This is a portion of the eBook at doi:10.7551/mitpress/11771.001.0001

1 Introduction: A Tool Kit for Understanding Infrastructure and Repair

Bridge Collapse in Minneapolis

On Wednesday, August 1, 2007, at 6:05 p.m., the Interstate 35W bridge over the Mississippi River near downtown Minneapolis suddenly and completely collapsed without warning, sending a roadway full of rush-hour traffic plunging more than one hundred feet into the river below.[1] Surveillance video shows the steel truss supporting the central span of the roadway giving way and dropping into the river in a cloud of spray, followed by the rapid collapse of the rest of the bridge.[2] Some approaching drivers barely succeeded in stopping as the road in front of them vanished. Others were unable to stop and drove over the edge. Altogether, 111 vehicles were caught up in the collapse, including a school bus full of children; 145 people were injured and 17 died. Fortunately, quick action by bystanders and emergency responders led to the rescue of almost everyone who survived the initial collapse, including all the students on the bus.[3]

An event like this is shocking not just because of its human toll, but also in the way it upends expectations. Infrastructures like roads, sewers, and mobile phone networks are so central to daily life that when they are reliable, they tend to fade from conscious awareness. Even an iconic landmark like the Golden Gate Bridge, which is frequently visited, photographed, and seen in movies, is rarely appreciated for functional characteristics like the integrity of its girders, the stability of its footings, and its margin of safety under heavy traffic loads. The mundane, functional aspects of infrastructure tend to come to the surface when something has gone wrong: the reliability of the electrical grid might become a major topic of interest after a power outage; the locations of mobile phone towers might come to mind when cellular signal is lost. And while material objects like bridges or mobile phone towers are easy enough to track down if you choose to look for them, there is another mundane aspect of infrastructure that is more ephemeral: the constant repair and maintenance work crucial to keeping any infrastructure in working order decades after it is built. This work might not be noticeable on a daily basis, but when a bridge collapses suddenly after more than forty years of unproblematic service, it is natural to start thinking about whether it was in good repair.

So it went with the I-35W bridge collapse: a bridge that few people, even those who drove over it every day, paid much attention to suddenly became a top story on the national news, with a focus on its repair and maintenance.[4] Of particular interest was the fact that inspectors had rated the condition of the bridge superstructure as “poor” for seventeen consecutive years prior to the collapse, leading to a federal designation of the bridge as “structurally deficient.”[5] Reporters connected this to a broader narrative of nationwide infrastructure decay (which we discuss in more detail later in this chapter), a rare moment of focused national attention on infrastructure repair and maintenance and an opportunity for the general public to ponder some uncomfortable questions, such as: Is the infrastructure beneath our feet really as strong and solid as it seems? Are we as a nation placing enough of a priority on infrastructure maintenance? Who does all that repair and maintenance work anyway, and are they doing a good job? And what prevents bridges that we drive over every day from collapsing underneath us? Of course, as the disaster inevitably faded from memory, people went right back to driving over bridges without asking themselves these questions. More than a decade later, we would guess that most readers of this book have only a hazy recollection of this event, if they heard of it at all. Our goal for this book is to keep the focus on these uncomfortable questions and, more importantly, provide a set of tools and concepts to make sense of how repair and maintenance keep infrastructure in working order.

Repair as Social and Technical Work

Repair, as we use the term in this book, is the work required to maintain technologies of all kinds—from heroic efforts in moments of breakdown and crisis to the mundane and hidden maintenance work that keeps things running day-to-day.[6] The main aims of this book are to show how the enduring function and influence of infrastructure are made possible by the constant work of repair and to explore the causes and consequences of the strange, ambivalent, and increasingly central role of infrastructure repair in our lives today. To address these issues, we take a broad view of repair, which we describe briefly before returning to the I-35W bridge example.

While today the term *repair* is perhaps most often used to describe the hands-on work of restoring material things to working order, it has been used to describe the act of restoring or rebuilding all manner of things that are “damaged, worn, or faulty.” These include objects and structures; cities; countries; a person’s appearance or health; bodies and body parts; and immaterial things like friendships, honor, status, and finances.[7] In a more specialized use in sociology, *repair* is also used to refer to the methods we use to overcome misunderstandings and interruptions in conversations.[8]

We embrace all of these uses of *repair* because we see this process as fundamentally one of restoring both social and material order—a crucial point. Although we focus on material repair in this book, we argue that it almost always goes along with repairs to other forms of order. So, for example, restoring a fallen bridge may also serve to repair a city’s transportation network and public trust in engineers and politicians; repairing an office air-conditioning vent may also involve gently adjusting an office worker’s expectations about temperature and airflow; and retrofitting a bridge to resist earthquakes may also involve rebuilding trust between a state transportation agency and community activists, as well as maintaining the appearance of murals painted on the bridge columns. (These are all case studies we return to later in the book.)

More specifically, our perspective on repair emphasizes (1) the broad range of activities that go on under the heading of repair; (2) the dual social and technical nature of most material repair work; and (3) the variety of scales of repair work, from local fixes to broad, systemic efforts. We address each of these in turn.

Our first key point about repair emphasizes its ubiquity: we all engage in repair work on a daily basis, even when we might not realize we are doing it. Everyday aspects of repair work include hitting a machine just the right way so it stops making an annoying sound, debating with a family member about whether to continue repairing an older car that has seen better days, calling a tech support hotline to troubleshoot a computer problem, or emailing a local official to complain about the condition of roads in your

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neighborhood. In these cases, repair work is not always about directly fixing a piece of technology, and the actions are less specialized than those performed by an auto mechanic, tailor, or building contractor. Many of the examples we present in this book do focus on specialized repair workers, but in these cases, we show how their work is associated with broader discussions and arguments about what needs to be repaired, how it should be repaired, and even whether it is actually broken in the first place. These interactions can bring together a variety of individuals from different walks of life and play an important role in negotiating the evolving form and meaning of our infrastructures.

Expanding on our second point, looking at repair from a broad social and technological perspective provides a richer picture of infrastructures and how they function. Many infrastructures have a hard material structure, such as the columns and spans used to construct a bridge. By tracing the repair work of diverse actors, however, we start to see infrastructures as complex hybrids of material as well as social and political elements, and it is usually hard to separate them.

