qualitative aspects could be explored. For instance, if qualitative aspects could be quantified through checklists, for assessors to fill in. This could offer the advantage of generating measurable and comparable results and could enable analysis of correlations between quantitative aspects and system performance. However, it may introduce ambiguity for observed attributes that do not clearly fit into the checklist categories, requiring the assessor's judgement to determine whether the attribute should be included or excluded. This could potentially risk increasing subjectivity in the results.

7.5.3. Study incentives for CI operator participation

To improve the framework's effectiveness, understanding the incentives that motivate CI operators to partake in this type of actions is crucial. These insights can help identify ways to encourage greater engagement and participation in comprehensive resilience and interdependency assessments. For instance, examinations of how different CI operators currently approach resilience and assessments following disastrous events could identify areas where operators typical practices align with the framework. Additionally, the disadvantages perceived by operators of sharing data for holistic assessment and strategies for managing these perceived obstacles could be explored.

Furthermore, future studies should examine the incentives that motivate CI sectors to engage in cross-sectoral collaboration for assessing resilience and interdependencies. For instance, previous research conducted on Swedish CIs found that operators were more inclined to participate in cross-sectoral activities when they recognized that their dependencies could result in costly disruptions in the future (Sonesson et al., 2021). The study found that disasters can create incentives as they provide insights into the severity of dependency impacts. Additionally, operators were found more willing to engage in cross-sectoral activities when these were funded by external parties, or if they saw how the collaboration could potentially benefit themselves financially or efficiently. In conclusion, it is important to determine whether self-interest alone is sufficient for operators to participate in the assessment process or if institutions should create additional incentives, such as regulations or financial means. By further exploring these factors the framework and its application process can be better tailored to address these considerations.

7.5.4. Study areas where HACIRD application result could be valuable

To justify the efforts put into conducting post-disaster resilience assessments, it is essential to explore how the results could benefit different stakeholders. For CI operators, it is possible that there are aspects that the current framework does not cover but which would be valuable for them to know after a disaster. Other stakeholders like civil defense institutions or relief organizations may find the assessment results more valuable for certain activities they undertake compared to others. For instance, the results may be more useful for conducting realistic simulation exercises than for predicting system performance in future events. By investigating these factors, the framework can be refined to be more goal-oriented, with specific purposes of the results in mind.

8. Conclusion

This master's thesis set out to develop a framework for assessing infrastructure resilience and interdependencies after a disaster and apply it to the 2023 Kahramanmaraş earthquakes in Turkey to draw empirical findings. Four research questions (Q1-Q4) was outlined for investigation, see Section 1.3.

Q1: A framework was developed to *Holistically Assess Critical Infrastructure Resilience during Disasters* (HACIRD), expanding on and integrating previous scientific research. It assesses the systems resilience holistically by integrating assessments for individual CIs resilience with a holistic interdependency assessment. Resilience is assessed quantitatively and qualitatively of both individual CIs and the system-of-systems, regarding their anticipation, robustness, recovery, and adaptation against the disaster.

Q2: The case study found that the earthquakes had a relatively small national-level effect on CIs in Turkey, however on a local-level the effects were significant. The highways demonstrated a greater robustness and recovery compared to other CIs. In contrast, industries in the affected provinces suffered extensive damage and depended greatly on the functionality of other CIs, resulting in very long recovery times. Additionally, electricity had the greatest interdependent effect on the robustness of other CIs, while highway and telecommunication had the greatest effect on the recovery efforts of other CIs.

The assessment analysis concluded that there were observed indications of resilience in the Turkish CI system-of-systems during the earthquakes. However, it also identified areas for system improvement, including:

1. *Managing dependencies on electricity*
2. *Managing dependencies on telecommunication*
3. *Overall greater consideration of resilience in industries*
4. *Addressing bottlenecks in railway system*
5. *Better managing interdependencies through cross-sectoral forums*

Q3: Application of the framework faced many challenges. Obtaining detailed and reliable data from various CIs was challenging, due to limitations like a weak contact network in the affected areas, biases in data, and incompleteness in data. Analyzing the data were also challenging, due to having to make subjective assumptions affecting the results, or issues regarding how different CI sectors can be compared against each other, as well as how complexities such as shifting demands due to the earthquake should be considered. To address some of these challenges when applying the framework, this thesis recommends conducting the assessment at an appropriate time after the disaster. The assessor should also have prerequisites for establishing a network with relevant CI operators and encourage individual CI operators to carry out as much as possible of the individual assessments themselves.

Q4: The HACIRD framework has potential to help various stakeholders gaining a better understanding of the chain of events after a disaster by offering operators with insights into their dependencies and providing governing institutions with insights into system vulnerabilities. Additionally, the HACIRD results could serve as input data for planning tools, predictive modelling and simulation efforts, and more realistic exercises, in the end contributing to improved system CI resilience and better disasters preparedness.

9. References

9.1. Literature Review

9.1.1. Structured Literature Search

Aghababaei, M. T. S., Costello, S. B., & Ranjitkar, P. (2021). Measures to evaluate post-disaster trip resilience on road networks [Article]. *Journal of Transport Geography*, *95*, Article 103154. https://doi.org/10.1016/j.jtrangeo.2021.103154

Alberto, Y., De La Llera, J. C., Aguirre, P., Monsalve, M., & Molinos, M. (2022). Comparative Qualitative and Quantitative Analyses of the Seismic Performance of Water Networks during the Maule 2010, Christchurch 2010-2011, and Tohoku 2011 Earthquakes [Article]. *Journal of Water Resources Planning and Management*, *148*(4), Article 04022004. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001520

Cimellaro, G. P., Solari, D., & Bruneau, M. (2014). Physical infrastructure interdependency and regional resilience index after the 2011 Tohoku Earthquake in Japan [Article]. *Earthquake Engineering and Structural Dynamics*, *43*(12), 1763-1784. https://doi.org/10.1002/eqe.2422

Cimellaro, G. P., Tinebra, A., Renschler, C., & Fragiadakis, M. (2016). New Resilience Index for Urban Water Distribution Networks [Article]. *Journal of Structural Engineering (United States)*, *142*(8), Article 4015014. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001433

Kammouh, O., Cimellaro, G. P., & Mahin, S. A. (2018). Downtime estimation and analysis of lifelines after an earthquake [Article]. *Engineering Structures*, *173*, 393-403. https://doi.org/10.1016/j.engstruct.2018.06.093

Kong, J., Zhang, C., & Simonovic, S. P. (2021). Optimizing the resilience of interdependent infrastructures to regional natural hazards with combined improvement measures [Article]. *Reliability Engineering and System Safety*, *210*, Article 107538. https://doi.org/10.1016/j.ress.2021.107538

Lam, C. Y., & Shimizu, T. (2021). A network analytical framework to analyze infrastructure damage based on earthquake cascades: A study of earthquake cases in Japan [Article]. *International Journal of Disaster Risk Reduction*, *54*, Article 102025. https://doi.org/10.1016/j.ijdrr.2020.102025

Ma, J., Chen, G., Zeng, T., Zhou, L., Zhao, J., & Zhao, Y. (2023). Methodology for Resilience Assessment of Oil Pipeline Network System Exposed to Earthquake [Article]. *Sustainability (Switzerland)*, *15*(2), Article 972. https://doi.org/10.3390/su15020972

Mühlhofer, E., Koks, E. E., Kropf, C. M., Sansavini, G., & Bresch, D. N. (2023). A generalized natural hazard risk modelling framework for infrastructure failure cascades [Article]. *Reliability Engineering and System Safety*, *234*, Article 109194. https://doi.org/10.1016/j.ress.2023.109194

Osei-Kyei, R., Almeida, L. M., Ampratwum, G., & Tam, V. (2022). Systematic review of critical infrastructure resilience indicators [Review]. *Construction Innovation*. https://doi.org/10.1108/CI-03-2021-0047

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems [Review]. *Reliability Engineering and System Safety*, *121*, 43-60. https://doi.org/10.1016/j.ress.2013.06.040

Qiang, Y., & Xu, J. (2020). Empirical assessment of road network resilience in natural hazards using crowdsourced traffic data [Article]. *International Journal of Geographical Information Science*, *34*(12), 2434-2450. https://doi.org/10.1080/13658816.2019.1694681

Shafieezadeh, A., & Ivey Burden, L. (2014). Scenario-based resilience assessment framework for critical infrastructure systems: Case study for seismic resilience of seaports [Article]. *Reliability Engineering and System Safety*, *132*, 207-219. https://doi.org/10.1016/j.ress.2014.07.021

Shubandrio, F. D., El-Maissi, A. M., Kassem, M. M., Masrilayanti, M., Rahmat, S. R., & Mohamed Nazri, F. (2022). Evaluating the Interdependencies of Infrastructure Critical Systems during Earthquake Event: A Case Study for Padang City [Article]. *Sustainability (Switzerland)*, *14*(23), Article 15926. https://doi.org/10.3390/su142315926

Zorn, C. R., & Shamseldin, A. Y. (2016). Quantifying directional dependencies from infrastructure restoration data [Article]. *Earthquake Spectra*, *32*(3), 1363-1381. https://doi.org/10.1193/013015EQS015M

9.1.2. Unstructured Literature Search

Almaleh, A. (2023). Measuring Resilience in Smart Infrastructures: A Comprehensive Review of Metrics and Methods. *Applied Science*. https://doi.org/10.3390/app13116452

Johansson, J., Cedergren, A., Arvidsson, B., Svegrup, L., Hassel, H., & Jangefelt, J. (2015a). Cascading Effects in Past Events – A Database Structured Around Originators and Dependencies, Deliverable. In *Modelling of dependencies and cascading effects for emergency management in crisis situations (CascEff)*. Lund University.

Johansson, J., & Hassel, H. (2010). An approach for modelling interdependent infrastructures in the context of vulnerability analysis. *Reliability Engineering & System Safety*, *95*(12), 1335-1344. https://doi.org/10.1016/j.ress.2010.06.010

Johansson, J., Jonason Bjärenstam, R., & Axelsdóttir, E. (2018). Contrasting Critical Infrastructure Resilience from Swedish Infrastructure Failure Data. *ESREL 2018*.

Luiijf, E., Nieuwenhuijs, A., Klaver, M., van Eeten, M., & Cruz, E. (2009). Empirical Findings on Critical Infrastructure Dependencies in Europe. *In International Workshop on Critical Information Infrastructures Security (pp. 302-310). Berlin, Heidelberg: Springer Berlin Heidelberg.* https://link-springer-com.ludwig.lub.lu.se/chapter/10.1007/978-3-642-03552-4_28

McDaniels, T., Chang, S., Peterson, K., & Mikawoz, J. (2007a). Empirical Framework for Characterizing Infrastructure Failure Interdependencies. *Journal of Infrastructure Systems*, *13*(3). https://doi.org/10.1061/(ASCE)1076-0342(2007)13:3(175)

McDaniels, T., Chang, S. E., Mikawoz, J., & Peterson, K. (2007b). Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. *Natural Hazards*, *41*, 337-358. https://doi.org/10.1007/s11069-006-9039-4

Sarkissian, R. d., Cariolet, J.-M., Diab, Y., & Vuillet, M. (2022). A holistic approach to assess the systemic resilience of critical infrastructures: Insights from the Caribbean island of Saint-Martin in the aftermath of hurricane Irma. *United Nations Office for Disaster Risk Reduction*. https://www.undrr.org/publication/holistic-approach-assess-systemic-resilience-critical-infrastructures-insights

van Eeten, M., Luiijf, E., Nieuwenhuijs, A., & Klaver, M. H. A. (2011). The State and the Threat of Cascading Failure Across Critical Infrastructures: The Implications of Empirical Evidence from Media Incident Reports. *Public Administration*, *89*(2), 381-397. https://doi.org/10.1111/j.1467-9299.2011.01926.x

9.2. Other Literature

Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32008L0114

Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022L2557

Abrahamsson, M., Johansson, H., Fredholm, L., Eriksson, K., & Jacobsson, A. (2007). Analytical Input to Emergency Preparedness Planning at the Municipal Level – A Case Study. *Lund University*.

Alexander, D. E. (2013). Resilience and disaster risk reduction: an etymological journey. *Natural Hazards and Earth System Sciences*, *13*, 2707–2716. https://doi.org/10.5194/nhess-13-2707-2013

Anderson, K., Hotchkiss, E., Myers, L., Stout, S., Grue, N., Gilroy, N., Aldred, J. R., & Rits, M. (2020). After the hurricane: Validating a resilience assessment methodology. *International Journal of Disaster Risk Reduction*, *51*. https://doi.org/https://doi.org/10.1016/j.ijdrr.2020.101781.

Becker, P. (2014). Resilience — From Panacean to Pragmatic. In *Sustainability science : managing risk and resilience for sustainable development* (pp. 149-176). Elsevier Science Ltd.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., & Winterfeldt, D. V. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, *19*(4), 733-752.

Chodosh, S. (2017). How to make sewage drinkable. *Popular Science*. https://www.popsci.com/wastewater-cycle/

der Sarkissian, R., Dabaj, A., Diab, Y., & Vuillet, M. (2021). Evaluating the implementation of the “build-back-better” concept for critical infrastructure systems: Lessons from saint-martin’s island following hurricane irma. *Sustainability*, *13*(6). https://doi.org/10.3390/su13063133

Ertem, H., & Velibeyoglu, K. (2020). A Review on Critical Infrastructure and Its Applications. *Conference: 2nd International Disaster & Resilience Congress (IDRC 2020): Resilience of/in Megaregions*. https://www.researchgate.net/publication/353326512_A_Review_on_Critical_Infrastructure_and_Its_Applications

EUR-Lex. (2006). *European Programme for Critical Infrastructure Protection*. https://eur-lex.europa.eu/EN/legal-content/summary/european-programme-for-critical-infrastructure-protection.html

European Commission. (2006). *Critical infrastructure*. https://home-affairs.ec.europa.eu/pages/page/critical-infrastructure_en

European Commission. (2020). *Evaluation study of Council Directive 2008/114 on the identification and designation of European critical infrastructures and the assessments of the need to improve their protection: Final report*. https://data.europa.eu/doi/10.2837/864404

Guikema, S. D., Nateghi, R., Quiring, S. M., Staid, A., Reilly, A. C., & Gao, M. (2014). Predicting hurricane power outages to support storm response planning. *Ieee Access*(2), 1364-1373. https://ieeexplore-ieee-org.ludwig.lub.lu.se/stamp/stamp.jsp?arnumber=6949604&tag=1

Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). Lifelines: The Resilient Infrastructure Opportunity. *Sustainable Infrastructure;. © Washington, DC: World Bank.* http://hdl.handle.net/10986/31805

Johansson, J., Hassel, H., Cedergren, A., Svegrup, L., & Arvidsson, B. (2015b). Method for describing and analysing cascading effects in past events: Initial conclusions and findings. *ESREL 2015, Zürich, Switzerland*.

Johnson, D., & Levin, S. (2009). The Tragedy of Cognition: Psychological Biases and Environmental Inaction. *Current Science*, *97*(11), 1593-1603.

Karabacak, B., & Ozkan, S. (2009). *Critical Infrastructure Protection Status and Action Items of Turkey* International Conference on eGovernment Sharing Experience, Antalaya, Turkey. https://fuse.franklin.edu/facstaff-pub/40/

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Annals of internal medicine*, *151*(4), 264-269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

NATO. (2019). *Resilience: the first line of defence*. NATO review. https://www.nato.int/docu/review/articles/2019/02/27/resilience-the-first-line-of-defence/index.html

NATO. (2023). *NATO member countries*. https://www.nato.int/cps/en/natohq/topics_52044.htm

Naucodie, F. (2014). Critical Infrastructure Protection: The EU Perspective. *IOS Press*. https://doi.org/10.3233/978-1-61499-357-5-13

OECD. (2017). Report on the implementation of the recommendation of the council on the governance of critical risks - Turkey. https://www.oecd.org/gov/risk/risk-governance-country-factsheet-turkey.pdf

OECD. (2019). Good Governance for Critical Infrastructure Resilience. *OECD Reviews of Risk Management Policies, OECD Publishing, Paris*. https://doi.org/10.1787/02f0e5a0-en

OECD. (2023). *Who we are*. OECD. https://www.oecd.org/about/

Park, J., Seager, T. P., Rao, P. S. C., Convertino, M., & Linkov, I. (2013). Integrating Risk and Resilience Approaches to Catastrophe Management in Engineering Systems. *Risk Analysis*, *33*(3). https://doi.org/10.1111/j.1539-6924.2012.01885.x

Pescaroli, G., & Alexander, D. (2015). A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. *Planet@ risk 3.1 (2015): 58-67.*

Pursiainen, C., & Kytömaa, E. (2023). From European critical infrastructure protection to the resilience of European critical entities: what does it mean? *Sustainable and Resilient Infrastructure*, *8*, 85-101. https://doi.org/10.1080/23789689.2022.2128562

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE control systems magazine*, *21*(6), 11-25.

