A Sociotechnical Framework for Understanding Infrastructure Breakdown and Repair

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> The 2009 Report Card for America's Infrastructure finds not much has changed since the last edition four years ago. Years of delayed maintenance and lack of modernization have left Americans with an outdated and failing infrastructure that cannot meet our needs.
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> Infrastructure has a direct impact on our personal and economic health, and the infrastructure crisis is endangering our nation's future prosperity. For the safety and security of our families, we can no longer afford to ignore the congested roads, aging dams, broken water mains, and deficient bridges we face every day. As a society, we must become better stewards of the environment through the use of sustainable infrastructure practices. The quality of life for this and future generations depends on our willingness to rise to the challenge.
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> - D. Wayne Klotz, *President,* American Society of Civil Engineers 2008–2009

This paper looks at how and why infrastructure is repaired. With a new era of infrastructure spending underway, policymakers need to understand and anticipate the particular technical and political challenges posed by infrastructure repair. In particular, as infrastructure problems are increasingly in the public eye with current economic stimulus efforts, the question has increasingly been asked: why has it been so difficult for the United States to devote sustained resources to maintaining and upgrading its national infrastructure? This paper provides a sociotechnical framework for understanding the challenges of infrastructure repair, and demonstrates this framework using a case study of seismic retrofit of freeway bridges in California.

The design of infrastructure is quite different from other types of design work even when new infrastructure is being designed. Infrastructure projects are almost always situated within, and must work with, existing infrastructure networks. As a result, compared to design of more discrete technological artifacts, the design of infrastructure systems requires a great deal of attention to interfaces as well as adaptation of design to the constraints imposed by existing systems. Also, because of their scale, infrastructural technologies engage with social life at a level where explicit political agendas may play a central role in the design process. The design and building of infrastructure is therefore often an enormously complex feat of sociotechnical engineering, in which technical and political agendas are negotiated together until an outcome is reached that allows the project to move forward. These sociotechnical settlements often result in a complex balancing of powerful interests around infrastructural artifacts; at the same time, less powerful interests have historically often been excluded or marginalized from such settlements.

The repair or retrofit of existing infrastructure poses many of these same problems, but with even greater constraints on the design and building process. With time, the sociotechnical settlements around infrastructure projects can become even more solidified, and extended as more and more social groups integrate the infrastructure into their political agendas and patterns of daily life. Any significant project to upgrade existing infrastructure risks disrupting these hard-won settlements of conflicting interests. In addition, repair and restoration projects must wrestle with the obduracy of the object as it already exists, requiring countless small accommodations in the design and building process. There is little opportunity in this type of work to make grand engineering gestures; the work is much more about getting countless details right.

As this discussion indicates, infrastructure repairs, upgrades, and updates, like any kind of engineering work, are thoroughly sociotechnical activities. As my colleague and collaborator Chris Henke has pointed out, even nominally technological breakdowns are usually breakdowns in social order as well, and repair involves restoring both technology and social order. Chris draws an analogy between this process and the processes of conversational repair identified in the field of ethnomethodology. Conversational repair occurs when there is a potential breakdown in intersubjective meaning, and the participants cooperatively deploy various strategies to restore conversational order. Sociotechnical repair similarly involves the restoration of order and shared meaning, albeit in a larger social and technical sense.

Chris also makes an important distinction between repair-as-maintenance and repair-as-transformation. The vast majority of sociotechnical repair is of the maintenance variety: efforts to simply sustain the status quo, making whatever small interventions are necessary to avoid disrupting existing sociotechnical arrangements. In fact, maintenance is what makes it possible for these arrangements to be durable. Faced with threats to sociotechnical stability, most institutions prefer to take a maintenance approach for as long as possible, in order to minimize disruption. But if this is not possible, and a breakdown occurs that is beyond the scope of routine maintenance, institutions may be forced to take the risk of making more transformational repairs. In an infrastructure context, this might involve things like retrofitting or rebuilding existing structures, or major work to upgrade aging components.

Infrastructure can break down in a number of different ways. All of these involve some kind of mismatch between normative notions of how infrastructure ought to perform, and perceptions of how it is actually performing in light of the demands placed on it. I call this mismatch *slippage*. Slippage can take a number of forms, but the most common are those we term degradation and obsolescence. Degradation is what happens when a technology is perceived to have aged or otherwise changed in such a way that it no longer performs as intended, even though functional requirements have not changed significantly. Obsolescence, on the other hand, reflects a perception that demands or engineering standards have changed such that certain interests are no longer being met, even though the technology itself may still be performing to its original specifications. Note that both the “is” and “ought” sides of this equation are interpretative processes: deciding what condition a bridge (for example) is in, and whether it has changed in a meaningful way, requires engineering and political judgment in much the same way as deciding whether it meets current needs.

Ordinarily, slippage is limited and is relatively easily controlled through routine maintenance. When the degree of slippage reaches a certain point, however, institutions may be forced to take more substantial action: infrastructure may be declared unsafe, or become the focus of political or social movements seeking improvement. We are now in the realm of transformational repair. A variety of approaches may be taken at this point, ranging from repair to complex retrofit or even complete replacement of existing structures. Any of these will involve the repair of institutions and social relations as well as the material elements of infrastructure. Although I don't discuss this in detail here, it is also possible for repair to occur entirely at the institutional level, for example by changing standards or usage patterns so the breakdown is repaired without any material intervention.