For this reason, we follow the lead of other scholars of science, technology, and society in describing infrastructures as *sociotechnical systems*.[9] This term emphasizes the tangled messiness of infrastructures, which are made not only of concrete, steel, and wires but also budget appropriations, engineering standards, and backroom dealmaking. A sociotechnical lens helps us see how repair can engage more diverse sets of people and things than we might expect, because the work of repair can include tinkering with any of these elements. In addition, understanding infrastructures as complex sociotechnical systems, with histories of contingency and change, makes it clear that they are part of our culture and politics. They are therefore connected to the broader structures of privilege, inequality, and justice that shape who has control and whose interests are ignored when it comes to building and repairing infrastructures. An infrastructure that seems to be working just fine to one group of people may seem in desperate need of repair to another.

Finally, addressing our third point, repair takes place at many different scales, particularly where infrastructural systems are concerned. Much of the hands-on work of infrastructure repair is done by individuals or small groups focused on solving local problems. But infrastructures can also fail in global ways, leading to the intervention of system operators, engineers, managers, and even political leaders, which can bring various interest groups and the general public into the process as well. On a global scale, international standard-setting organizations and negotiations among nation-states may also play an important role. Our view of repair encompasses the activities of all of these actors and their interactions: whether repairing infrastructures through logistical or political means, or through direct material engagement, a diverse range of players each have their own crucial roles in identifying and repairing infrastructure breakdowns.

Sociotechnical Repair and the I-35W Bridge

The I-35W bridge collapse is a useful example for understanding how some of these aspects of repair and maintenance come into play in a real-world infrastructural context. It is particularly relevant because much of the subsequent investigation centered around issues of repair and maintenance, meaning that we have an unusually deep record of the role of these activities in the life of this bridge. As we will see, the fact that this bridge collapsed does not mean there was anything particularly special about its repair or maintenance history; what is special is that we have such a good public record of these routine activities due to the investigation.

After opening for traffic in 1967, the bridge was inspected annually starting in 1971, as required by federal regulations.[10] This was a fairly involved process, taking five or six days, in which a team of inspectors closely examined every piece of the bridge—in some years from a required distance of 24 inches or less.[11] Inspection was mostly visual, with some help from tools for detecting cracks not yet visible.[12] These kinds of inspections are how bridge engineers identified repair and maintenance needs. Inspectors rated the bridge “structurally deficient” starting in 1991, mostly due to the rusty condition of its bearing devices.[13] Although this sounds serious, it did not indicate a major safety concern, but rather that the bridge was in a condition to be eligible for additional federal maintenance funding.[14] If inspectors felt there was a safety issue, they had the option of finding a “critical deficiency” and closing the bridge to traffic. They never took that step.

Beyond efforts to address rust and other more expected wear and tear, repair workers commonly fixed cracks in the steel, which was usually done by drilling out a hole 1.5 to 2.0 inches in diameter at each end of the crack, preventing it from spreading farther.[15] Occasionally workers would add reinforcements to the steel in areas where cracks had become particularly bad.[16] Eventually engineers realized the cracks were due to metal fatigue,[17] and the Minnesota Department of Transportation (MnDOT) funded several studies on ways of retrofitting the bridge structure to minimize this issue,[18] which were still underway when the bridge collapsed.[19]

Besides repairing wear and tear, MnDOT added several new features to the bridge over the years to address changing needs. First, in 1977, they increased the thickness of the concrete on the bridge deck to protect against corrosion due to road deicing chemicals. By 1998, the median barrier and railings on top of the bridge no longer met current safety standards, so these were removed and replaced. At the same time, a computer-controlled anti-icing system was added to address the large number of winter accidents on the bridge.[20] In 2007, contractors were in the process of grinding down and replacing the aging concrete of the bridge deck when the bridge collapsed.

Despite the prominence of repair and maintenance issues in the investigation, the National Transportation Safety Board (NTSB) ultimately concluded they had almost nothing to do with the collapse of the bridge. They instead found that the bridge was done in by a mistake in the design of its gusset plates, the metal plates that are used to attach bridge girders to one another: the plates were much too thin, and they would have eventually led to the collapse of the bridge even if it was in perfect condition.[21] This issue was missed throughout the lifetime of the bridge because gusset plates were generally built so much stronger than necessary that bridge engineers and inspectors never gave them much thought. So firm was this bias that even when inspectors had noticed that the gusset plates were bowed, they assumed it to be a relatively harmless construction defect, not a sign of imminent structural failure.[22]

Others vehemently disagreed with the NTSB's conclusions. In particular, construction attorney Barry LePatner has argued that the NTSB report downplays deterioration and maintenance problems with the bridge. He suggests that if efforts to retrofit the bridge to address the fatigue cracking issue and add structural redundancy had proceeded with more urgency, the resulting improvements might have prevented the collapse, and the gusset plate design error might have been noticed earlier.[23] And even the NTSB agreed that repairs to the bridge deck were, ironically, the immediate cause of the collapse: the weight of piles of construction materials, which ordinarily would not have been a problem, turned out to be the last straw that caused the weak gusset plates to give way.

After the bridge collapsed, additional repair concerns emerged around construction of a new bridge and how to prevent similar accidents in the future. For the Minnesota state legislature, the solution was to spend money to fix older bridges regardless of the NTSB findings. A few months after the collapse, the legislature passed a gas tax increase with bipartisan support that was used to fund a major bridge improvement program, with a focus on updating fracture-critical and structurally deficient bridges. They did this over the veto of Governor Tim Pawlenty, who used the NTSB findings to argue that the spending was unnecessary. Thanks to these improvements, the percentage of urban freeway traffic traveling over "structurally deficient" bridges in Minnesota had dropped from almost 6 percent to a little over 1 percent by 2016.[24]

For the NTSB, since their investigation identified a design error as the cause, the question became how to catch similar errors in the future. Instead of material changes to bridges, their recommendations called for improvements in design and inspection processes. These included new design quality assurance procedures, new bridge inspection procedures related to gusset plates, new procedures for assessing bridge load capacity, and new guidelines for placement of construction material.[25] Essentially the board identified breakdowns in the behavior of bridge engineers and inspectors, and the way to repair these breakdowns was to change the regulations that governed their actions. Again, this reveals that what keeps a bridge functioning is not just steel beams, gusset plates, rivets, and concrete, but an entire sociotechnical system that includes things like documents and training, professional standards, and organizational procedures.