Rød, B., & Johansson, J. (2023). Critical infrastructures: How resilient are they? *[Manuscript submitted for publication]*.

Shen, L., Cassottana, B., Heinimann, H. R., & Tang, L. C. (2020). Large-scale systems resilience: A survey and unifying framework. *Quality and Reliability Engineering International*, *36*(4), 1386-1401. https://doi.org/10.1002/qre.2634

Sonesson, T. R., Johansson, J., & Cedergren, A. (2021). Governance and interdependencies of critical infrastructures: Exploring mechanisms for cross-sector resilience. *Safety Science*, *142*. https://doi.org/10.1016/j.ssci.2021.105383

Tyson, J., & Pollette, C. (2001). How Internet Infrastructure Works. *HowStuffWorks.com*. https://computer.howstuffworks.com/internet/basics/internet-infrastructure.htm

UN. (2015). *Sendai Framework for Disaster Risk Reduction 2015-2030*. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

Wohlin, C. (2014). Guidelines for Snowballing in Systematic Literature Studies and a Replication in Software Engineering. *Blekinge Institute of Technology*. http://dx.doi.org/10.1145/2601248.2601268

Woods, D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety*, *141*, 5-9.

Zio, E. (2016). Challenges in the vulnerability and risk analysis of critical infrastructures. *Reliability Engineering and System Safety*, *152*, 137-150.

9.3. Case study data

AA. (2023, February 6). Ulaştırma ve Altyapı Bakanlığı, depremler nedeniyle bazı tren seferlerine ara verildiğini duyurdu. *Anadolu Ajansı*. https://www.aa.com.tr/tr/gundem/ulastirma-ve-altyapi-bakanligi-depremler-nedeniyle-bazi-tren-seferlerine-ara-verildigini-duyurdu/2808289

Abraham, L., Leatherby, L., Reinhard, S., & White, J. (2023, March 13). Thousands of Buildings Collapsed in One Turkish City. Thousands More May Have to Come Down. *The New York Times*. https://www.nytimes.com/interactive/2023/03/13/world/middleeast/antakya-damage-assessment.html

AFAD. (2014). *2014-2023 Kritik Altyapıların Korunması Yol Haritası Belgesi*. https://afyonluoglu.org/PublicWebFiles/Reports-TR-SG/2014-2023-AFAD-Kritik%20Altyap%C4%B1larin%20Korunmasi%20Yol%20Haritasi.pdf

AFAD. (2019). *AFAD Strategic Plan 2019-2023*. https://en.afad.gov.tr/kurumlar/en.afad/e_Library/plans/AFAD_19_23-StrategicPlan_Eng.pdf

Aksan, S. (2023, February 28). Elektrik sistemleri deprem sınavını geçti. *TRT Haber*. https://www.trthaber.com/haber/gundem/elektrik-sistemleri-deprem-sinavini-gecti-749504.html

ANF News. (2023). Four months after the earthquake, people of Hatay still can't access clean water. *ANF News*. https://anfenglish.com/news/four-months-after-the-earthquake-people-of-hatay-still-can-t-access-clean-water-67755

BBC Türkçe. (2023). BTK'ya göre depremlerin ardından yaşanan aksaklıklarda baz istasyonlarının rolü az. *BBC Türkçe*. https://www.bbc.com/turkce/articles/c51qly4x9n0o

Butler, D., & Coskun, O. (2023, February 9). Anger over Turkey's temporary Twitter block during quake rescue. *Reuters*. https://www.reuters.com/world/middle-east/anger-over-turkeys-temporary-twitter-block-during-quake-rescue-2023-02-09/

Can, M. F., Yılmaz, A. b., & Mazlum, Y. (2019). A Meta-Analysis: Geo-statistical approach on the THQ values of Cu, Zn, and Fe accumulation in some fish species from İskenderun Bay, North-Eastern Mediterranean. *Conference: V. International Congress on Natural And Health Sciences*. https://www.researchgate.net/publication/338231020_A_Meta-Analysis_Geo-statistical_approach_on_the_THQ_values_of_Cu_Zn_and_Fe_accumulation_in_some_fish_species_from_Iskenderun_Bay_North-Eastern_Mediterranean

Çelik, H. (2023). Vodafone Türkiye CEO'su Engin Aksoy - Depremde İletişim Neden Kesildi? [Video]. *Youtube*. https://www.youtube.com/watch?v=zOMRwpADepQ&t=486s

Çetin, K. Ö., Ilgaç, M., Can, G., & Çakır, E. (2023). Preliminary Reconnaissance Report on February 6, 2023, Pazarcık Mw=7.7 and Elbistan Mw=7.6, Kahramanmaraş-Türkiye Earthquakes. *Earthquake Engineering Research Center*.

Chambers, S. (2023, February 20). Three months to get Iskenderun terminal operations back to normal. *Splash 247*. https://splash247.com/three-months-to-get-iskenderun-terminal-operations-back-to-normal/

Cumhuriyet. (2023, March 29). Türk Telekom yöneticisi Ali Gürsoy'dan skandal açıklama: Şanslı bir depremdi! *Cumhuriyet*. https://www.cumhuriyet.com.tr/turkiye/turk-telekom-yoneticisi-ali-gursoydan-skandal-aciklama-sansli-bir-depremdi-2066096

Daily Sabah. (2023a, February 13). Azerbaijani oil sets sail from Türkiye’s Ceyhan port after quakes. *Daily Sabah*. https://www.dailysabah.com/business/energy/azerbaijani-oil-sets-sail-from-turkiyes-ceyhan-port-after-quakes

Daily Sabah. (2023b, February 7). Türkiye rushes to detect, restore damaged energy infrastructure. *Daily Sabah*,. https://www.dailysabah.com/business/energy/turkiye-rushes-to-detect-restore-damaged-energy-infrastructure

Dünya. (2023a, February 11). Bakan Dönmez açıkladı: Deprem bölgesindeki evlere elektrik verilecek mi? *Dünya* https://www.dunya.com/gundem/bakan-donmez-acikladi-deprem-bolgesindeki-evlere-elektrik-verilecek-mi-haberi-685515

Dünya. (2023b). GSM şirketlerinden 'İstanbul' depremi itirafı! Garanti vermemiz çok zor. *Dünya*. https://www.dunya.com/gundem/gsm-sirketlerinden-istanbul-depremi-itirafi-garanti-vermemiz-cok-zor-haberi-689940

EERI, & GEER. (2023). *February 6, 2023 Türkiye Earthquakes: Report on Geoscience and Engineering Impacts*. https://learningfromearthquakes.org/images/2023_02_06_nurdagi_turkey/GEER_2023_Turkey_Earthquake_FullReport_ReducedSize.pdf

Elektrik Mühendisleri Odası. (2016). Türkiye Elektrik Sistemi ve Sistem Sorunları. *Elektrik Mühendisleri Odası*. https://www.emo.org.tr/ekler/91c64a4f58f3c88_ek.pdf?tipi=2&turu=X&sube=14

Enerji Atlasi. (2023). *Şehirlerin Elektrik Santrali Kurulu Güçleri ile Üretim ve Tüketim Bilgileri*. Retrieved October from https://www.enerjiatlasi.com/sehir/

EPİAŞ. (2023). *Şeffaflık Platformu*. https://seffaflik.epias.com.tr/transparency/uretim/gerceklesen-uretim/gercek-zamanli-uretim.xhtml

Ergur, S. (2023, January 11). Turkey's Power Grid. *Climate Scorecard*. https://www.climatescorecard.org/2023/01/turkeys-power-grid/

Gazete Duvar. (2023). İddia: İskenderun Liman yangını Limak'ın riskli konteynerlerinden çıktı. *Gazete Duvar*. https://www.gazeteduvar.com.tr/deprem-yardimlarini-calan-4-belediye-personeli-adliyede-haber-1602841

Ghosh, T., Elvidge, C., & Zhizhin, M. (2023). VIIRS day/night band power outage analysis for the February 6, 2023 earthquake in Turkey and Syria. *Payne Institute Commentary Series: Briefs*. https://doi.org/10.25676/11124/16505

Türkiye büyük millet meclisi kahramanmaraş merkezli depremlerin sonuçlarinin tüm yönleriyle araştirilmasi, depreme dirençli yapi stokunun oluşturulmasi ve kentsel dönüşüm uygulamalarinin etkinliğinin artirilmasi için alinmasi gereken tedbirlerin belirlenmesi amaciyla kurulan meclis araştirmasi komisyonu (10/6996, 7004, 7005, 7006, 7007, 7009, 7010, 7024, 7026, 7034, 7035, 7036, 7037, 7038, 7039, 7040, 7041, 7042, 7043, 7044, 7045, 7046, 7047, 7048, 7049, 7050), (2023) (9th Meeting). https://www5.tbmm.gov.tr/develop/owa/komisyon_tutanaklari.goruntule?pTutanakId=3137

Haber Turk. (2023). TCDD deprem bölgesinde hasar gören rayların onarım ve bakım çalışmalarını sürdürüyor. *Haber Turk*. https://www.haberturk.com/tcdd-deprem-bolgesindeki-hasarli-raylari-onariyor-3566003

Hellenic Shipping News. (2023, February 24). Current Status of Turkey's Mersin and Iskenderun Ports: Earth Quake Affects Continues after 18 Days. *Hellenic Shipping News*. https://www.hellenicshippingnews.com/current-status-of-turkeys-mersin-and-iskenderun-ports-earth-quake-affects-continues-after-18-days/

HT, B. (2023, March 7). Kamuoyunda dikkatler GSM şirketlerine yönelik deprem soruşturmasında. *Bloomberg HT*. https://www.bloomberght.com/kamuoyunda-dikkatler-gsm-sirketlerine-yonelik-deprem-sorusturmasinda-2326453

International Medical Corps. (2023). Syria/Turkey Earthquakes Situation Report #7, March 8, 2023. *Reliefweb*. https://reliefweb.int/report/syrian-arab-republic/syriaturkey-earthquakes-situation-report-7-march-8-2023

İTÜ. (2023). *İTÜ den 2023 Deprem Raporu*. https://haberler.itu.edu.tr/haberdetay/2023/02/17/itu-den-2023-deprem-raporu

Karayolları Genel Müdürlüğü [@KarayollariGM]. (2023, February 6). *Deprem Nedeniyle Kapanan Yollar ve Alternatif Güzergâhlara İlişkin Türkiye Haritası*Twitter. https://twitter.com/KarayollariGM/status/1622573527499960320/photo/1

Kearney. (2021). *MW100 Türkiye'nin En Büyük 100 Elektrik Üreticisi Araştırması 2021*. https://www.kearney.com/documents/1350241/116625748/Mw100+Raporu+2021+Tek+Tek+Final.pdf/4c272fa9-cdaa-a990-1200-72b23b1734d2?t=1619654055000

KGM. (2019). *Karayolu ve Demiryolu Köprü ve Viyadükleri*. https://www.jmo.org.tr/resimler/ekler/a157fdec1d64bb1_ek.pdf

KGM. (2022a). *2022 Faaliyet Raporu*. https://www.kgm.gov.tr/SiteCollectionDocuments/KGMdocuments/Kurumsal/FaaliyetRaporu/2022Faaliyet.pdf

KGM. (2022b). Trafik ve Ulaşım Bilgileri 2022. *Karayolları Genel Müdürlüğü*. https://www.kgm.gov.tr/SiteCollectionDocuments/KGMdocuments/Istatistikler/TrafikveUlasimBilgileri/22TrafikUlasimBilgileri.pdf

KGM. (2023a). 5. Bölge Müdürlüğü | Mersin. *Karayolları Genel Müdürlüğü*. https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Bolgeler/5Bolge/Bolge5.aspx

KGM. (2023b). 8. Bölge Müdürlüğü | Elazığ. *Karayolları Genel Müdürlüğü*. https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Bolgeler/8Bolge/Bolge8.aspx

KGM. (2023c). *About Us*. https://www.kgm.gov.tr/Sayfalar/KGM/SiteEng/Root/Gdh/GdhRoadNetwork.aspx

KGM. (2023d). *Genel müdürlüğümüz deprem bölgesinde çalişmalarini araliksiz sürdürüyor*. Karayolları Genel Müdürlüğü. Retrieved September from https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Duyurular/DuyuruDetay.aspx?Parameter=1250

KGM. (2023e, 06 March). Yaraları sarmak için zamanla yarıştık. *Karayolları Genel Müdürlüğü*. https://www.kgm.gov.tr/SiteCollectionImages/KGMimages/Root/BasindaKGM/Mart2023/T%C4%B0CAR%C4%B0+HAYAT_20230306_1.jpeg

Küçükbarak, E. (2023, March 2). GSM şirketlerine deprem soruşturması. *Ankara Masasi*. https://www.ankaramasasi.com/haber/2072483/gsm-sirketlerine-deprem-sorusturmasi

Lewis, O. (2023, February 9). Mobility Data Shows Movement Away from Some Urban Areas After Deadly Earthquake. *Direct Relief*. https://www.directrelief.org/2023/02/mobility-data-shows-movement-away-from-some-urban-areas-after-deadly-earthquake/

Merkezi, H. (2023, February 10). Yüzyılın felaketi vurdu telefonlar sustu! 190 mobil baz istasyonu sevk edildi. *Dünya*. https://www.dunya.com/gundem/yuzyilin-felaketi-vurdu-telefonlar-sustu-190-mobil-baz-istasyonu-sevk-edildi-haberi-685414

Michaelson, R. (2023, February 21). Turkey hit by two more powerful earthquakes two weeks after disaster. *The Guardian*. https://www.theguardian.com/world/2023/feb/20/turkey-new-6-point-4-magnitude-earthquake-hatay

My Logistics Magazine. (2023). Iskenderun Port in Turkey to reopen in 3 months. *My Logistics Magazine*. https://mylogisticsmagazine.com/breaking-stories/iskenderun-port-in-turkey-to-reopen-in-3-months/

NTV. (2023, February 20). Deprem bölgesinde içme suyu altyapısının yüzde 98'i onarıldı. *NTV*. https://www.ntv.com.tr/turkiye/deprem-bolgesinde-icme-suyu-altyapisinin-yuzde-98i-onarildi,qe1iV5GrOkq3Uh8ogWsGlA

OnTheWorldMap. (2023). *Turkey Provinces Map*. www.OnTheWorldMap.com. Retrieved August from https://ontheworldmap.com/turkey/turkey-provinces-map.html

Ozen, C., & Kaya, K. (2023). Earthquake Effects on Electricity Network: A Case Study in Turkish Grid *5th Global Power, Energy and Communication Conference (IEEE GPECOM2023), June 14-16, 2023*. https://ieeexplore-ieee-org.ludwig.lub.lu.se/stamp/stamp.jsp?arnumber=10175728&tag=1

Paone, A. (2023, February 7). Fire at Turkey's Iskenderun Port extinguished -defence ministry. *Reuters*. https://www.reuters.com/world/middle-east/shipping-containers-ablaze-turkeys-iskenderun-port-operations-halted-2023-02-07/

Republic of Turkey Prime Ministry Investment Support and Promotion Agency. (2011). Turkey's Electricity Distribution Industry. *Republic of Turkey Prime Ministry Investment Support and Promotion Agency*. https://www.turkey-japan.com/business/category5/category5_426.pdf

Republic of Türkiye Ministry of Energy and Natural Resources. (2023). *Electricity*. https://enerji.gov.tr/infobank-energy-electricity

Resililinc. (2023, 28 February). Turkey Earthquake: Key Industries, Exports, and Sites Impacted. *Resililinc*. https://www.resilinc.com/blog/turkey-earthquake-2023/

Sagbas, G., Garjan, R. S., Sarikaya, K., & Deniz, D. (2023). Field reconnaissance on seismic performance and functionality of Turkish industrial facilities affected by the 2023 Kahramanmaras earthquake sequence. *Bulletin of Earthquake Engineering*. https://doi.org/10.1007/s10518-023-01741-8

Satariano, A. (2023). Twitter Was Blocked in Turkey, Internet-Monitoring Group Says. *The New York Times*. https://www.nytimes.com/2023/02/08/world/europe/turkey-earthquake-twitter-blocked.html

Saygin, D., Tör, O. B., Cebeci, M. E., Teimourzadeh, S., & P. Godron. (2021). Increasing Turkey's power system flexibility for grid integration of 50% renewable energy share. *Energy Strategy Reviews*, *34*. https://doi.org/10.1016/j.esr.2021.100625

Sezer, C., Edwards, R., & Payne, J. (2023, February 6). Turkey's Ceyhan oil terminal, Iraq's KRG pipeline halted after quake. *Reuters*. https://www.reuters.com/markets/commodities/ceyhan-oil-terminal-halts-ops-after-turkey-quake-shipping-agency-2023-02-06/

Soylu, R. [@ragipsoylu]. (2023). *Port of Iskenderun continues to burn with massive flames* Twitter.