The final question was what to do about the gaping hole that now existed in the center of the Minneapolis road transportation network. This is yet another level of repair, related to issues of scale. There was no longer any question of repairing the bridge itself, which lay in a tangled mess on the river banks. Instead, attention shifted to repairing the larger infrastructure system it was part of. In the short term, this meant rerouting traffic and adding travel lanes to alternative roadways.[26] In the longer term, it required replacing the bridge. With quick action to secure federal funds and an accelerated contracting and construction process, a state-of-the-art replacement bridge was completed and opened to traffic just thirteen months after its predecessor's collapse—quite a contrast to the drawn-out efforts to repair structural issues with the older bridge before its collapse.[27]

In the end, this story suggests two distinct ways in which maintenance and repair were integral to the life, and demise, of the bridge. First, repair and maintenance were absolutely essential to protect the bridge from degradation through aging and wear and tear. In concluding that inadequate repair and maintenance were *not* to blame for the collapse of the bridge, the NTSB's conclusions give short shrift to the role they may have played in preventing a collapse. Were it not for the extensive efforts of engineers to address fatigue cracking and other mundane impacts of aging, it seems quite possible that the bridge could have collapsed sooner than it did. Yet other efforts to prevent degradation, like adding concrete to the bridge deck to resist corrosion, may have indirectly contributed to the collapse by increasing the load on the structure—and, in the case of the final effort to refurbish the bridge deck, directly contributed to the collapse. The complex role of repair and maintenance in these events, however, makes it clear how essential these activities are to understanding the existence of infrastructure over time.

Second, the story of the I-35W bridge shows that not all repair and maintenance work is necessarily driven by material changes in infrastructure. The drawn-out efforts to address the fracture-critical design of the bridge are a case in point. These were driven not by aging or wear and tear, but by changes in engineering knowledge and safety standards over time, which led to features of the bridge that had seemed perfectly acceptable in the 1960s being seen as dangerous flaws only a few decades later. Through these developments, the materiality of the bridge was interpreted in new ways, leading it to appear very different to engineers by the 1990s. These changes in knowledge and standards are common during the life spans of major infrastructures and are another important driver of repair and maintenance work—which in this context are often described in terms of *retrofit*, a topic we explore in more detail in chapter 3.

In summary, the story of the I-35W bridge collapse illustrates the complex, materially and socially entangled nature of breakdown and repair, particularly with regard to infrastructure systems. The cast of characters includes bridge inspectors who did not see distorted bridge components, designers making inexplicable errors, MnDOT personnel who moved slowly to retrofit an obsolete bridge, contractors who designed and built a new bridge in record time, and congressional representatives who quickly pulled together the votes to pay for a new bridge. On the material side, a varied cast of entities also make appearances: rust and cracks, gusset plates, roadway surfaces, construction materials, and road networks, to name a few. They come together in many different locations: the banks of the Mississippi, the bridge deck high above, the drafting tables of bridge designers, meeting rooms of the MnDOT, and ultimately the halls of the US Congress. Taking a broad, sociotechnical perspective on repair and infrastructure enables us to see how repair plays out across this wide spectrum of people, things, and places.

Infrastructures as Vulnerable Systems

Infrastructure has become an increasingly settled and necessary term for a central phenomenon of modern life: the large, interconnected, standardized technological systems that play an essential role in our everyday activities. However, this use of the term has relatively recent origins that are closely connected to an interlocking set of interests around defense, economic development, and the engineering profession. The concept of infrastructure has historically become relevant when people are concerned about the destruction, sustainability, repair, and maintenance of socially essential systems. With this in mind, the focus on repair and infrastructure in this book is not just an arbitrary convergence of two unrelated topics; in fact, this convergence cuts to the heart of what both infrastructure and repair are all about and why we as a society care about these topics at this historical moment.

The earliest use of the term *infrastructure* in something similar to the modern sense was in the 1950s, mainly in a military context, to refer to the “fixed installations which are necessary for the effective deployment and operations of modern armed forces,”[28] including not only military installations, but highways, bridges, airports, and power plants—all of which were seen as potential targets for strategic bombing.[29] Also in the 1950s and 1960s, the concept of infrastructure gained currency in the field of international economic development, where it was used to describe the “capital base” a country needs to invest in to enable the development of other economic activities. Again, this included things like highways and power plants, but over time, it came to encompass a wider range of systems, including social institutions like education and health care.[30] Building on these earlier uses of the term, infrastructure became more broadly relevant starting in the early 1980s, this time embedded in alarming narratives about the poor condition of US infrastructure, here referring mostly to public works such as roads, bridges, water pipes, and sewers. This usage was tied to economic recession and the argument that investment in infrastructure was critical to restoring economic prosperity. Planning and public works organizations released influential reports with dramatic titles like *America in Ruins* that emphasized this point.[31] Although investment in new infrastructure was encouraged, these reports also documented a dire need for the maintenance of existing infrastructure.

This narrative has proven remarkably durable, in part because of the strategy of assigning grades to US infrastructure, which originated in a 1988 report and has since been taken up by the American Society of Civil Engineers (ASCE).[32] The ASCE has published its version of a national “Infrastructure Report Card” every two to four years since 1998, which has never given US infrastructure a grade higher than a close-to-failing D+.[33] This provides a powerful rhetorical framing that seems to be invoked any time infrastructure becomes problematic. One reason the collapse of the I-35W bridge briefly resonated at the national level was that multiple media accounts attached it to this preexisting, easily understood narrative.[34] This narrative remains relevant as we write this book, having been a major topic of bipartisan interest in the 2016 US presidential election campaign.[35]

Since the 1990s, and especially after the terrorist attacks of September 11, 2001, infrastructure has gained broader relevance, particularly in the United States, in the context of “homeland security” and protection of “critical infrastructure” from natural disasters and attacks.[36] In this role, its meaning has come to encompass all of the sectors mentioned above—from massive engineered systems to complex, changeable sociotechnical arrangements like health care and financial services (see the text box).

As this brief history indicates, the concept of infrastructure encompasses not just a particular set of technological systems, but a central anxiety of modern life: the idea that we increasingly depend on vast, complex, interconnected webs of essential systems that may be unexpectedly vulnerable, placing economic and political stability at risk. In other words, the concept of infrastructure emerged alongside and as part of a larger social discourse on risk, vulnerability, technological decay, and repair and maintenance.

The 2013 US National Infrastructure Protection Plan

A series of executive orders and policy directives by the presidential administration of Barack Obama led the US Department of Homeland Security to develop the 2013 National Infrastructure Protection Plan (NIPP), itself an outgrowth of security policy directives from the George W. Bush administration in the first several years after 9/11. The NIPP identifies sixteen critical infrastructure sectors "considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof."[1] These sixteen sectors provide a useful orientation to the wide range of systems considered to be infrastructure in this context.