Steel Orbis. (2023, March 10). Ekinciler resumed production after the earthquake. *Steel Orbis*. https://tr.steelorbis.com/celik-haberleri/guncel-haberler/ekinciler-depremin-ardindan-yeniden-uretime-1281986.htm

Strateji ve Bütçe Başkanlığı. (2023). 2023 Kahramanmaraş ve Hatay Depremleri Raporu. *Strateji ve Bütçe Başkanlığı*. https://www.sbb.gov.tr/wp-content/uploads/2023/03/2023-Kahramanmaras-ve-Hatay-Depremleri-Raporu.pdf

TCDD. (2018). *Annual Statistics 2014-2018*. https://www.tcdd.gov.tr/en/organizational/statistics

The Global Economy. (2023). *Turkey: Port traffic*. https://www.theglobaleconomy.com/Turkey/Port_traffic/

The World Bank. (2016). Republic of Turkey: Sustainable Urban Water : reaching compliance with the European Union’s water framework directive in a sustainable way – challenges and opportunities for Turkey’s water supply and sanitation sector http://documents.worldbank.org/curated/en/136911483599565083/Updated-report

The World Bank. (2023). *Earthquake Damage in Türkiye Estimated to Exceed $34 billion: World Bank Disaster Assessment Report* https://www.worldbank.org/en/news/press-release/2023/02/27/earthquake-damage-in-turkiye-estimated-to-exceed-34-billion-world-bank-disaster-assessment-report

Toroslar EDAŞ. (2023a). *Our History*. Retrieved 25 July from https://www.toroslaredas.com.tr/sayfa/tarihce

Toroslar EDAŞ. (2023b, February 11). Toroslar EDAŞ deprem bölgesinde afet haberleşme sistemini devreye aldı. *www.toroslaredas.com.tr*.

https://www.toroslaredas.com.tr/basin-bulteni/toroslar-edas-deprem-bolgesinde-afet-haberlesme-sistemini-devreye-aldi/1089

TR Haber. (2023). Bakanlık deprem bölgesinde çalışıyor! Mobil baz istasyonu sayısı 400'ü aştı. *TR Haber*. https://www.trhaber.com/gundem/bakanlik-deprem-bolgesinde-calisiyor-mobil-baz-istasyonu-sayisi-h88895.html

UNOSAT, & Wuhan University. (2023). Power Supply Recovery Assessment following the Marash / Antep Earthquake (6 February 2023, Mw 7.8) using Night-time Light Imagery. https://unosat.org/products/3565

USGS. (2023a). *The 2023 Kahramanmaraş, Turkey, Earthquake Sequence*. https://earthquake.usgs.gov/storymap/index-turkey2023.html

USGS. (2023b). *Tectonic Map of Turkey Region*. https://www.usgs.gov/media/images/tectonic-map-turkey-region

www.automeris.io. (2022). *WebPlotDigitizer*, *Version 4.6*. https://automeris.io/WebPlotDigitizer/

Yazan, A. (2023, March 22). Deprem bölgesinde güvenli suya erişim ne durumda? *BBC Türkiye*. https://www.bbc.com/turkce/articles/c9r04yw6qn2o

Ünker, P. (2023, February 18). Deprem bölgesinde sağlıklı suya ne zaman erişilecek? *Deutsche Welle*. https://www.dw.com/tr/deprem-b%C3%B6lgesinde-sa%C4%9Fl%C4%B1kl%C4%B1-suya-ne-zaman-eri%C5%9Filecek/a-65034261

Appendix A - Energy

A.1. Description of infrastructure

The functionality of the electricity systems are essential for the functioning of society. The Turkish, like in most countries, electrical system consists of three types of entities: electricity generation, electricity transmission, and electricity distribution.

Electricity generation involves converting different forms of stored energy, such as potential energy (hydroelectric plants), kinetic energy (wind plants), or internal energy (coal plant), into electrical energy. To maintain a stable system the amount of electricity produced are regulated by the demand, meaning that an increase in demand will lead to an increase in generation and vice versa. As of June 2023, Turkey´s yearly electricity generation amounts to 326.2 TWh, primarily from hydroelectrical plants (30.1%), followed by natural gas (23.2%), coal (20.8%), wind (11%), solar (9.7%) and other sources (Republic of Türkiye Ministry of Energy and Natural Resources, 2023). The largest electricity generating company in Turkey is the state-owned Elektrik Üretim A.Ş (EÜAŞ), responsible for producing approximately 22% of the countries electricity (Kearney, 2021). It is followed by the private-owned ENKA and Enerjisa, both contributing with around 4% of the country's electricity generation each.

Electricity transmission is the process of moving high amount of electrical energy over long distances across the country, from power generating sources to distributors, as seen in Figure 26. In Turkey, this is done by transmitting the electricity as high voltage, either 400kV and 154kV, through overhead power lines. These lines, stretching the country side, consists of wires strung between steel transmission towers placed at regular intervals. The transmission is synchronised at a frequency of 50 Hertz with neighbouring Greece and Bulgaria, enabling the import and export of electricity (Saygin et al., 2021). The system consists of over 700 substations that connects transmission lines and transform the voltage (Ergur, 2023). The system is constantly monitored and controlled by a supervisory control and data acquisition (SCADA) system. In Turkey, the transmission grid is owned and governed by the Turkish Electricity Transmission Corporation (TEİAŞ)

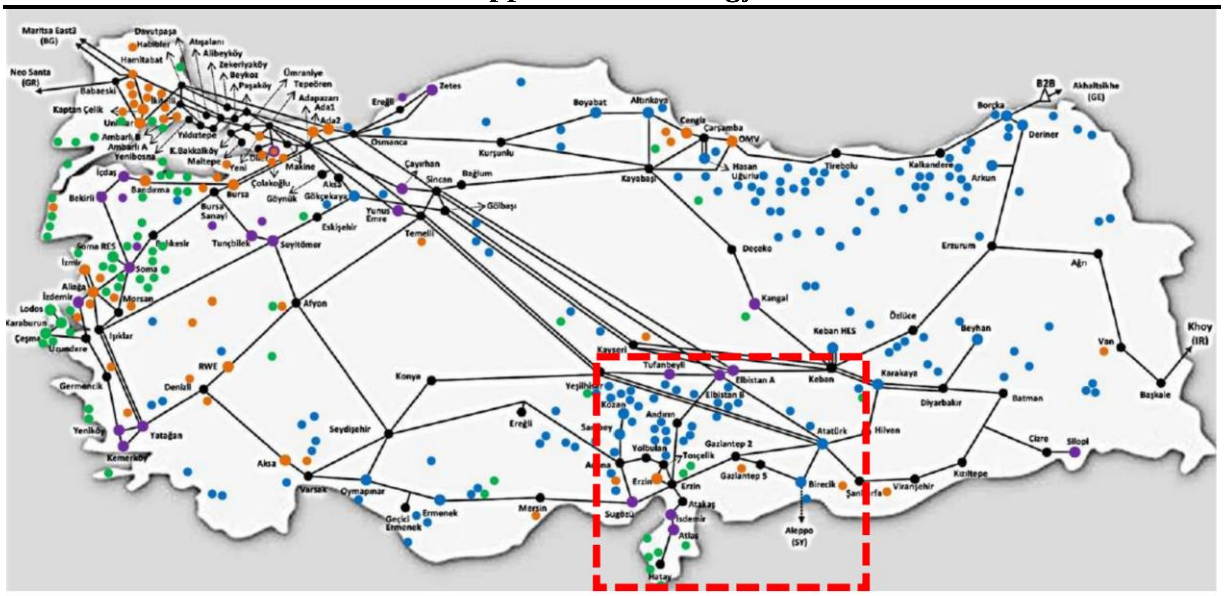


Figure 26. Turkish electricity transmission grid (black) and location of electricity generation plants. Green = Wind, Blue=Hydroelectric, Purple = Coal, Orange = Natural gas. Red square marks area affected by earthquake. Image from Elektrik Mühendisleri Odası (2016)

The distribution grid is the final link in the chain that delivers electricity from its generation to the end user. The distribution process involves substations that transforms the incoming high voltage electricity, either 400 kV or 154 kV, from the transmission network to a lower voltage, below 36 kV (Ergur, 2023). This lower voltage is more suitable for the distribution grids, transferring electricity into both cities and rural areas. The Turkish distribution grids typically consists of approximately 80% overhead lines and 20% underground cables. In Turkey the transmission grid connects to 21 different distribution systems, see Figure 27. A large part of the earthquake-affected area received electricity distribution through the Toroslar Elektrik Dağıtım A.Ş network. Since 2018, this distributor has been part of and managed by Enerjisa Enerji A.Ş and E.ON (Toroslar EDAŞ, 2023a).

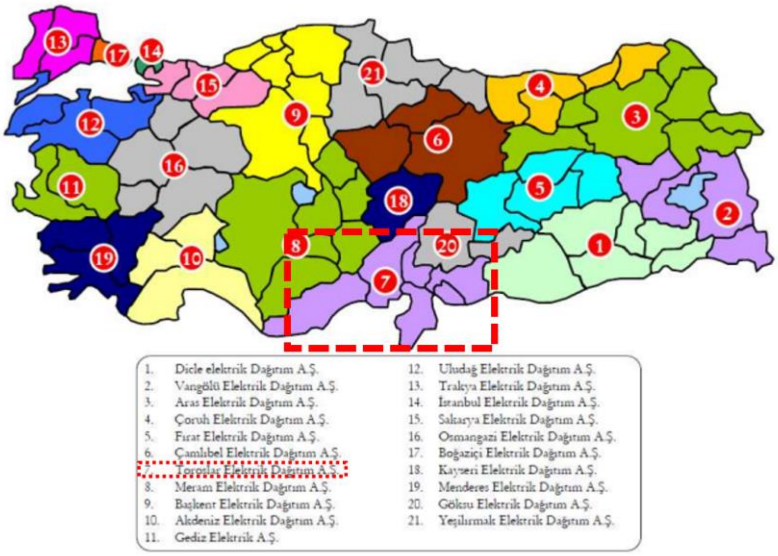


Figure 27. Turkeys 21 electricity distribution grids. Image from Republic of Turkey Prime Ministry Investment Support and Promotion Agency (2011)

Turkey is further highly dependent on natural gas. As about a quarter of the country's electricity generation is done by natural gas powerplants, and natural gas is used for heating of buildings. The company owning the oil and gas pipelines in Turkey is BOTAŞ Petroleum Pipeline Corporation

A.2. Earthquakes impact

The earthquakes severely disrupted the energy supply, resulting in widespread blackouts in affected cities, such as Kahramanmaraş, Hatay and Gaziantep, see Figure 28. The blackouts can be attributed to various factors, including the earthquakes impact on the supply of fuel to power plants, the functioning of the power plants themselves, damages to electricity transmission and distribution systems, and damages to the end-users devices or facilities.

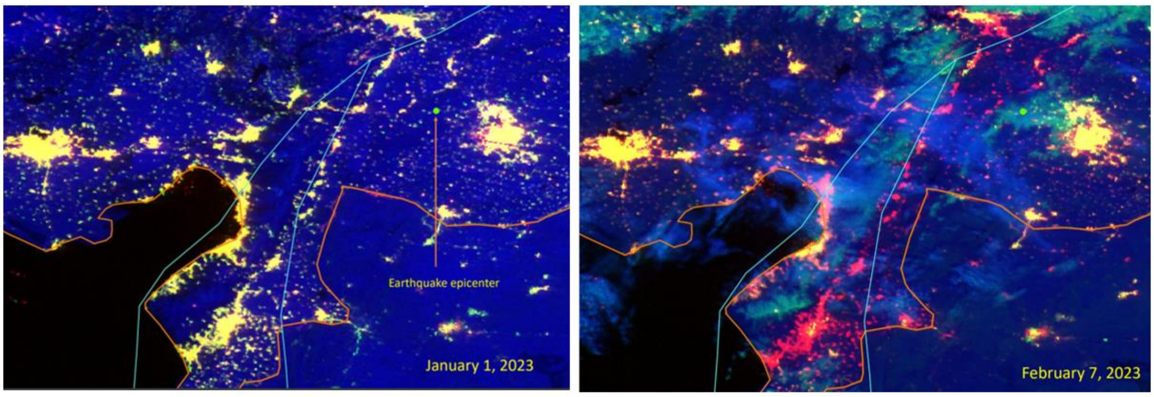


Figure 28. Satellite image capturing the visible infrared light of southern Turkey, where the blue lines represent the fault lines. The first image illustrates a typical day before the earthquake, where illuminated areas are shown in yellow. The second image shows the day after the earthquake showing how areas with power outage (areas in red) follow the fault lines. Image from Ghosh et al. (2023) CC BY 4.0.

The earthquake caused damage to the power plants. For instance, a 1300 MW coal power plant in Elbistan experienced cracks and structural damage in its cooling towers, as well as broken components and oil leaks in its transformers (EERI & GEER, 2023). As of February 22, all the reactors at this power plant were still offline. Another 1000 MW coal power plant in Iskenderun experienced broken valves inside turbines making the generators inoperable, but was restored to operation after about a week. In contrast, the hydroelectric dams suffered less damage, mainly from rockfall, and were able to resume operation as soon as the transmission grid was restored. The sudden dip in generation caused by the earthquake resulted in a noticeable drop in voltage to distribution networks on the opposite side of turkey, more than 400 km away from the area directly affected by the earthquake (Ozen & Kaya, 2023).

According to reports, the earthquake caused significant damage to the TEİAŞ electricity transmission system, with approximately 1,128 km of transmission lines affected. Around 11 steel transmission towers completely collapsed (Strateji ve Bütçe Başkanlığı, 2023) , see Figure 29. These collapses were caused for instance by landslides triggered by the seismic forces (EERI & GEER, 2023). Additionally, around 30 transmission substations suffered various degree of damage (Daily Sabah, 2023b). This was caused by factors such as cracks in transistors, falling debris, and collapsing structures (EERI & GEER, 2023). Furthermore, 91 transistor lines were broken(Grand National Assembly of Turkiye, 2023). However, most of the assessments suggest that the electricity transmission system experienced milder impacts compared to other CIs during the earthquake (EERI & GEER, 2023; Strateji ve Bütçe Başkanlığı, 2023). Additionally, the effect of the earthquake on the transmission network was mainly contained within the areas directly affected, and there were little to no observed cascading effects across the transmission network (Aksan, 2023). Within about three days after the earthquake, the major issues in the transmission system had been largely resolved, and the system was more or less back to normal operation.