The Sixteen Critical Infrastructure Sectors according to the NIPP

Chemical
Commercial Facilities
Communications
Critical Manufacturing
Dams
Defense Industrial Base
Emergency Services
Energy
Financial Services
Food and Agriculture
Government Facilities
Healthcare and Public Health
Information Technology
Nuclear Reactors, Materials, and Waste
Transportation Systems
Water and Wastewater Systems[2]

[1] US Department of Homeland Security, "Critical Infrastructure Sectors," Department of Homeland Security, March 5, 2013, https://www.dhs.gov/cisa/critical-infrastructure-sectors.

[2] US Department of Homeland Security, "NIPP 2013: Partnering for Critical Infrastructure Security and Resilience," 11. https://www.cisa.gov/sites/default/files/publications/national-infrastructure-protection-plan-2013-508.pdf.

Infrastructure in Science and Technology Studies

Alongside the increasing public interest in infrastructure, it has become a core topic in the field of science and technology studies (STS), the primary community we participate in as scholars, and in related fields like anthropology, geography, urban studies, and information studies.[37] Work in all of these fields is diverse, yet united in treating infrastructures as sociotechnical systems, which is also key to our perspective here.

STS takes a broad view of infrastructure that incorporates both its small- and large-scale properties, and the tensions that emerge between these scales. At a larger scale, STS studies have emphasized the structural characteristics of infrastructures, focusing on those that distinguish infrastructures from other kinds of sociotechnical systems. From this top-down perspective, which originated from historical studies of large technological systems, a system becomes an infrastructure when it transcends its regional context to connect with other systems and gains national or global reach.[38] For example, early electric lighting systems served a single neighborhood or city but have evolved into nationally or internationally connected power grids.[39] This kind of global reach is enabled by the development of universal gateways and standards, such as physical plugs and sockets, communication protocols, and classification frameworks.[40] At this scale, structural connections among infrastructure networks, geophysical forces, and governance become more important than local interactions.

STS studies have also examined infrastructures in localized settings where people work and interact. Here, infrastructures are distinguished more by their relationships to other elements of these settings than by their structural features. Specifically, infrastructures show up as integrated resources that support and enable a wide range of local activities and technologies, becoming infrastructures *for* those activities and technologies.[41] This research, which has more sociological roots, represents a kind of bottom-up perspective, focusing on how infrastructures enable and constrain users: for example, something that serves as functional infrastructure for one person or group—such as stairs—may become a barrier to others—for example, people who use wheelchairs.[42] In this view, infrastructures are characterized by the way they are embedded, “sunk into and inside of other structures, social arrangements, and technologies.”[43]

There are important connections between the top-down and bottom-up perspectives on infrastructure in STS: the global reach and standardization of large-scale infrastructure systems makes it easier to integrate them into a wide range of localized activities, but the local work of assembling and adapting infrastructure resources to meet local needs shapes demand and spurs efforts toward repair and innovation.

The Growing Interest in Repair and Maintenance

Increasing public concern about breakdown, repair, and maintenance of infrastructure has also coincided with increased interest in these topics in STS and related fields, particularly in the past decade or so. Starting well before this recent surge of interest, our own work played an early role in establishing repair and maintenance as important topics in STS and sociology contexts, beginning with Henke's 2000 article, "The Mechanics of Workplace Order: Toward a Sociology of Repair," a close ethnographic study of repair and maintenance technicians at a university, and his 2008 book on the role of repair in the California agricultural industry.[44] This work, along with related work by STS and urban studies scholar Stephen Graham and geographer Nigel Thrift[45] and sociologist Tim Dant,[46] helped prepare the ground for more recent work that makes a broader case for the importance of repair and maintenance as a topic of academic as well as practical interest, supported by numerous new case studies.[47]

STS and information studies scholar Steven Jackson, writing in 2014, coined the evocative term *broken world thinking* to explain why repair and maintenance must become central to our understanding of the nature of technology.[48] Broken world thinking is ubiquitous in the twenty-first century, which is increasingly "a world of risk and uncertainty, growth and decay, and fragmentation, dissolution, and breakdown."[49] By taking a broken world perspective, according to Jackson, we come to appreciate the tension between "an always-almost-falling-apart world"[50] and the ongoing processes that hold things together and generate productive change. Repair plays a key role in managing this tension: "The fulcrum of these two worlds is repair: the subtle acts of care by which order and meaning in complex sociotechnical systems are maintained and transformed, human value is preserved and extended, and the complicated work of fitting to the varied circumstances of organizations, systems, and lives is accomplished."[51] As we have discussed, infrastructure too is a concept that has its origins in a kind of broken world thinking, and this is reinforced by the always-under-repair character of infrastructures emphasized in the I-35W bridge example.

Jackson goes on to argue that repair is in fact a key aspect of innovation itself, with the development of world-changing technologies like the internet driven not by straightforward processes of design and implementation, but rather by messy processes of implementation, breakdown, problem solving, and repair that over time lead to increasingly stable systems. He also argues that paying attention to breakdown and repair illuminates aspects of technology we might otherwise ignore, in particular the relationships of care and engagement that people have with technology.

STS and history of technology professors Andrew Russell and Lee Vinsel have taken a more activist approach to repair and maintenance issues, organizing a scholarly community and series of conferences under the rubric of "The Maintainers,"[52] and writing about these issues in nonacademic publications like the *New York Times*.[53] In a 2016 piece for *Aeon*, they argue that America has an unhealthy obsession with innovation and "flashy, shiny, trivial things," while we tend to ignore the reality that most technical work and much of the value we derive from technology involves the maintenance of old or unexciting technologies.[54] To counter this tendency, they argue that we should pay more attention to what they call "the maintainers, those individuals whose work keeps ordinary existence going rather than introducing novel things."[55] Their definition of the maintainers extends beyond what we might typically associate with maintenance work, to include those who engage in domestic labor and other forms of care work that are often ignored. They also associate the lack of attention to maintainers with our similar lack of attention to unglamorous technologies like infrastructure, with its continuing need for repair and maintenance. Compared to Jackson, who emphasizes the unexpected continuity between repair and innovation, Russell and Vinsel articulate a more urgent moral agenda aimed at uncovering and promoting the values of care and sustainability they see as going along with repair and maintenance.

Like these authors, we believe that maintenance and repair have a particularly important role in relation to infrastructure and that both of these topics are often understudied and undervalued; that understanding repair and maintenance is absolutely essential to understanding how infrastructures and social institutions can persist, adapt to, and drive change; and that repair provides an essential window into the ethics of care around socio-technical systems. Along with Jackson, we see repair and maintenance as agents of change and innovation as much as conservation of existing arrangements.

Our approach is distinct from these authors primarily in the way we connect repair and maintenance more closely to sociological concepts and theories, in particular by emphasizing the continuity between technological and social order, and the role of conflict and power relations in shaping repair. As a result, we are perhaps a little less interested in making a case for the virtues of the activities of repair and maintenance and more interested in their value as a probe into the complexities and contradictions of our current relationship with technology. We are mindful that repair can serve to prevent needed social change, exclude or remove certain people or groups from positions of power, and stabilize problematic infrastructures and institutions, often at great social cost. However, we do agree that the path from breakdown to repair is a messy, conflicted, and potentially creative process that can also open up opportunities for (sometimes radical) social and technological change. Our approach in this book is also, we hope, particularly concrete and systematic, going beyond establishing why or how repair is important and into developing more specific tools and concepts for understanding and analyzing it.

Alongside repair and maintenance, a number of other concepts also play important roles in broken world thinking. In particular, resilience and sustainability have gained wide currency in many fields as frameworks for recognizing and designing for the inevitability of breakdown and repair.[56] Although we discuss sustainability at length in chapter 5, our overall focus remains on repair and maintenance because these concepts connect more directly to the level of concrete practices—the specific, day-to-day actions people take to pull together social and material resources and get things done. This work is done by people from many walks of life, from well-paid professionals to manual laborers, with different sorts of training and skills, from those learned in college classrooms to those picked up from years of hands-on, on-the-job experience. Indeed, in our definition, repair work is something we all engage in almost daily. By tracing how this work gets done across a broad spectrum of society, we are better able to understand how the stability, resilience, and sustainability of infrastructures are realized in practice, including all the messiness, complexity, contingency, problem solving, and power struggles this can involve. While we, like many others currently writing about repair, ultimately offer sociotechnical repair as a broader framework for understanding aspects of the modern world, we believe that a framework that emphasizes work and practice can provide uniquely grounded insights into the workings of sociotechnical systems.

Repair, Infrastructure, and the Maintenance of Modernity

The increasing interest in repair and maintenance is just one expression of a larger, ongoing societal reckoning with the risks and limitations of science and technology, and their relationship with the human and natural world. The processes of industrialization and modernization that built the world we live in today were largely motivated by the belief that rational, systematic planning and design could provide solutions to nearly every human problem. In this modern ideal, meticulously designed technological systems would ultimately insulate human society from the hazards of the natural world and the tedium of mundane labor.

This vision has proven amazingly productive in some ways but problematic in others. Since at least the 1960s, recognition has been increasing that industrial systems can themselves fail in myriad ways and create entirely new sets of risks their designers did not anticipate.[57] Ulrich Beck, Anthony Giddens, and other social theorists have argued that these aspects of modernity lead to a *risk society*, in which risks are increasingly difficult to anticipate and global in their impact, transcending national borders and social distinctions. This in turn leads to a new *reflexive modernity*, in which belief in technological progress is balanced by attempts to understand and manage the resulting risks to nature and society.[58] One effect of this new modernity is to muddy the sharp distinctions modern planners were trying to build among society, technology, and nature, revealing that they were perhaps never so separable after all.[59] Although much of this literature focuses on the globalization of environmental risks, the increasing globalization of infrastructure systems is equally relevant, tying people around the world to common technological paradigms, with potentially common failure modes.

While these developments are arguably part of the origin of broken world thinking, they tell only part of the story—the part about modern sociotechnical systems inevitably breaking down or creating unanticipated problems. By contrast, most current writers about repair and maintenance take a somewhat more optimistic approach, focusing on the possibility of renewal and sustainability even in a world of constant breakdowns. While we share this sense of optimism, we also see a need for a more skeptical and reflexive view of repair itself to address the role it might play in sustaining some of the very problems pointed out by scholars of the risk society. We return to these concerns in chapter 5.

The Tool Kit

Just as repair workers need a set of tools for their work, we need a conceptual tool kit to help dig up the often-hidden work of repair and maintenance and expose its significance. We focus on three key analytic tools. First, to understand how repair is connected to both things in the material world, and how people think about, talk about, and organize repair of those things, we look closely at the interplay between *materiality and discourse*. Second, to examine how repair can support or threaten cultural and political power structures, and how both infrastructures and those who work on them can become invisible even as they remain essential, we emphasize the relationship between *power and invisibility*. Finally, we examine *scale*—the temporal and spatial scope of infrastructure repair, and how it shapes technological systems in time and space.

Materiality and Discourse

The material work of repair does not take place in isolation. Instead, it is usually accompanied by a great deal of thinking, talking, and writing about what went wrong and how to fix it. Looking at repair through the lens of materiality and discourse provides a tool for analyzing the full range of social and technical relationships that surround repair. In particular, material repair is usually accompanied by discussion and negotiation, however informal, over issues including whether a breakdown occurred at all, what the breakdown was, how to fix it, and what a successful repair looks like. This discourse shapes and is shaped by our engagement with the material system under consideration. For example, a repair technician called in to address a cold office might spend as much time managing the perceptions of the occupants as working on the heating and ventilation hardware (see chapter 2).

In sociology, the most extensive body of work on repair is not about material repair at all, but about what people do to repair shared understanding when confusion arises in conversations. Although seemingly far removed from activities like fixing a bridge or bicycle, this work is a useful starting point for thinking about the discursive elements of all kinds of repair. In the sociological fields of ethnomethodology and symbolic interaction, *repair* refers to the small yet continual efforts people make daily to maintain social order. In conversations, sociologists observe that there are frequent ambiguities that lead to small misunderstandings—you thought “she” referred to Maria, but the speaker was talking about Margaret; you were asking a question, but the other person interpreted it as a statement. People use a variety of interactional strategies to identify these breakdowns and fix them through clarification, redirecting the conversation, and other conversational techniques of repair so communication can proceed uninterrupted.[60]

This perspective suggests social order is an ongoing practical accomplishment, constantly maintained through interaction and negotiation among participants. While we all recognize basic social structures and cultural meanings, the actual everyday enactment of these structures and meanings is highly improvisational. The flow of interactional repair is so ubiquitous that we usually do not pay much attention to it, but we are constantly involved in a dynamic exchange of interactions that create stability as well as possibilities for change. Possibilities for stability and change in infrastructural systems are similarly embedded in a continual flow of maintenance, breakdown, and repair. This flow incorporates both material interventions and repair of meaning in discourse and other forms of social interaction. In fact, these activities are so thoroughly intertwined that it is hard to separate them, so they are best captured through a more general idea of *sociotechnical repair,* which identifies the full scope of material and discursive interventions that make it possible to maintain modern technological systems. Sociotechnical repair includes both routine maintenance and crisis response, fixes to organizations as well as material structures, and a range of scales from local interactions to large-scale institutional processes.