Figure 29. Collapsed steel transmission tower. Image from EERI and GEER (2023)

The distribution network experienced great damage, particularly the underground power lines due to collapsing structures and shear stress forces. However, as the distribution circuits often were designed as a ring network, electricity could bypass damaged sections as long as was an alternative undamaged circuit. As many as 27 communities were affected, leaving more than 13,000 distribution transformers without power and causing the disruptions for millions of citizens (Grand National Assembly of Turkiye, 2023). Toroslar EDAS, in response to the situation, received assistance from Enerjisas other distribution companies, including extra personnel and vehicles. On the first day of the earthquake, they were able to mobilize from 350 to 1011 personnel, and by the fifth day, they had managed to mobilize 2073 personnel, working to restore the system (Toroslar EDAŞ, 2023b).They deployed a total of 606 generators, out of which 180 were large, to provide electricity to areas that could not be supplied through the grid. In the immediate aftermath, Toroslar EDAS prioritized providing lightning for search and rescue operations and ensuring critical facilities had access to electricity. By March 6, they had restored most of the previously non-electrified distribution transformers, except for those located near collapsed buildings (Grand National Assembly of Turkiye, 2023).

The main natural gas transmission pipeline in Turkey was damaged causing leakages. As many as 18 major damages were found on the pipeline, with a significant damage at the Türkoğlu area, leaving homes and power plants in Kahramanmaraş, Gaziantep and Hatay without supply natural gas (Dünya, 2023a). Critical facilities were to some extent supplied with natural gas while repair were in process (Çetin et al., 2023). By February 11, most of the ruptures were fixed and the gas supply was back in operation (Dünya, 2023a). Although, fear of leakages due to collapsed buildings made the gas distributor to leave some areas without gas supply for an extended period of time.

A.2.1 Quantitative data

To assess the robustness and rapidity of electricity supply, data was first thought to be got from the electricity distribution company Toroslar EDAS. However, it became apparent from their general outage data, where they provide real time outage information such as number of household affected by outage, that for the most severely affected provinces, such as Hatay, there was a gap in reporting directly after the earthquake, which lasted for weeks. This is most likely due to the extent of damage, which both made it difficult to assess the magnitude of disruptions as well as lack of time to report this type of data. An alternative approach to estimate the robustness and rapidity was used which included using an analysis of satellite data from NASAs visible infrared imaging radiometer suite (VIIRS) studying the nighttime light across the different regions (UNOSAT & Wuhan University, 2023). Data was collected from graphs as images showing average brightness each day, see Figure 30. The data points from these graphs was then converted to a table by using WebPlotDigitizer tool (www.automeris.io, 2022).

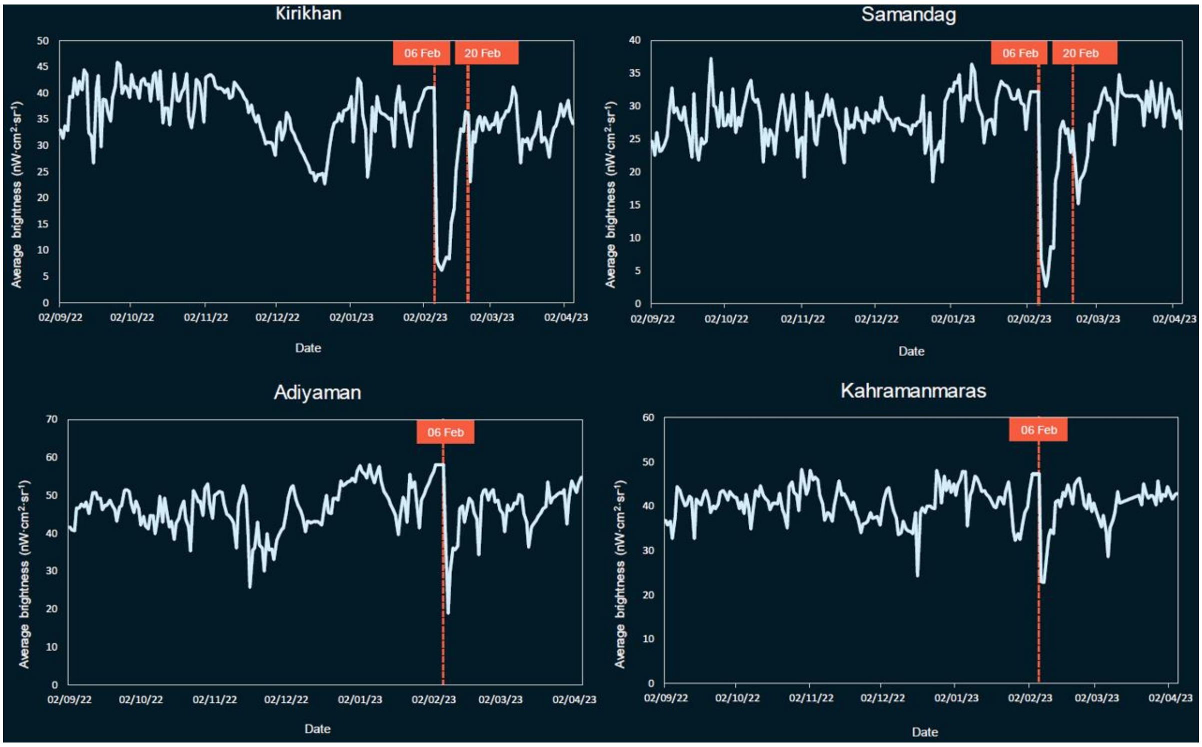


Figure 30. Average brightness observed from the VIIRS satelite over four of the affected regions before and after the earthquake (UNOSAT & Wuhan University, 2023).

To measure the system performance, the average daily brightness of the 100 days before the earthquake was used as the 100% target performance. The system performance on May 5th was set to this value. The authors of the VIIRS analysis noted that weather can affect the measured average daily brightness, so there is a lot of fluctuations in the data (UNOSAT & Wuhan University, 2023). To account for this, some of the system performance data was refined using logarithmic regression, while other parts of the data was simply smoothed out to remove fluctuations. The resulting recovery is shown in Figure 31.

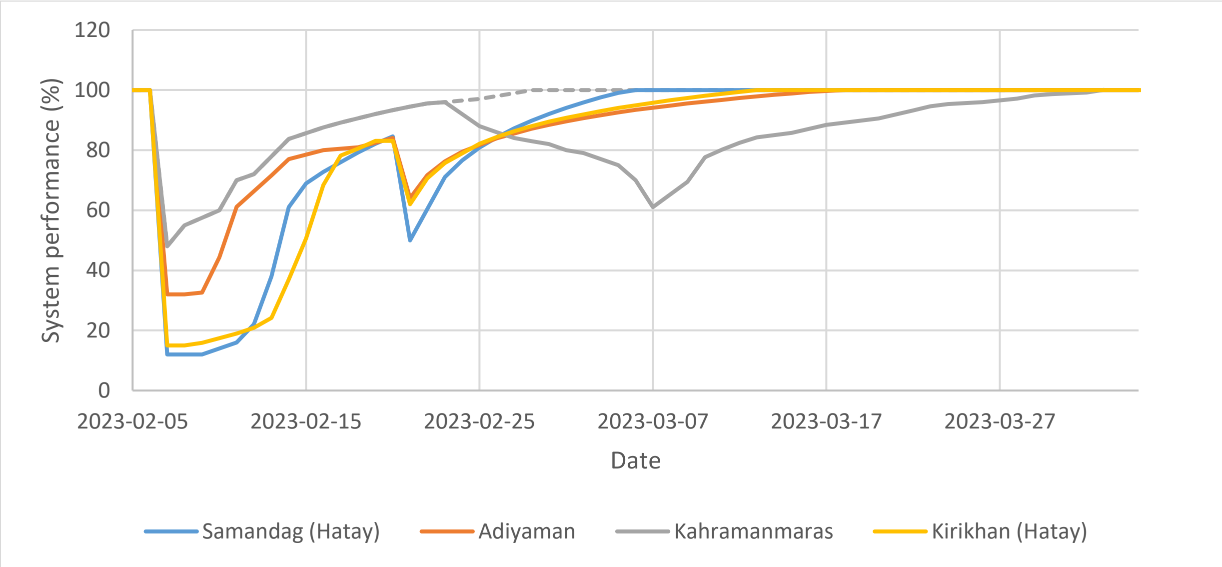


Figure 31. System performance of electricity infrastructure

On February 20, there was a large aftershock in the Hatay province, which explains the sudden drop in performance in the Hatay and Adiyaman provinces (Michaelson, 2023). However, there was no clear explanation for the gradual decline in Kahramanmaraş after February 24, and this was thus assumed to possibly be the result of cloudy weather in the province. Therefore, actual performance curve was approximated based on the appearance and slope of the curve before February 24. Considering this extrapolated approximated curve, Adiyaman was the last city to fully recover by March 18. The relative resilience score (RR) for each province between Feb 6 and March 18 was calculated. The robustness and recovery are presented in Table 8.

Table 8. Robustness and recovery for distribution of electricity.

City	**Robustness (%)**	**Recovery (days)**
Kirikhan (Hatay)	15	~35
Samandag (Hatay)	12	~28
Kahramanmaraş	48	~22
Adiyaman	32	~38

A.2.2 Transmission system

To assess whether disruptions in the transmission network explain the long disruption in electricity supply, data was collected from statements made by the transmission company TEIAS during a hearing at the Grand National Assembly of Türkiye (Grand National Assembly of Turkiye, 2023). According to the managers testimony, there were around 125 transformer stations in the earthquake affected areas, and Figure 32 illustrates the percentage of these transformer stations that remained operational after the earthquake. Since the transmission system was able to restore its functionality rather quickly, it is unlikely that it was the primary factor contributing to the delayed recovery of the electricity supply.

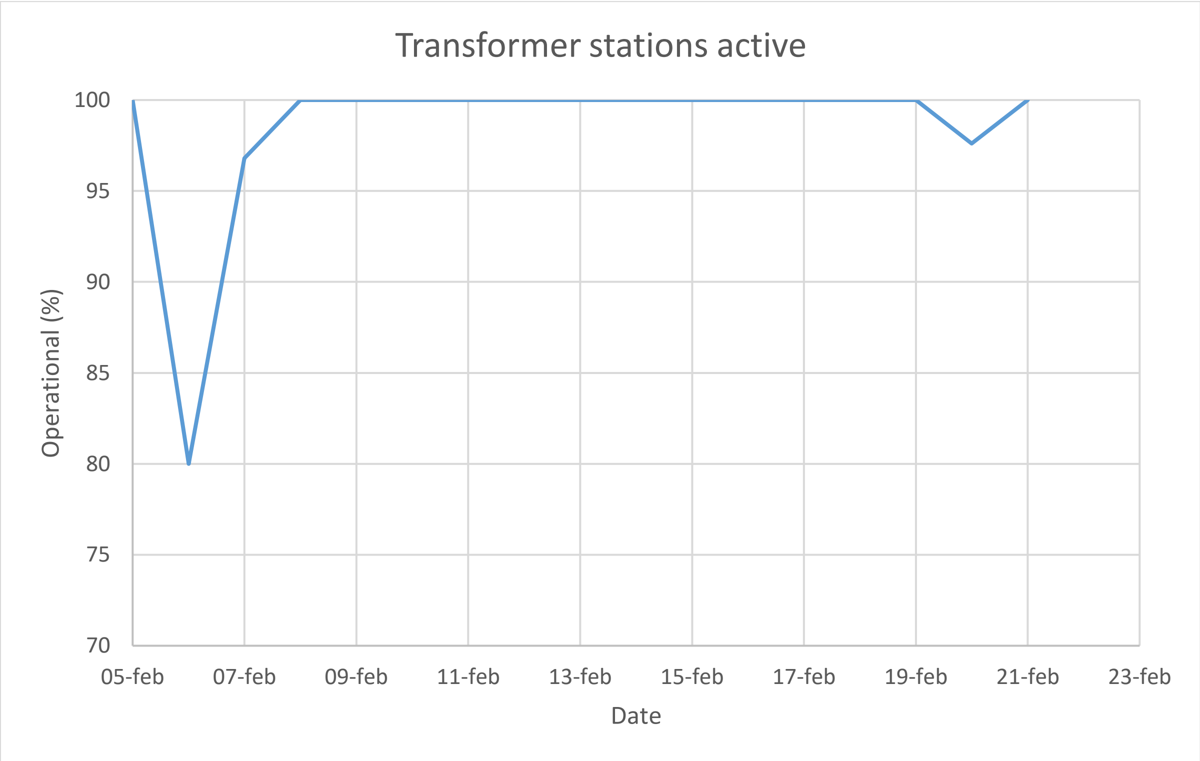


Figure 32. Percentage of operational transformer stations in the transmission network.

A.2.3 Electricity generation

To assess whether disruptions in the electricity generation could be explanatory of the large disruption of electricity supply an assessment was made of the functionality data of the 3 largest power generating in each province failities were collected, see Table 9. Data on the electricity generation was collected from the databases of Enerji Piyasaları İşletme A.Ş., and energy market institution that offers real-time data on various aspects related to energy (EPİAŞ, 2023). To calculate the functionality a baseline normal value was taken as the median of the 2 months preceding the earthquake.

Table 9. Top 3 largest electricity generation facilities in five of the provinces in the earthquake affected area (Enerji Atlasi)

Province	Facilities	Type	Max generation (MW)
Hatay	İskenderun Atlas Termik Santrali	Coal	1260
	Erzin Doğalgaz Santrali	Natural Gas	904
	İskenderun Demir Celik Termik Santrali (Isdemir)	Coal	239
Kahramanmaraş	Afşin Elbistan B Termik Santrali	Coal	1440
	Afşin Elbistan A Termik Santrali	Coal	1355
	Sır Barajı ve Hidroelektrik Santrali (HES)	Hydro Electric	284
Adiyaman	Atatürk Barajı ve HES	Hydro Electric	2405
	Birecik Barajı ve HES	Hydro Electric	672
	Şanlıurfa OSB Enerji Santrali	Natural Gas	147
Gazientep	Karkamış Barajı ve HES	Hydro electric	189
	Kartaldağı RES	Wind	63
	Goren 1 Doğalgaz Santrali	Natural gas	49 (no data found)
Osmaniye	Berke Barajı ve HES	Hydro electric	510
	Aslantaş Barajı ve HES	Hydro electric	138
	Osmaniye Gökçedağ RES	Wind	135

Overall, the electricity generation infrastructure performed well with a barely noticeable nationwide impact, see Figure 33. Across various generation types, only coal power plants showed observable significant national effects from the earthquake. Turkey which otherwise is a large electricity exporter saw an slight increase in electricity import in the aftermath of the earthquake which turned the net export/import briefly negative before swiftly recovering to pre-disaster levels.

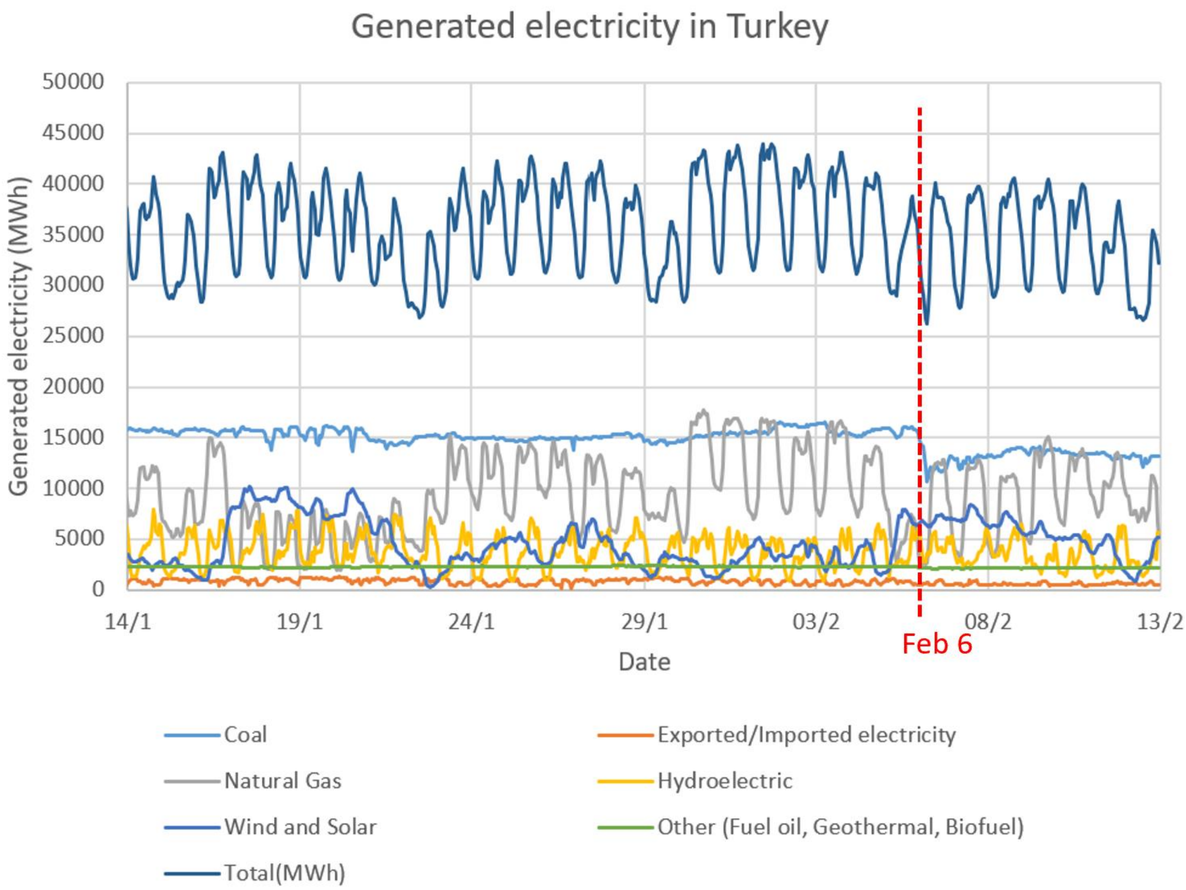


Figure 33. Sector-specific real time data of generated electricity in Turkey.