The concept of sociotechnical repair helps make sense of interactions surrounding breakdown and repair in cases like the I-35W bridge collapse. Sociotechnical repair is given shape and specificity through our various accounts of what went wrong and what should be done to fix it. These accounts can invoke a wide range of causes, from material flaws and physical forces to human error and poorly written documents. Repair efforts often go beyond material restoration, to encompass changes in policies, procedures, and communication that serve to restore public confidence in administrators and technical experts. This reflects the thoroughly sociotechnical nature of infrastructures. Their stable material form is inseparable from the array of technical and organizational activities that sustain them. Paying attention to the material and discursive elements of repair helps us map these sociotechnical connections.

While we will not attempt to give a complete account of all possible relationships between discourse and materiality in sociotechnical repair, one thing we have observed is that discourse about repair is often framed in terms of what we call *slippage*, which draws a contrast between a system's current state and some desired state, and poses repair as a way to bridge the gap.[61] One common way of articulating slippage is in terms of change or degradation in a system that renders it unable to fulfill a desired function, as in the case of a bridge that has become too weakened by rust to safely carry traffic. Just as often, however, changes in a system's surrounding circumstances are used to motivate repair—for example, when a bridge comes to be seen as inadequate due to changes in user requirements or engineering standards. This emphasizes the point that breakdowns do not always take the form of something literally falling apart, but can involve much more complex appraisals of functionality in light of many related factors.

Power and Invisibility

Discourses and materiality are inherently tied up in relationships of power; when one or another group of actors controls discourses of repair, for example, they can set the agenda for a sociotechnical system. Those lacking this power can be marginalized, even though they may play an important part behind the scenes for a particular infrastructure. Therefore, understanding the role of power and invisibility in the repair and maintenance of infrastructures is another important element of our analytical tool kit.

Invisibility, or rather tension between visibility and invisibility, is a key theme in infrastructure studies. While infrastructure systems are often intended to be so standardized and reliable that they fade into the background, in other circumstances, they are made very visible, by accident or by design.[62] This tension shows up in several ways in relation to infrastructure and repair.

First, those of us who have access to reliable infrastructures as end users often take them for granted—our use of them becomes so routine across such a wide range of activities and contexts that we may not give them much conscious thought on a day-to-day basis. When infrastructures break down, however, they can become problematic and visible indeed. Think of the household difficulties posed by power outages, or the unexpected and shocking nature of the I-35W bridge collapse, which became an international news story. Other breakdowns emerge more gradually as members of the public, professional communities, or political actors advance agendas for change and repair. And some infrastructures are never fully reliable, existing in a constant state of disrepair. In any of these cases, breakdowns can provide useful insights into the nature of infrastructure, making its more obscure aspects visible in ways that force us to reckon with its materiality and social roles in new ways, a form of what Geoffrey Bowker has called *infrastructural inversion*.[63] Repair and maintenance are aspects of infrastructure that often come to the fore in these situations. Once people believe a breakdown has been resolved, however, these aspects tend to recede into the background once again.

Second, the people who maintain and repair infrastructures are often not very visible to outsiders. In part, this is tied to the general tendency of infrastructure itself to fade into the background. But sociologists also observe that jobs involving “dirty work”—relating to activities, materials, or people society as a whole would prefer to ignore—are often stigmatized and kept out of sight.[64] Repair and maintenance work, particularly when it involves close contact with the material elements of infrastructure, can be “dirty” in two senses. First, it often involves engagement with dirty or dangerous materials, such as oil, dust, or infectious waste. Second, it is associated with breakdowns in material and social orders and may serve as an uncomfortable reminder of the fragility of these orders.[65] Higher-level professionals who manage infrastructure and repair, like engineers, administrators, and planners, may have higher social status, but the nature of their work is often obscure to the general public.

Finally, infrastructures can affect the visibility of certain individuals and communities in social and political life: lack of wheelchair access keeps people with disabilities out of many public places despite recent progress in this area in some regions of the world; freeway bridges and viaducts are often built through neighborhoods with little political power and enable drivers from elsewhere to bypass those communities (see chapter 3); and some rural areas and urban neighborhoods are marginalized by limited access to internet services.[66]

All of these issues with visibility and invisibility reflect the larger connection between infrastructure systems and systems of cultural and political power. When people are marginalized in relation to infrastructures, they also tend to be subordinated within power structures; conversely, infrastructure projects often enhance the power of states and social elites. Infrastructures enable large-scale access to and movement of natural resources, support economic activity, and serve as symbols of administrative competence and control over state territory.[67] In this role, they are subtle reminders of the ubiquity of state and institutional control, as we discuss in chapter 4. And some elements of infrastructure are anything but invisible, instead taking on the status of civic or cultural icons. Think of the aesthetic qualities and visual prominence of major bridges, train stations, and airports, or the way certain cars or cell phones function as status symbols.[68] These dynamics of visibility and invisibility of both material structures and communities play a key role in the Coronado Bridge case study presented in chapter 3.

When infrastructures break down, they can threaten the stability of systems of power, as well as provide opportunities for marginalized groups to gain power. For this reason, infrastructure repair is often as much about restoring or extending systems of power as it is about restoring material order—hence, the political urgency of replacing the I-35W bridge. At the same time, it can be a location for power struggles and renegotiation of social and material orders.

One useful way of understanding the relationship between repair and power is by distinguishing two general approaches to repair: *repair as maintenance* and *repair as transformation*. The goal of repair as maintenance is conservation of the status quo: protecting or restoring a preexisting set of practices, relationships, and power structures. Groups and individuals who benefit from the current sociotechnical order are likely to support this kind of repair, particularly if it helps them hold their position in systems of power. Our use of the term *maintenance* here encompasses a lot more than routine maintenance and upkeep; we also include more focused repair efforts in response to unexpected breakdowns both large and small as long as the goal is a return to the status quo. The replacement of the I-35W bridge, along with associated changes in bridge design and inspection procedures, is a good example of repair as maintenance. Despite the extraordinary effort involved, its results were not exactly transformative: it restored the local transportation network to its former configuration, while preventing a potential breakdown in public confidence in powerful groups, including city and state leaders, government agencies, and the engineering profession. No wonder it was agreed to, funded, and completed so quickly.