Analyzing data from the three largest power plants in each province provided insights into how the earthquakes effect varied across regions in terms of electricity generation, see Figure 34. The data generally indicated that, with the exception of Hatay and Kahramanmaraş, the earthquakes impact on overall generation often within the range of natural fluctuations. For Hatay and Kahramanmaraş, the earthquakes had a notable effect, causing certain plants to shut down the generation entirely. It took approximately 115 days for the largest generation facilities to restore 90 % functionality in Hatay and around 151 days in Kahramanmaraş, see Figure 35. Considering the limited effect the earthquake had on electricity generation nationwide, and that the electricity transmission is done through a grid, disruptions in electricity generation can not be considered to be the main cause of the disruption of distributed electricity supply.

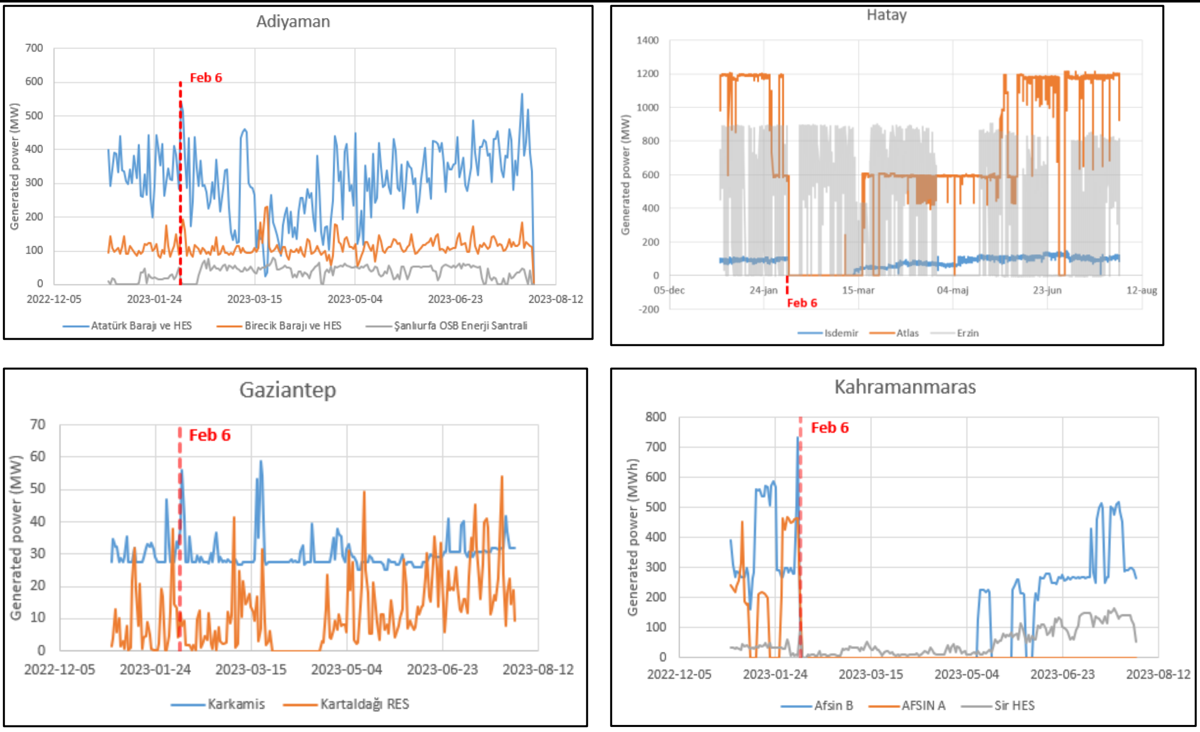


Figure 34. Generated power for the largest generation facilities in four provinces

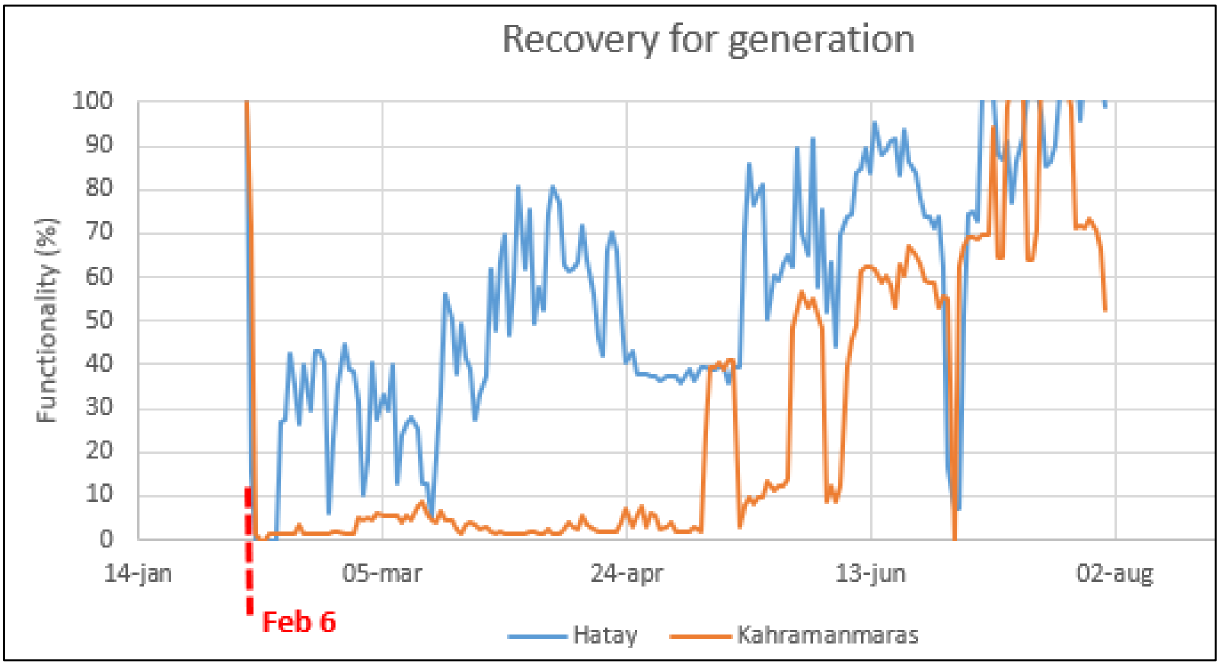


Figure 35. Recovery curve for electricity generation for the three largest generating facilities in Hatay and Kahramanmaraş combined.

Appendix B - Transportation

Transportation in turkey can be divided into maritime, roads, railroad and air traffic. This appendix focus particularly on highway transportation, railway and ports used for maritime transportation.

B.1. Roadway

B.1.1 Description of infrastructure

The Turkish road network extends approximately 349,445 km and is categorized into different types, each managed by a specific responsible entity. Urban and village roads are managed by local authorities, while the motorways, state highways, and provincial roads falls under the responsibility of the General Directorate of Highways (KGM, 2023c). The motorways, state highways and provincial roads connecting the earthquake-affected cities of Adana, Kilis, Osmaniye, Hatay, Gaziantep and Kahramanmaraş are part of the 5th Regional Directorate (KGM, 2023a). The 5th Regional Directorate network stretches a total length of 5280km. Adiyaman, Malatya, and Elazig are part of the 8th Regional Directorate which stretches 3920 km (KGM, 2023b). The road networks consist of roads, bridges and tunnels. Figure 36 illustrates the 5th traffic network and its daily traffic, and Table 10 shows the length of the network within each province.

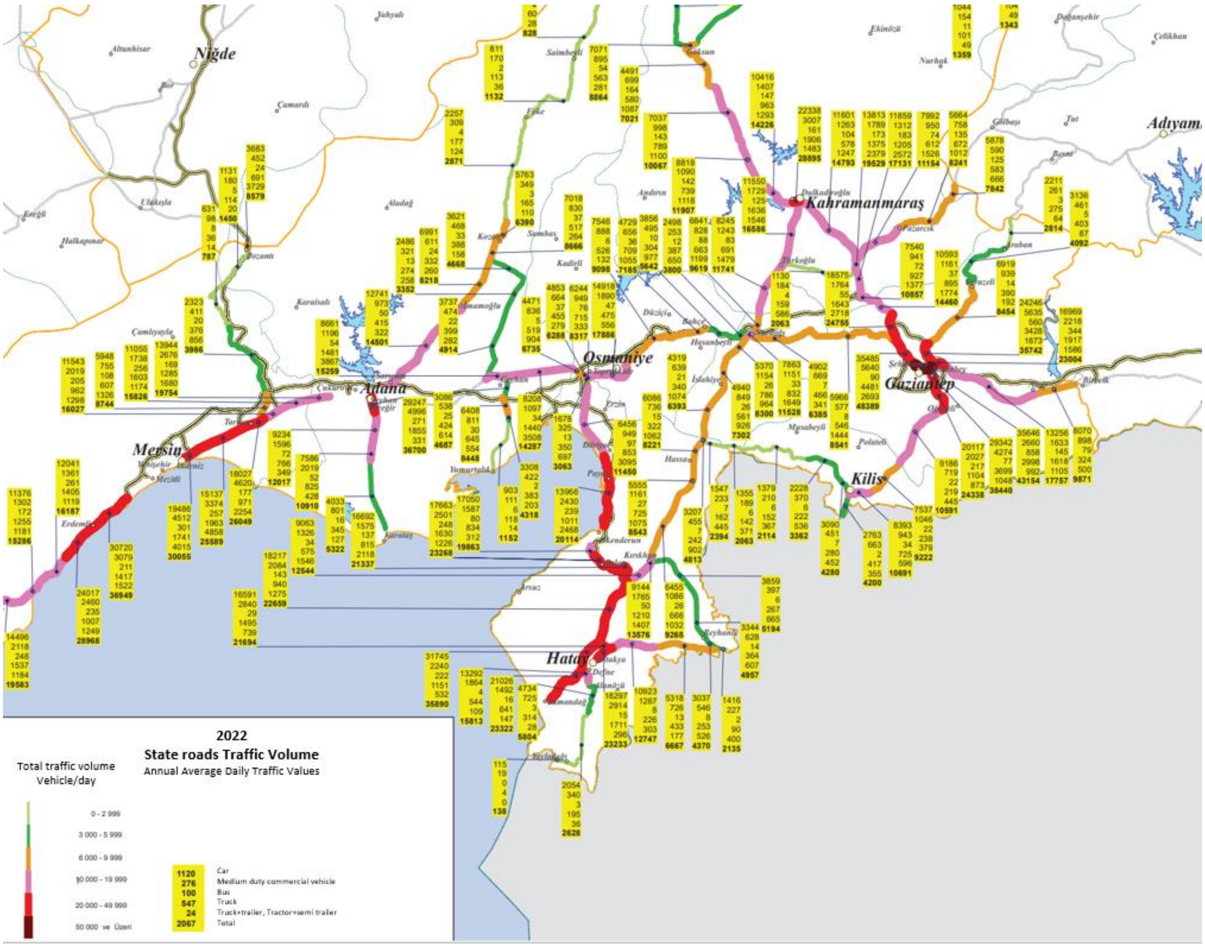


Figure 36. The 5th regional directorate. Image translated from KGM (2022b)

Table 10. Road network length per province (KGM, 2023a)

Province	Road network length (km)
Adana	956
Hatay	658
Gaziantep	651
Kahramanmaraş	974
Mersin	1472
Kilis	151
Osmaniye	365

B.1.2 Earthquake Impact

The earthquake caused extensive damage to motorways, state highways and provincial roads, primarily due to landslides, rockfall, lateral spreading and embankment failures (EERI & GEER, 2023). Additionally, some bridges, tunnels and viaducts for road traffic were damaged. Several highways, such as one near Hatay, one between Gaziantep and Osmanye, and another near Adiyaman were completely closed due to damages caused by the earthquake, see Figure 37. Some other roads were closed to only be used by emergency personnel. However, by February 12 most of these roads had been repaired and reopened for normal operation. Approximately 10,000km of various types of roads were temporarily closed for usage after the earthquake.

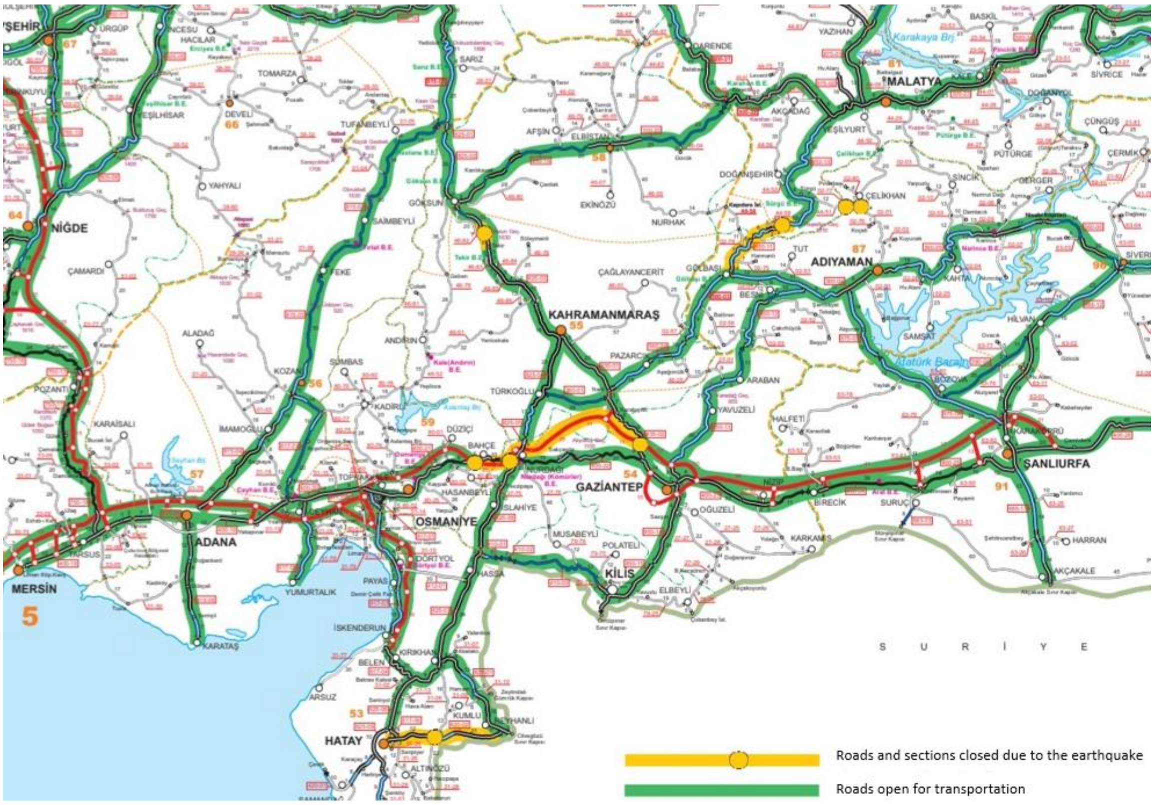


Figure 37. Closed main roads on Feb 6 after the earthquakes. Image translated from Karayolları Genel Müdürlüğü (2023)

According to their yearly activity reports KGM frequently participate in disaster risk management exercises organized by AFAD, and as late as 2022 the KGM participated in a national drill focusing where they focused on coordinating recovery efforts after an earthquake event (KGM, 2022a). During the same year managers from the 5th and 8th directorates participated in disaster exercises on sandstorms respective tornado scenarios. KGM continuously work to update their regulations for bridges, highways and roads against seismic hazards to increase robustness (KGM, 2019)

KGM mobilized around 3900 personnel and 2500 machines to the affected areas shortly after the earthquake (KGM, 2023d).

The SBB recommended assessments and strengthening efforts to be carried out taking into consideration the disaster proneness of the regions. They also recommend that traffic control stations to be upgraded importance and thus regulated by better earthquake resistant design as 5 of the 29 traffic control stations collapsed (Strateji ve Bütçe Başkanlığı, 2023).

B.1.3 Quantitative data

The 5th directorate of KGM, which has approximately 5280 kilometers of road, experienced road closures due the earthquake. To calculate the system performance of the whole 5th directorates road network, data of reported road closures provided by KGM was used. The total length of disrupted road segments was divided by the total length of roads over time, and the results are presented in Figure 38.

Hatay is a province under the jurisdiction of the 5th Directorates and has 5 major highways connecting different cities. The earthquake caused the disruption and closure of one of highway sections for five days, see Figure 37. Closed main roads on Feb 6 after the earthquakes. Image translated from Karayolları Genel Müdürlüğü (2023). To calculate the system performance within Hatay it was assumed each of these highway sections were equally long and important, and the minimum functionality was calculated by taking the non affected sections (4 out of 5) divided by the total number of sections (5), resulting in a value of 80%, as illustrated in Figure 38.

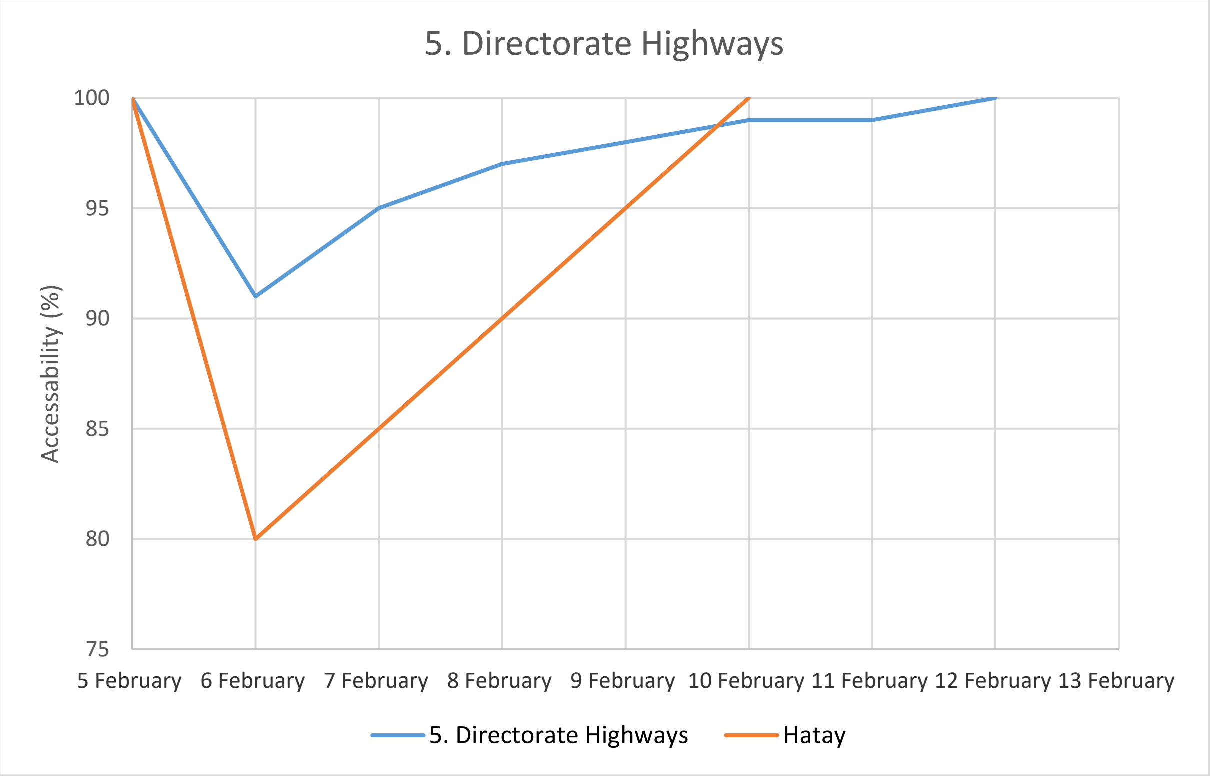


Figure 38. Percentage of highway sections accessable after the earthquakes

Province	Robustness	Recovery
5th Directorate	91%	7 days
Hatay	80%	5 days

B.2. Railway

B.2.1 Description of infrastructure

The State Railways of the Republic of Turkey (TCDD) owns and manages the railway network in Turkey. TCDD is also the owner of one of the largest passenger and freight train operator in the country, the TCDD TAŞIMACILIK A.Ş (TCDD, 2018). As of 2018, the total nationwide length of the railway network is 12,740 km. The areas directly affected by the earthquake fall under the is located within the 5th and 6th Regional Directorate of the TCDD. The specific length of railway within each affected province can be found in Table 11.

Table 11. Railway network length per province (TCDD, 2018)

Province	Railway length (km)
Adana	231
Adiyaman	55
Hatay	78
Gaziantep	287
Kilis	26
Malatya	259
Osmniye	74
Kahramanmaraş	222
Total	1232

B.2.2 Earthquake Impact

The railway was severely affected by the earthquake with approximately 1280km of rail closed as a result, see Figure 39. Particularly affected were lines in the provinces of Kahramanmaraş, Gaziantep and Malatya. These include lines are a known bottleneck in the Turkish railway system, and critical for much of the freight transport of for example steel to Iskenderun port (Strateji ve Bütçe Başkanlığı, 2023). Damages observed on the lines were for example lateral spreading of tracks, as shown in Figure 40, rockfall and landslides onto the tracks and damaged substations. In some provinces, such as Hatay, railway lines remained operational but were reserved for emergency purposes only. This included transport of personnel, essential items such as food, vital supplies, container homes and to facilitate the evacuation of those in need (Haber Turk, 2023). Additionally, railway bridges, tunnels and viaducts experienced various degrees of structural damage (Strateji ve Bütçe Başkanlığı, 2023). By March 6, approximately 1182 km of the affected lines were restored and back to operation (KGM, 2023e).

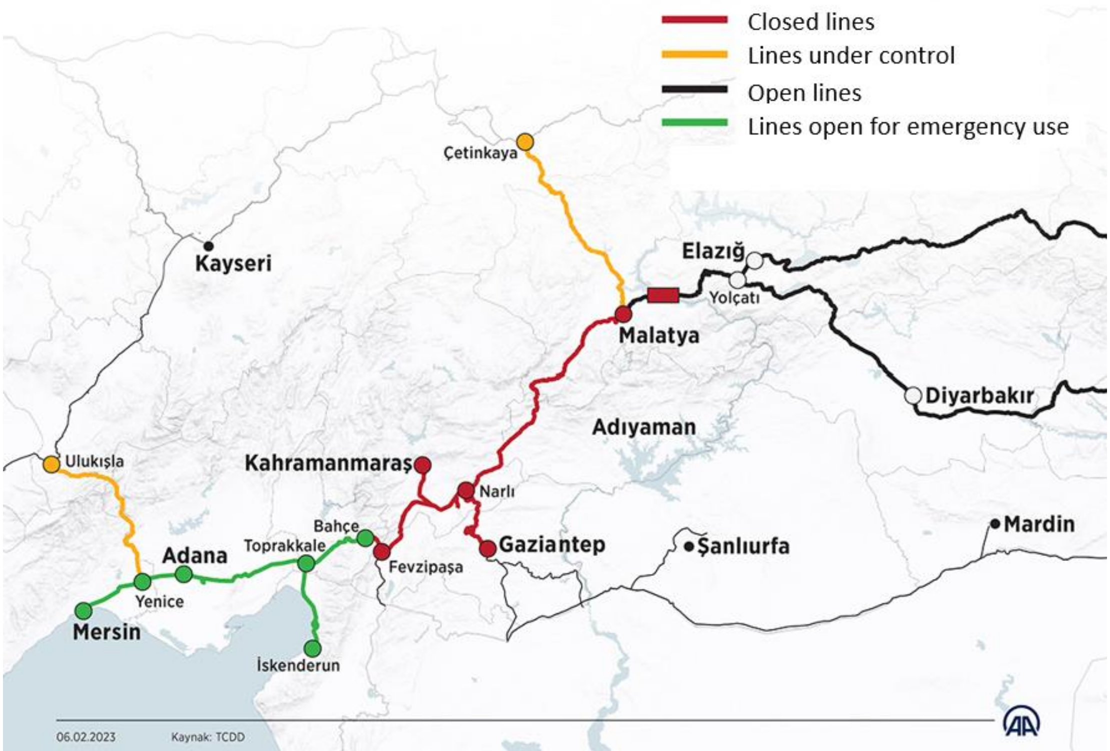


Figure 39. Railway lines affected on Feb 6 after the earthquakes. Image translated from AA (2023)

Figure 40. Lateral spreading across railway track. Image from Strateji ve Bütçe Başkanlığı (2023)

B.2.3 Quantitative data

Based from reports it is reasonable to assume that the earthquake affected nearly all of the railway lines within the 5th and 6th directorates. While some lines were open for emergency use, nearly none were open for commercial usage, see Figure 40. However, no detailed data regarding the restoration was obtained. According to TCDD , around 92% (1182 out of 1280) of the railway had been restored by March 6 (KGM, 2023e). Observing the logarithmic appearance of how the road network was restored it could be reasonable to also assume that the restoration process of the railway network would follow a similar logarithmic function. A logarithmic function was implemented as:

$$SP(t) = a * \ln((t - t_0) + 1)$$

The value for the constant was calculated as:

$$a = \frac{SP(t)}{\ln((t-t_0)+1)} = \frac{92\%}{\ln((march\ 6 - feb\ 6)+1)} = 27.32$$

The calculations assume that the disruption in Hatay was of similar magnitude as the 5th and 6th directorate in general. The system performance for Hatay over time is illustrated in Figure 41 and the calculated robustness and recovery is shown in Table 12.

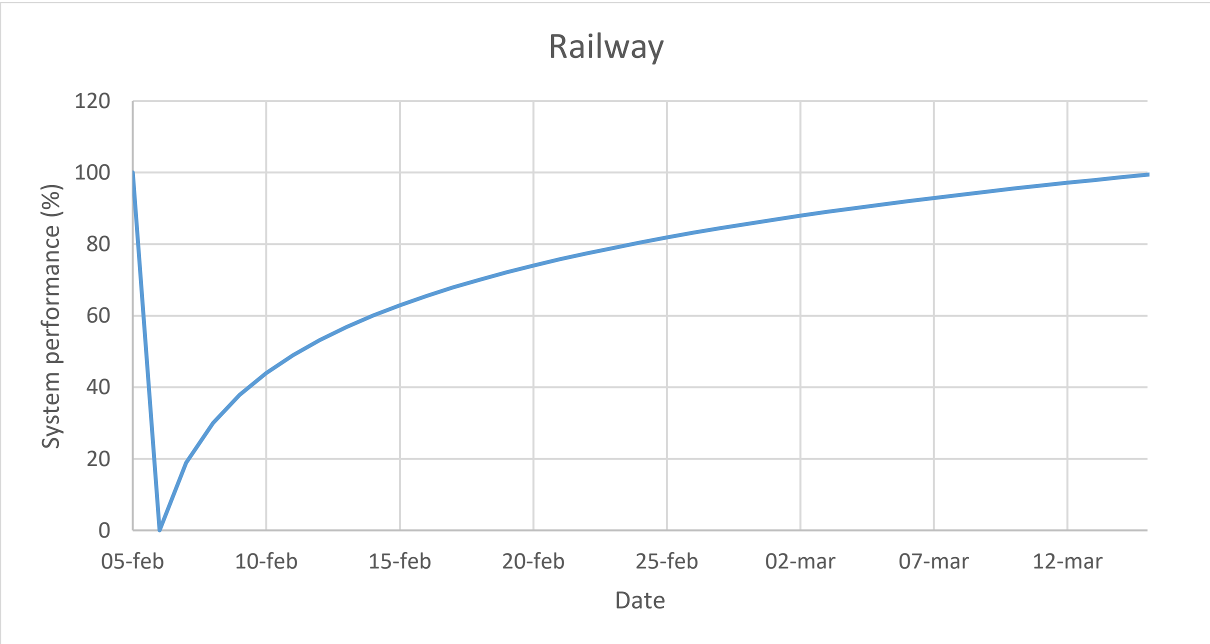


Figure 41. System performance of railway sections during the earthquakes.

Table 12. Calculated robustness and recovery for the province of Hatay during the earthquakes.

Province	Robustness (%)	Recovery (days)
Hatay	0	38

B.3. Ports

B.3.1 Description of infrastructure

Maritime transport involves the movement of goods and passengers using ships. For ships to load and unload goods, port infrastructure is essential and different types of goods require specific types of ports. For instance, gas, oil and containers need different type of infrastructure. In 2021, the ports in Turkey handled approximately 12.59 million twenty-foot equivalent units (TEU) of containers, which is roughly equivalent to 34,000 TEUs per day (The Global Economy, 2023). The earthquake-affected area is located within the Gulf of İskenderun, which has 12 ports or harbors (Figure 42). Among them is Iskenderun port which is one of Turkeys 10th largest container port, handling around 40 000 TEU per month (My Logistics Magazine, 2023). The management of Iskenderun port falls under responsibility of the General Directorate of Turkish State Railways (TCDD).

Figure 42. Ports of Iskenderun Bay. Image from Can et al. (2019)

B.3.2 Earthquake Impact

The earthquake caused a major fire at Iskenderun port, see Figure 43, resulting in the closure of port operations. The exact cause of the fire remains unclear, but there are reports suggesting that some containers at the terminal contained highly flammable materials. Critics points out that the port lacked the necessary infrastructure and proper training to handle such containers safely (Gazete Duvar, 2023). The fire was put out after 4 days using ships with water cannons, and waterbombing using planes and military helicopters (Paone, 2023). Operations were then able to gradually return. However, one analyst estimated that the damages to the port could result in the port taking up to 3 months to return to normal operation (Chambers, 2023). Ships originally scheduled to dock at Iskenderun port were redirected to Mersin port (Hellenic Shipping News, 2023). Although Mersin port had the capacity to accommodate additional ships, the large increase in ships led to congestions, requiring ships to wait outside Mersin before they could dock. This congestion is believed to have had a nationwide impact on industries' access to raw materials.

The earthquake also disrupted the operations of the Ceyhan oil harbor. This harbor is a significant oil export hub for oil from Iraq and Azerbaijan, handling approximately 650,000 barrels a day. The damage it suffered resulted in oil leaks, forcing the harbor out of operation until operational again February 13 (Daily Sabah, 2023a; Sezer et al., 2023).

Figure 43. Fire at Iskenderun port. Image by @ragipsoylu on twitter (Soylu, 2023).

B.3.3 Quantitative data

Based on data from news reports and official reports the functionality of each port within the Iskenderun Bay were assessed, see Table 13.