Sometimes, however, repair is presented as an opportunity for more radical change in existing structures and practices. Transformative repair may serve the interests of the powerful when some fundamental breakdown has occurred that permanently threatens their place in the current order. Such was the case in the US nuclear weapons complex at the end of the Cold War. With no prospect of maintaining the infrastructures that enabled the building and testing of new nuclear weapons, weapons scientists were able to construct a stewardship role for themselves that leaned heavily on a new modeling and simulation infrastructure. This fundamentally changed their role but maintained their professional status and credibility (discussed in more detail in chapter 4).[69] But transformative repair may also be championed by those who are excluded from existing power structures or otherwise see repair as an opportunity to advance their interests. This was the case with the community activists who became involved in the Coronado Bridge retrofit project described in chapter 3.

To summarize, understanding how an infrastructure system distributes risk, benefits, and social status unevenly across different groups and individuals can help us understand how it intersects with systems of cultural and political power. This, in turn, can make it easier to understand what is at stake in its repair: sometimes the stakes are large, sometimes small; sometimes there is broad agreement about a course of action, sometimes conflict driven by who gains and who loses in repair. Proposed repair strategies can reflect not only immediate material and technical needs, but also the interests of stakeholders in maintaining or changing the existing social and material order.

Scale

Close examination of the scale of repair in both space and time is a tool that enables us to analyze how repair works on infrastructures at a range of social and material levels, from our daily local practices, to the national politics of infrastructure, to management of global systems of exchange. While many studies of repair focus on local practices, the temporal and spatial extent of repair activities can vary tremendously across these levels. A focus on scale ensures that we do not miss any important aspects of materiality and discourse, or power and invisibility, due to preconceptions about the scope of repair. In keeping with the importance of scale, this book is organized in chapters that address successively larger scales of repair, from local negotiations to systemic, national, and global interventions. This should not be taken to imply that these scales are necessarily distinct from each other in actuality, and we emphasize interactions and continuities across scales throughout.

Questions of scale are important in infrastructural repair in part because infrastructure systems occupy intermediate scales between the human body and the geophysical world in terms of size, temporal horizons, and ability to exert force. This connection between scales can serve as a powerful amplifier of human action and ability to control the natural environment.[70] By the same token, dependence on infrastructure creates new sources of vulnerability, because when natural forces do overwhelm infrastructure systems, the effects can reverberate back down to the scale of fragile human lives. As a result, most natural disasters in the modern world are simultaneously infrastructural disasters.[71] In short, both infrastructures and nature now function as increasingly integrated parts of a larger material environment that both provides us with resources for daily living and presents dangers we must protect ourselves against.

One way researchers in STS and related fields have managed issues of scale in the study of infrastructure is by considering it from both top-down and bottom-up perspectives, the first emphasizing the large-scale structural characteristics of infrastructure systems, the second focusing on their role as a resource supporting local technological and social arrangements. These two perspectives also suggest useful ways of analyzing scales of repair.

From a bottom-up perspective, repair emerges from a complex tangle of relationships among material objects and systems, social relationships, and embodied skills. In the bottom-up view, repair is mainly about negotiating and renegotiating local forms of technological and social order. Examples might include a mechanic fixing a car, a technician adjusting ventilation airflow in an office, or a nurse repositioning a patient to minimize pain.

One key aspect of repair at the local level is the relationship between the repair worker's body and the material world. When we engage in diagnostic or repair work, this connection is readily apparent: we use our hands and body to physically manipulate the thing being repaired, usually with tools as an intermediary; position our eyes to get different views on the repair; feel for vibrations and temperature; listen for unusual sounds; and so on. Another key aspect of local repair is the way it fixes human as well as material relationships. A successful repair is not only a material accomplishment; repair also creates a shared narrative of what went wrong and how it was fixed, persuading participants that local sociotechnical order has been restored (see chapter 2).[72]

From a larger, systemic point of view, the work of repair can extend across multiple locations, institutions may take a larger role than individuals, and repair may be more extended in time. Examples include the rebuilding of levees and other infrastructure after Hurricane Katrina devastated New Orleans,[73] or the reconfiguring of nuclear weapons infrastructure following the Cold War.[74] From this perspective, the emphasis may shift from hands-on repair workers to professional managers, planners, and engineers; the organizations that employ them; and governmental and professional decision-making bodies. These entities engage with the social and material aspects of infrastructure on a larger and more abstract scale, which might involve managing the movement of large quantities of material, purchasing and deploying large construction equipment, or interacting with political actors and the general public. Much like infrastructure itself, repair at this level can be regulated through standards and common frameworks.[75] Discourses and narratives of repair are still important at larger scales, but may be constructed in more public ways, including through media reporting, public meetings, social media, and the political process. It is at this level that questions of institutional and state power become most noticeable.

We talk about scale here in terms of perspectives because, in reality, what we see when we look at different scales of repair are just different aspects of a single phenomenon in which sociotechnical systems are reconfigured and adapted to changing circumstances. Infrastructure systems, in particular, tend to span multiple scales, so we need to look at them from different perspectives to put together a complete picture of repair. This perspectival approach to repair also helps us avoid the pitfall of equating scale with hierarchy or suggesting that some levels have more importance than others.[76]

But while it is important to understand the continuities between different scales of repair, it is also important to recognize discontinuities where they do occur. One source of discontinuity is the fact that infrastructure systems are often deliberately structured in modular or layered configurations as a strategy for managing their complexity.[77] For example, roads and bridges are pieces of infrastructure that are embedded in very specific local settings and activities, but at a larger scale, they are components in a road transportation infrastructure that includes interchanges, traffic lights, cars, trucks, and drivers. This larger infrastructure can experience breakdowns even if the bridges and roads remain intact—for example, due to unexpected traffic volumes or major car accidents or failures in lower-level components like the I-35W bridge that can also damage the larger system. These different layers of infrastructure can be distinctive both socially and technically; they may be managed by different groups of professionals, may employ distinct technologies, and may evolve somewhat independently despite their interconnections. For example, the replacement of the old, fracture-critical I-35W bridge with a new, high-tech bridge represented a leap forward in bridge technology, but by design, it had a limited impact on the overall transportation system in the Twin Cities area. Because of these distinctions, repair practices can also evolve somewhat independently within different layers. We may find, for example, that bridge engineers and bridge construction and maintenance workers are distinct communities with different perspectives that have to be reconciled when new kinds of repair become necessary.[78]