Table 13. Details on ports in Iskenderun Bay

Port	Province	Type of cargo	Out of operation	Back in service	Source
Port of Yumurtalık	Adana	Fish	No (none reported)	-	
Botas oil terminal-Ceyhan	Adana	Oil	Yes	Feb 13	(Daily Sabah, 2023a)
Toros Gubre terminal-Ceyhan	Hatay	Liquid cargo	No (none reported)	-	
Botaş Dörtyol LNG Storage Facility	Hatay	LNG	No (active)	-	
Delta Rubis Terminal-Ceyhan	Hatay	Liquid cargo	No (none reported)	-	
Aygaz terminal	Hatay	LPG	No (none reported)	-	
Port of Isdemir	Hatay	Steel	unknown	-	
Ekinciler port Iskenderun	Hatay	Steel	Yes	March 10	(Steel Orbis, 2023)
Sanseki port	Hatay	Fertilizer	No (none reported	-	
Port of Iskenderun	Hatay	Freight	Yes	Approx. 3 months back to full	(Chambers, 2023)

Based on this data recovery curves were made illustrating how different type of cargo were affected by the earthquake. The recovery was assumed linear, gradually returning the system capacity, see Figure 44. System recovery was estimated both for the entire Iskenderun Bay, and for Hatay which has 8 ports in the Iskenderun Bay, see Figure 45, and the recovery and robustness was calculated, see Table 14.

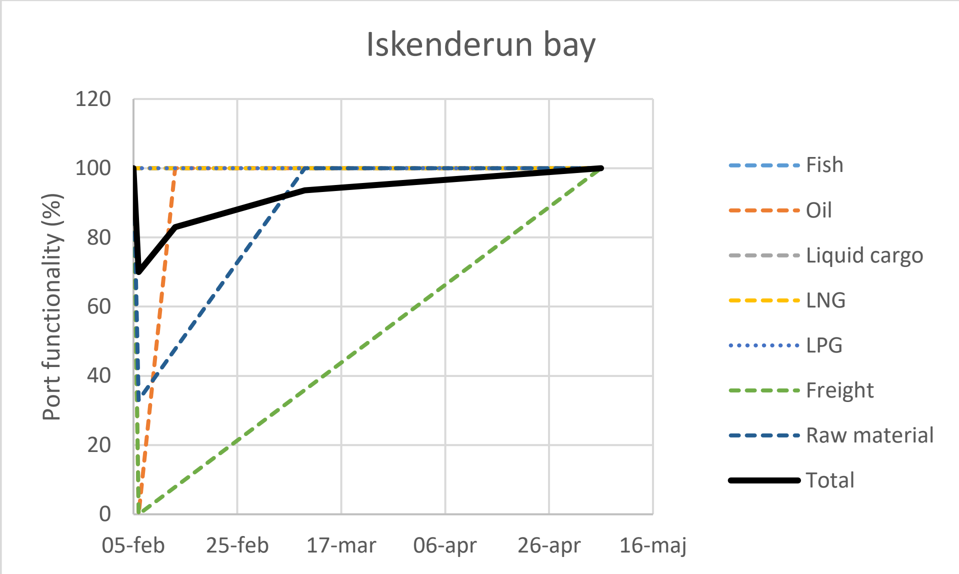


Figure 44. Functionality of the 10 ports in Iskenderun Bay, categorized by type of goods handled at the port.

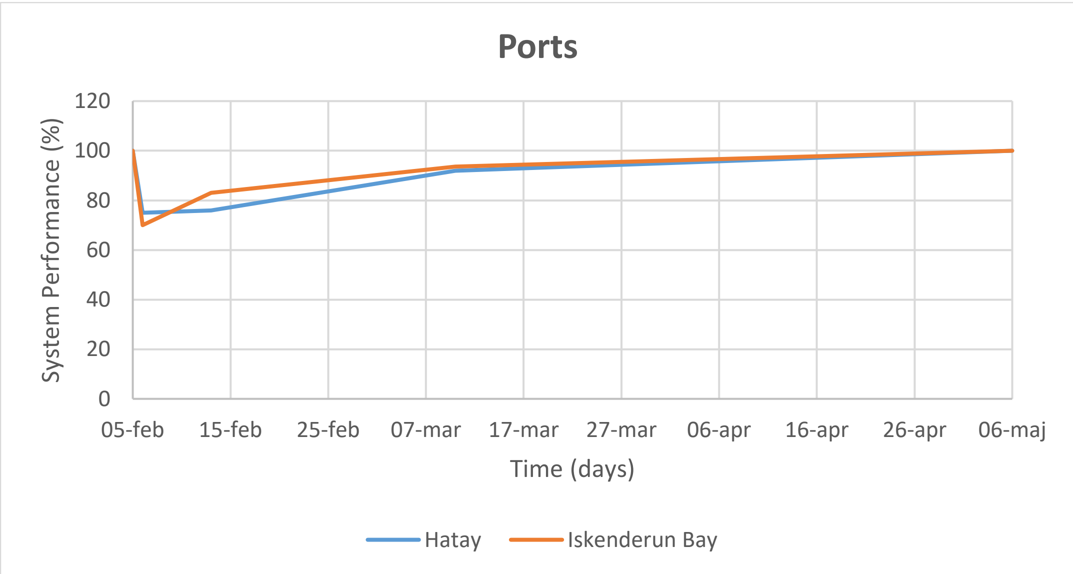


Figure 45. System performance of port infrastructure during the earthquakes

Table 14. Calculated robustness and recovery for ports during the earthquakes.

Ports	Robustness	Recovery
Iskenderun Bay	70%	89 days
Hatay	75%	89 days

Appendix C - Water

C.1. Description of infrastructure

Water infrastructure serves multiple purposes. It ensures the availability of safe water to residents for drinking and personal hygiene, as well for industries where water often is crucial for manufacturing processes. Furthermore, water infrastructure is essential for protecting the environment and ecosystems against waste produced by humans. Lastly, it is essential for the protection of human settlements against flooding. Thus, water infrastructure can be categorized as either freshwater supply, wastewater treatment, and stormwater management.

Sewage water treatment involves collecting the water from residences and industries through sewers and pipes, directing it to treatment facilities for processing (Chodosh, 2017). The treatment process typically begins with sedimentation tanks, where large particles settle at the bottom of the tank for removal. Subsequently, the water is then transferred to tanks equipped with stirs, which mixes the water with active chemicals such as bacteria, which break down organic contaminants, causing their byproducts to settle down. Lastly, the water is often filtered through some kind of fiber membrane, ensuring only liquids is being released to the surrounding nature. This treatment process plays a crucial role in both the management of infectious waterborne diseases in urban settings, such as cholera, and to mitigate the emission of environmentally hazardous chemicals.

The supply of freshwater, also known as potable water, begins with pumping up water from sources such as groundwater aquifers or lakes which are determined safe and clean enough for drinking. This water is then typically treated similarly to sewage water treatment, involving filtration through sedimentation tanks, and the addition of substances to kill microbes but also substances that balances the water to have the right amount minerals such as calcium. Following treatment, pumps are used to transport the water either directly to the customer or to be stored in water towers where the stored potential energy is used to pressurize the water. From there the treated water is distributed to the customers.

According to The World Bank (2016), around 91% of the Turkish population has access to piped water supply and wastewater treatment. The regions without these services are predominantly located rural areas. In Turkey, the management of freshwater supply, wastewater treatment and stormwater management falls under the responsibility of municipal water and sewer departments, like HATSU in Hatay. In larger cities such as Adana and Gaziantep these tasks are managed by autonomous water and sewer administrations (SKIs), such as Adana ASKI and GASKI.

C.2. Earthquake impact

The earthquakes significantly impacted the water infrastructure in parts of Turkey, particularly the provinces of Hatay, Kahramanmaraş and Gaziantep (EERI & GEER, 2023). For instance, in Gaziantep the earthquakes resulted in over 80,000 damages to the water infrastructure, and in Hatay 6 out of 15 districts experienced severe damages with reports of no water for many weeks. The damage sustained by the pipes include pullout of unrestrained joints and ruptures leading to severe leaks in the system. Additionally, the earthquake caused structural damage to water tower, many of which were constructed with concrete, resulting in extensive concrete spalling.

There were also extensive damage to the freshwater and wastewater treatment facilities. These facilities experienced damages to structures such as sedimentation tanks which in some cases allowed water to bypass the sedimentation process (EERI & GEER, 2023). There were also reported damage to electrical equipment such as pumps, as these were often un-anchored allowing them to slide and fall due to the seismic forces. Due to power outages, many of the treatment facilities and distribution pumps had to rely on generators for electricity. The facilities experienced difficulties in obtaining personnel to operate and repair, due to them as well being affected. For example, out of HATSUs 2540 personnel they could only get hold of around 200.

The damage caused to the distribution systems forced residents to rely on alternative sources for drinking water. For example, a large part of Hatay had to be supplied with drinking water through tank trucks for more than 20 days. By February 14, the drinking water distribution across all 10 affected provinces had been restored to 95 % (Ünker, 2023), and by February 20 it had been restored to 98% (NTV, 2023). As of March 19 most drinking water in Hatay were supplied through the distribution system (EERI & GEER, 2023). However, there were reported challenges in maintaining adequate water pressure due to leakages and out of the 15 wastewater treatment plants operated by HATSU, only 10 were operational as of March 19. Moreover, even as of June 19, there were reports of many undamaged and inhabited buildings in Hatay that still were not supplied water through the distribution network, and whose residents were left to obtain water from occasional refill from tank trucks but mainly by buying water from the market (ANF News, 2023).

Even after the systems were operational again, there were still concerns about the potential spread of waterborne diseases from water sources as the extent of leakage from the sewers were unclear (Ünker, 2023). Additionally, there was a fear that hazardous chemicals emitted from the debris caused by the earthquake could contaminate the surrounding environment, including the groundwater aquifers (Yazan, 2023). As a safety measure, many freshwater treatment facilities included liquid chlorine into the drinking water to kill any bacteria (EERI & GEER, 2023).

C.3. Quantitative description

Based on the reports, only 9 out of the 15 districts in Hatay (60%) were supplied with water through the system after the earthquake, and it was not restored fully until March 19 (EERI & GEER, 2023). It is important to note that the quality and suitability for drinking was not considered. This data was used to estimate the system performance using linear interpolation, see Figure 46, and for calculating the system robustness and recovery, see Table 15.

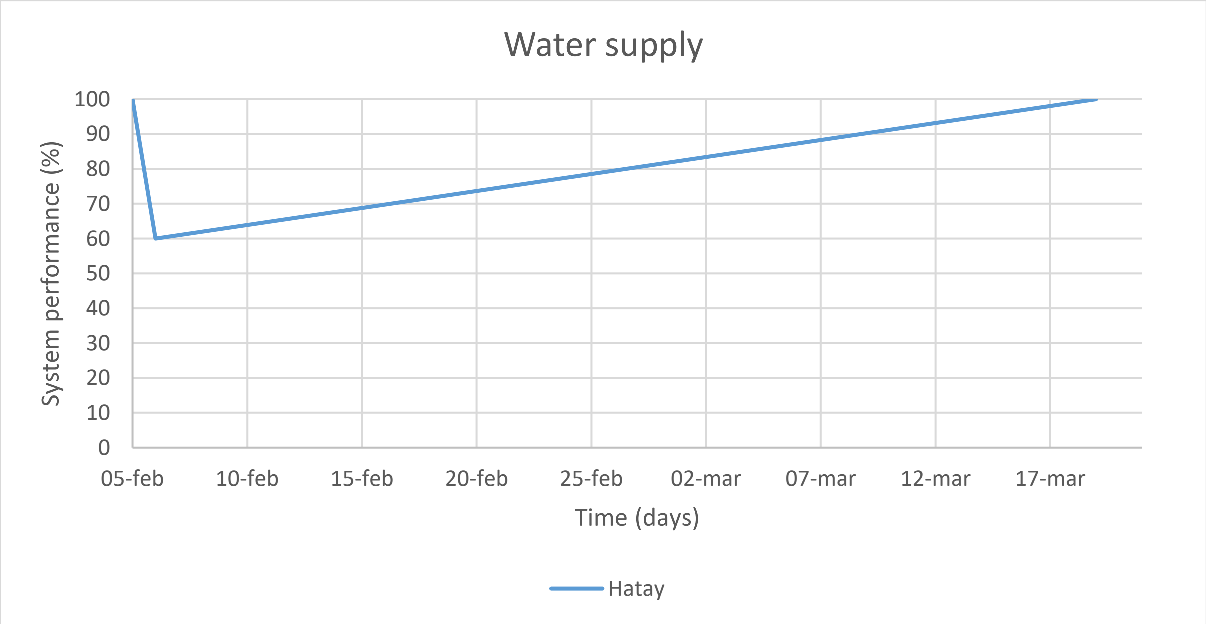


Figure 46. System performance for water supply in the province of Hatay during the earthquakes

Table 15. Calculated robustness and recovery for the province of Hatay duing the earthquakes

Robustness	Recovery	RR
60%	41 days	80%

Appendix D - Industry

D.1. Description of infrastructure

Industries play a vital role for the economic well-being and the functioning of society. Some industries are particularly important as they manufacture components which are crucial for both civil society and the national defense. According to OECD (2019), Turkey considers certain industries as critical infrastructures. However, no data of which or what type of industries they regard as critical could be found. Therefore, for the purpose of this analysis, we will treat all industries as critical.

In Turkey, industries are located in three main types of sites: organized industrial sites (OIZ), small industrial sites (IS), and free sites (FS) (Sagbas et al., 2023). As the name implies OIZ are the more thoroughly planned sites that provide the industries with well-organized lifeline infrastructure, utility services and security within the sites. Turkey holds a position as one of the worlds largest textile exporter, and the areas affected by the earthquake has a significant textile industry (Resililinc, 2023). Additionally, several steel mills and automobile manufacturing facilities are located in these areas.

D.2. Earthquake impact

The seismic impact led to significant damage to industry buildings. According to a reconnaissance conducted after the earthquake, approximately 30% of the inspected industries in the five most severely affected provinces had either completely or partially collapsed, and 54% of the industries experienced severe non-structural damage to equipment. In total around 77% of the industries were completely closed approximately 2 weeks after the earthquake (Sagbas et al., 2023). Most of these buildings were constructed using precast or cast-in-place concrete. The collapses were often in the form of pancake or soft-story failures, indicating issues with the quality of building materials, design and maintenance. In addition to the collapsed buildings, there were reports of fires, which were ignited by causes such sparks from collapsing building parts, or arcs from damaged wiring or electrical equipment such as solar panels collapsing with the roofs. The industries also suffered extensive damage to machinery and equipment which also resulted in a pause in production.

The extent of damage varied across different regions, with industries in Kahramanmaraş and Hatay experiencing significantly more damage than those in Adana, which aligns with the variation in seismic forces measured in these areas (Sagbas et al., 2023). Undamaged or mildly damaged industries attributed staff shortages and disruptions in power, water and gas services as reasons why they had to close down operation for weeks after the earthquake. According to representatives from the industries, the restauration process could take anywhere from 3 months to 2 years to return to normal operations.

D.3. Quantitative description

In the assessment conducted by Sagbas et al. (2023), the structural damage industries sustained was categorized into five different levels, ranging from negligible damage (level 1) to collapse (level 5), see Table 16. Operators mentioned that the restoration process for damaged buildings could take between 3 months and 2 years, depending on the level of damage it sustained.

To calculate the system performance (measuring the percentage of operational industries), I assumed a direct linear relationship between the damage level and recovery time. Specifically, a level 2 damage, sustaining minor damage, would take 3 months to recover. Subsequently, each higher damage level added an extra 7 months to the estimated recovery time, as shown in Table 16. Additionally, I assumed that all industries sustaining any level of structural damage, to be out of operation until the damage is restored. The calculated system performance over time is illustrated in Figure 47, and the calculated robustness and recovery is demonstrated in Table 17.

The authors of the reconnaissance study had collected comprehensive data on the severity levels of structural damage to industries in Hatay. Email correspondence was established with these authors, with an agreement that they would share the data later. However, they stopped responding to emails, and no detailed data for Hatay was collected. Consequently, the system performance in Hatay was instead assumed to be the same as the five worst affected provinces combined.