The temporal scale of repair is closely related to its spatial scale.[79] Many smaller, local repairs take place within short, well-defined time limits. Rebuilding after a disaster like the I-35W bridge collapse may take longer, but can be planned as a one-time event and without much concern for the overall life cycle of infrastructure. More systemic repairs can encompass a wider range of timescales: restoration of a levee system after a hurricane may take a few years, while restoration of housing and street life in flooded neighborhoods might take decades and connect to long-term economic, demographic, and political trends. Concepts like routine, preventive, or life cycle maintenance envision repair as an ongoing process throughout the life span of a technological system. Sometimes repair work never really restores a system to a desired state, and continues indefinitely in a state of incompletion (see the text box in chapter 4).[80]

The temporal relationship between breakdown and repair can also be important. While it might at first seem that all repair must take place after a breakdown is identified, this is not always true. Preventive maintenance, for example, might mean monitoring a system for signs of approaching failures and fixing the system before they can occur. Breakdowns can increasingly be anticipated through experiments, tests, and computer simulations, enabling planning for repair of systems that have not even been built yet.[81]

These ways of thinking about spatial and temporal scale are important tools for analyzing repair because they allow us to more easily trace the full scope of repair and its connections to what comes before and after. By carefully tracing connections in space and time, apparently simple cases of repair can reveal themselves to be much more complex, interesting, and challenging than they seem at first glance. Indeed, one of the most important aspects of repair may be the way it serves to continually connect and reconnect sociotechnical systems across space and time, which is part of what makes the characteristic scope and persistence of infrastructure systems possible.

Structure of the Book

The remainder of this book is structured around the scale of infrastructural repair. We begin in chapter 2 with the local context of repair, focusing on how people negotiate the social and material aspects of repair in specific places. We introduce the concept of the networked body to describe how the capacities and senses of the human body serve as a crucial link between the material and the social in repair. We explore this concept through a number of case studies, including Henke's studies of university maintenance workers. We conclude by examining the connections between repair and maintenance work and care work, and examining the emergence of local repair collectives in various global settings.

In chapter 3, we move up in scale to examine interactions between local negotiations and systemic considerations in repair of infrastructure systems. This chapter focuses on several episodes from Sims's work on California's efforts to retrofit its bridges to protect them from earthquakes, with a focus on how this systemic repair effort collided with local concerns surrounding the San Diego–Coronado Bridge. We explore how the construction of this bridge devastated the Barrio Logan community in San Diego and how the community fought back to repair this intrusion by taking control over the area under the bridge to build a community park, incorporating a series of monumental murals painted on the bridge columns. We then examine how engineers in California came to recognize that bridges in the state were not adequately designed to resist earthquakes and how a community of state engineers and academic researchers came together to develop a program for seismic retrofit of bridges. Finally, we explore how these professional communities negotiated with the Barrio Logan community to find a retrofit solution for the San Diego–Coronado Bridge that would not damage the murals. This chapter emphasizes the potential complexity of power relations around infrastructure and repair—in particular, how the connections infrastructure makes between marginal and highly valued urban spaces can open up possibilities for disenfranchised communities to challenge established power structures through processes of repair.

Chapter 4 focuses on how repair plays out through large-scale relationships between experts, infrastructure, and the modern state. It shows how, beginning in the seventeenth century, infrastructure increasingly became an engine for developing state power and reinforcing national identities. In particular, infrastructure projects became important tools for accumulating capital under elite control, while also serving as highly visible symbols of the capability of the state and its ability to serve its citizens. In these roles, infrastructure became a crucial instrument of governmentality, placing expertise and technical knowledge at the heart of modern state formation. The chapter then draws on our previous work to explore how these issues came into play in the efforts to preserve US nuclear weapons knowledge and infrastructure after the end of nuclear testing and the Cold War. This case study shows how experts and elites can mobilize to repair systems that give them power in ways that preserve that power, sometimes even at the cost of massive transformations in how these systems operate.

Finally, in chapter 5, we turn to a global scale, examining the place of infrastructure and repair in the Anthropocene, a new geological era that has been proposed to describe the increasingly global impact of human activities on the natural environment. Infrastructural systems are arguably the key drivers of the changes that mark the beginning of the Anthropocene, whether we trace those changes to the beginnings of systematic agriculture and its impact on natural ecosystems, the development of massive carbon emissions generated by transportation and energy production, or the radioactive traces generated by nuclear weapons testing and production systems. This raises concerns about the ethics of repairing systems that may ultimately have adverse and unsustainable effects on the natural world and human health and prosperity and leads to a critical question: Can we repair infrastructural repair itself to ensure that we have infrastructural systems that are not just stable but resilient and sustainable in the long term? To explore this question, we examine how infrastructures became increasingly globalized in the course of the twentieth century, how global governance structures have emerged to regulate these infrastructures, and how understanding these impacts requires massive information and data-gathering infrastructures. We close with a discussion of different visions for the future of infrastructure and repair and some guidelines for practicing and analyzing repair reflexively, acknowledging complexities and contradictions in the relationships between humans, infrastructures, and the natural world in the Anthropocene.

Repairing Infrastructures

The Maintenance of Materiality and Power

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Citation:

Repairing Infrastructures: The Maintenance of Materiality and Power
By: Christopher R. Henke, Benjamin Sims
DOI: 10.7551/mitpress/11771.001.0001
ISBN (electronic): 9780262360692
Publisher: The MIT Press
Published: 2020

The open access edition of this book was made possible by generous funding and support from Arcadia – a charitable fund of Lisbet Rausing and Peter Baldwin

The MIT Press

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A charitable fund of Lisbet Rausing and Peter Baldwin

This book was set in ITC Stone Serif Std and ITC Stone Sans Std by New Best-set Typesetters Ltd.

Library of Congress Cataloging-in-Publication Data

Names: Henke, Christopher, 1969- author. | Sims, B. (Benjamin), author.
Title: Repairing infrastructures : the maintenance of materiality and power / Christopher R. Henke and Benjamin Sims.
Description: Cambridge, Massachusetts : The MIT Press, 2020. | Series: Infrastructures series | Includes bibliographical references and index.
Identifiers: LCCN 2020002135 | ISBN 9780262539708 (paperback)
Subjects: LCSH: Public works—United States. | Infrastructure (Economics)—United States.
Classification: LCC HD3885 .H44 2020 | DDC 363.6068—dc23
LC record available at https://lccn.loc.gov/2020002135

10 9 8 7 6 5 4 3 2 1