Table 16. Percentage of industries sustained different state level of structural damage

Structural damage level	**Percentage of industries**	**Time for recovery**
1	36%	0 months
2	19%	3 months
3	5%	10 months
4	6%	17 months
5	33%	24 months (2 years)

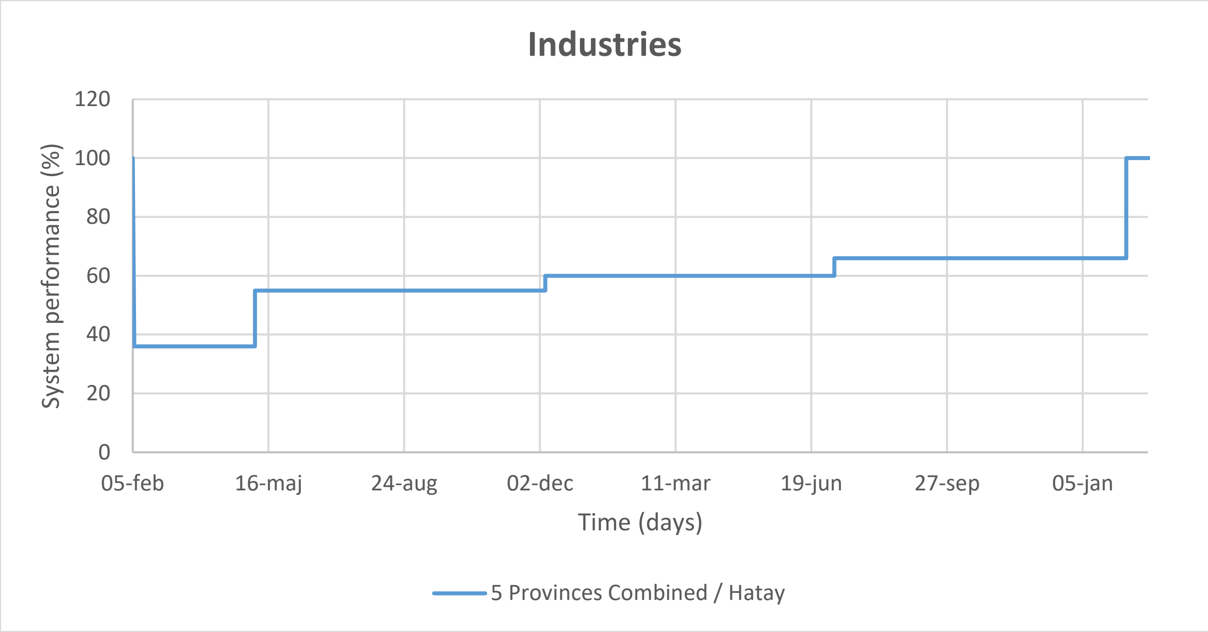


Figure 47. System performance of Industries during the earthquakes.

Table 17. Calculated robustness and recovery for industries during the earthquakes.

Provence	Robustness	Recovery
Total of 5 provinces	36%	730 days
Hatay	36%	730 days

Appendix E - Telecommunication

E.1. Description of infrastructure

Telecommunication (telecom) infrastructure enables the exchange of information over long distances. The term covers various types of systems for exchanging information such as cellphone, radio or internet infrastructure.

Cellphone infrastructure includes many base stations with transmitters and receivers spread out over urban and rural areas for coverage. These base stations communicate with users through radio waves, and information is then sent to a mobile telephone switching office (MTSO) and redirected to the intended user. The same base stations are used for 3G/4G access to the internet infrastructure.

Internet infrastructure involves users, either directly or through base stations, connected through fiberoptic to internet service providers facilities (ISP). These facilities consists of switches and routers which in turn connect the users to the larger network of network (Tyson & Pollette, 2001). Internet exchange ports allow different ISPs to interconnect, enabling communication between users and servers outside their own providers network. Companies and organizations store information in servers which can sometimes be small scale and located in their own offices, and sometimes outsourced and co-located with multiple other organizations information in large server facilities. In Turkey, the largest telecom service providers, both cellphone and internet, are Turkcell, Vodafone and Turk Telekom.

E.2. Earthquake Impact

The earthquake severely affected the three largest telecom providers in the affected area, Turk Telekom, Vodafone and Turkcell. The loss of telecom service were primarily caused by power outages, although many base stations also suffered damages. For instance, Turk Telekom reported that 165 of its 2573 base stations in the affected areas were either heavily damaged or completely destroyed (Cumhuriyet, 2023). In many cases, the damage could be attributed to the collapse of the building on which the base station was placed. In total 2451 of the 8900 base stations (28%) in the affected areas were disabled after the earthquake (Merkezi, 2023). However, the ISP and MTSO facilities experienced minimal or no disruptions, and thus the core network services were operational shortly after the earthquake (BBC Türkçe, 2023).

Based on assessments by Cloudflare Radar, see appendix A, there was a rapid decline in internet traffic after the earthquakes. In Turkey as a whole, the observed internet traffic was approximately 80% of the normal levels on the day of the earthquake, and it took about a week for the national internet traffic to return to normal levels. However, for the provinces that were directly affected by the earthquake the impact was significantly greater. For instance, Adiyaman's internet traffic was only around 3% of the normal levels on the day of the earthquake, and even after 3 weeks it still had less than 20% of the usual traffic.

To restore the functionality, authorities coordinated with telecom providers and technology companies the instalment of over 400 temporary satellite connected mobile base stations across the affected regions (TR Haber, 2023), see Figure 48. Almost half of these mobile base stations were installed in the Hatay province. These along with the undamaged stationary base stations were powered by generators. However, the generators could only supply the base stations with energy for about 3-4 hours before needing refill of fuel (Strateji ve Bütçe Başkanlığı, 2023). Because there were significant logistical issues in supplying the generators with fuel, the network experienced unstable connections (Dünya, 2023b). As response, the GSM operators used a lot of human resources to find fuel for the generators (Çelik, 2023).

Figure 48. Mobile satellite base station. Image from TR Haber (2023)

On February 8th, the Turkish government temporarily shut down access to Twitter in some of the affected areas to tackle the spread of misinformation about the earthquake on the social media platform (Butler & Coskun, 2023; Satariano, 2023). This shutdown was met with massive criticism from emergency relief organizations, as Twitter had proven to be an important platform for damage assessment and crisis communication. As a result of the backlash, access to the platform was restored after about 8 hours.

There was an observed widespread public dissatisfaction with the three major telecom operators due to the extent of disruptions caused by the earthquake and the slow recovery process. Arguments were raised that the companies had not adequately prepared for or proactively invested in infrastructure improvements against future earthquakes (HT, 2023; Küçükbarak, 2023). This dissatisfaction was significant enough for a criminal court case to be opened to investigate whether these companies had fulfilled their obligations during the earthquake or if they could be held responsible for obstructing efficient search and rescue efforts due to disruptions in communication infrastructure.

In response to the criticism, the deputy director of Vodafone defended the company´s efforts by pointing out that achieving sustainable and reliable recovery solutions are challenging without resolving the issues in energy, logistics and transportation, as these are crucial for restoring telecommunication (Dünya, 2023b). The Vodafone CEO also described in an interview that the telecommunication infrastructure should be greater prioritized when it comes to fuel and electricity infrastructure, as well as given pass in traffic during disasters similar to emergency rescues vehicles, arguing for its importance in society (Çelik, 2023).

Additionally, he argued, that while tower structured base stations have a greater coverage in rural areas, but in an urban highly dense area, these are ineffective and he thus suggested a more focus on building more redundant top of the line base stations over establishing more tower base stations in cities (Çelik, 2023). However, he also mentioned a public reluctance of having base stations placed on top of their residential buildings or near their homes, sometimes due to health concerns, which poses challenges when trying to build a more redundant urban telecom system. Further, he issued challenges for GSM operators to know the seismic resistance both of buildings on which the base stations are placed on top, but also for the neighboring buildings, and called for better and more open assessments of buildings suitability provided to the GSM operators. Finally, he also mentioned that telecommunication should prioritize certain critical entities in times of disaster, such as emergency personnel, hospitals and energy sector.

E.3. Quantitative description

System performance of telecommunication was estimated to corrolate with changes in internet traffic. The data for the internet traffic compared to previous weeks was collected using social media posts by Cloudflare Radar weekly during the month following the earthquake[2]. The data only covered the first three weeks, and certain provinces had not yet recovered fully. Table 18 demonstrates internet traffic for the

Table 18. Internet traffic for the affected provinces

Province	6-feb	27-feb
Gazientep	43%	30-60%
Kahramanmaraş	6%	20%
Osmaniye	12%	30-60%
Hatay	24%	30-60%
Kilis	37%	100%
Sanliurfa	30%	100%
Mardin	36%	100%
Adana	27%	100%
Adiyaman	3%	20%

For turkey in general, Cloudflare Radar measured the following recovery for the internet traffic:

Table 19. Internet traffic compared to normal for Turkey nationwide

6-feb	10-feb	14-feb
80%	91%	100%

[2] Sources for Cloudflare social media posts by date:

27 February: https://cloudflare.social/@radar/85323de5-01d7-4f9b-b13a-568bc4c87565

21 February: https://cloudflare.social/@radar/d6663eca-7a8d-4fef-95e9-44cfe83d4974/

14 February: https://cloudflare.social/@radar/d675f72d-acee-42fc-9778-3bf8bbb8ed0d/

6 February: https://twitter.com/CloudflareRadar/status/1622430747620528130

Since several regions did not restore by the last update of February 27, an extrapolation of data was used to estimate a restoration time. An assumption was made that restoration followed an exponential function, see equation (3), where t_0 is February 6.

$$F(t) = F(t_0) + e^{b*(t-t_0)} \tag{3}$$

To calculate the constant b was then calculated as:

$$b = \frac{\ln\left(F(feb\ 27) - F(feb\ 6)\right)}{feb\ 27 - feb\ 6}$$

This exponential function was used for both extrapolating the data for the provinces which had not yet recovered by February 27, and to interpolate the values for the provinces which had recovered. The estimated system performance curve for the affected provinces is illustrated in Figure 49, and the calculated recovery and robustness is presented in Table 20.

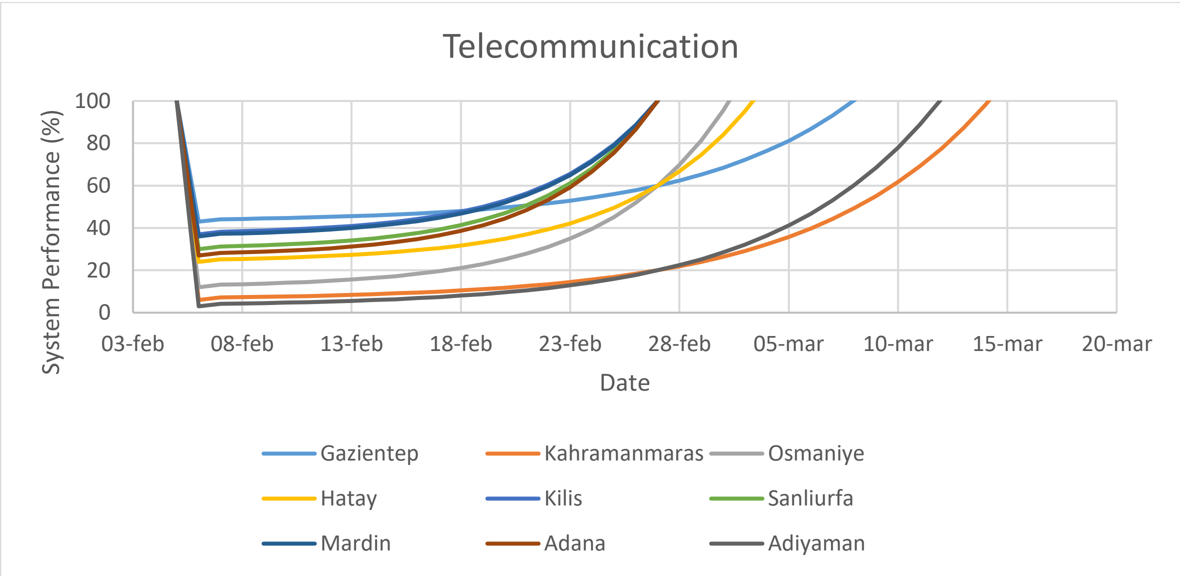


Figure 49. System performance for telecommunication during the earthquakes

Table 20. Calculated recovery and robustness for telecommunication during the earthquakes

Province	**Recovery (Days)**	**Robustness (%)**
Hatay	26	24
Gazientep	30	43
Kahramanmaraş	37	6
Osmaniye	25	12
Kilis	21	37
Sanliurfa	21	30
Mardin	21	36
Adana	21	27
Adiyaman	34	3

Appendix F - Interdependency

The following table describes both interdependencies observed and reported through news reporting and data is assessed from the respective infrastructure Appendixes above. As data was limited and there was a will to rather be conservative than optimistic, assumptions of interdependencies present were also included into the assessment.

The assumptions of interdependencies is categorized into two types. The first type assumes that if a specific interdependency was observed in one CI sector during the earthquakes, it could also be assumed to exist in another CI, unless proactive measures were in place. The second type of assumption is based on the presence of a particular interdependency in previous natural hazard or earthquake events, which could be assumed to also have been present in the earthquake of study.

Each observed interdependency were given a strength value based on its magnitude of impact on the other CIs robustness ($\mathbf{I_{Robustness}}$) and recovery ($\mathbf{I_{Recovery}}$), see Table 21. A value of 1 indicates a minor impact, while a value of 5 indicates a major impact. A value of zero indicates no assumed impact, although it may have had an impact that was unknown to the assessor.

Table 21. Interdependencies. Marked in yellow indicates assumed interdependencies due to observed occurrence in other CI. Marked in red indicates assumed interdependencies due to logical deduction

Dependent CI sector	**Originating CI sector**	**Observed Interdependency**	$\mathbf{I_{Robustness}}$	$\mathbf{I_{Recovery}}$
Electricity	Highway	Disrupted accessibility for reparation and maintenance of components	0	4
		Fuel imports for power plants such as coal disrupted due to disruption in railway	3	
	Fuel infrastructure	Disruption in pipeline infrastructure caused disruption in natural gas power plants	2	0

	Port	Fuel imports for power plants such as coal disrupted due to disruption in ports	1	0
	Railway	Fuel imports for power plants such as coal disrupted due to disruption in railway	1	0
	Telecommunication	Disruption in telecommunication makes coordination and reparation difficult	0	3
		Disruption in telecommunication resulting in disruption in control system	2	
	Other (Fuel infrastructure)	Shortage of fuel for machinery and equipment		3
Highway transportation				
	Telecommunication	Disruptions in telecommunication makes restorative efforts of roads more difficult	0	3
	Other (Fuel infrastructure)	Shortage of fuel for machinery	0	3
Railway transportation	Electricity	Many trains in the region is driven by electricity	5	0

	Highway transportation	Accesssability on highwasmportant for restoration	0	4
	Other (Fuel infrastructure)	Shortage of fuel for equipment and vehicles	0	3
Maritime transportation	Railway transportation	Much freight is transported to Iskenderun port by railway. As much of the railway were closed it can be assumed it caused a disruption of flow.	3	0
	Highway	Disrupted accessibility caused delay for reparation of ports	0	4
Potable Water Supply	Other (Wastewater treatment)	Uncertainties regarding leaks in sewage systems, caused supplier to raise caution about	4	0
	Electricity	Large scale power outages, disrupting the functionality of the water supply	4	2
Industry	Electricity	Large scale power outages, disrupting the ability to produce	5	0
	Water supply	Disruption in water supply affect industries	2	0

		where water is an important component		
	Maritime transportation	Fire at Iskenderun port caused congestion outside Mersin causing disruption in Raw material access	2	0
	Wastewater treatment	Inoperable Wastewater treatment makes it not possible to operate industries	1	
	Highway transportation	Disruption in roadways affect supply of materials used for production, and the distribution of products	3	
		Disruption also slows recovery and reconstruction efforts as it makes it difficult to transport heavy equipment		4
	Telecommunication	Disruption in telecommunication makes coordination and reparation difficult		3
Telecommunication	Other (Fuel infrastructure)	Shortage of fuel for generators		3
	Highway transportation	Disrupted accessibility for reperation and maintenance of generators		5

	Electricity	Large scale power outages, disrupting the functionality of the telecommunication	5	1