The Caltrans Seismic Retrofit Program

On February 9,1971, at 6 a.m., a strong earthquake — magnitude 6.6 — shook the San Fernando Valley, then a rapidly-developing suburban area of Los Angeles, causing extensive damage and loss of life. At the time, the California Department of Transportation (Caltrans) was in the process of building two major freeway interchanges in the area, and large portions of several finished (but not yet in service) structures collapsed in very dramatic fashion (Figures 2.2-2.4). Caltrans engineers were surprised at the extent of the damage, which they realized could have killed people if the structures had been open to traffic. They immediately launched an effort to determine what went wrong and how it could be fixed.

Figure 1. Collapse of bridge at I-5/I-210 interchange,1971 San Fernando earthquake. Source: Steinbrugge Collection, Earthquake Engineering Research Center, University of California, Berkeley.

They eventually came to focus on two aspects of seismic performance that were seen to be deficient in the San Fernando bridges that collapsed. First, they noticed that the roadways had come apart at the joints between segments of the bridges. Second, they saw that the steel reinforcement in the concrete columns had been inadequate, pulling out of the footings and not holding the concrete in the columns together under earthquake forces. In technical terms, the columns were not ductile enough because of inadequate confinement of the concrete. Concrete can be surprisingly strong and flexible as long as it is under compression; the purpose of the steel reinforcement in columns is to keep the concrete compressed. In this case, the reinforcement was not strong enough, allowing the concrete to break into pieces and the columns to fail.

Figure 2. Column damage caused by rupture of horizontal reinforcement hoops. Source: Steinbrugge Collection.

As a result of these observations, Caltrans immediately began a program to tie bridge joints together using steel cable fixtures. They also changed their bridge design criteria to require more extensive reinforcement of columns . At the time, Caltrans did not have the technical knowledge or facilities to be able to test methods of retrofitting columns, and in any case there was little funding available for retrofit work.

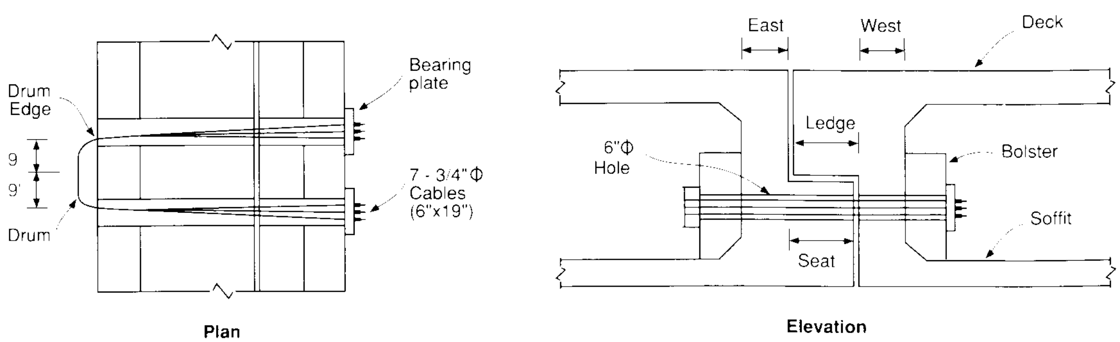

Figure 3. A standard version of the Caltrans expansion joint restrainer for concrete bridges. The restrainer is meant to keep the ledge from sliding off the seat. Source: Governor's Board of Inquiry 1990, 131.

This changed over time for a couple of reasons. First, the field of earthquake engineering came into its own during the 1970s and 80s, with improvements in computational tools and the establishment of major structural engineering research laboratories. UC Berkeley, and later UC San Diego, became major research centers, and Caltrans established a close working relationship with earthquake engineering experts at San Diego. This research led to a much better understanding of how to design steel reinforcement to maximize column ductility. Second, the 1989 Loma Prieta earthquake in the San

Francisco Bay area caused significant loss of life on freeway structures, resulting in the establishment of a board of inquiry and the funding of a massive bridge retrofit program that focused on column ductility. Putting steel jackets in place around existing bridge columns, a method suggested by UC San Diego earthquake engineers, became the standard solution for column retrofit.

Figure 4. Steel shell prior to installation, intersection of State Route 52 and Genesee Avenue, San Diego. Note irregular shape to fit around hexagonal flared columns, seen in background. Photograph by the author.

The breakdown in this case was not simply the failure of bridges in earthquakes, but rather a complex institutional and political process over twenty years, in which the inadequate seismic design of bridges became a salient issue not only to engineers but to politicians and the general public. In the terms used above, this breakdown was a case of obsolescence, because the bridges were not thought to have changed significantly since they were built. Rather, knowledge and standards of how bridges ought to be built to resist seismic forces changed, in such a way that existing structures, even in good condition, came to be seen as unsafe.

The San Diego-Coronado Bridge

The retrofit of the San Diego-Coronado bridge exemplifies many of the many of the themes raised above in relation to sociotechnical repair. This bridge is a major structure connecting the city of San Diego to the "island" of Coronado, across the bay. Coronado, which actually is attached to the mainland south of San Diego, is the location a major military facilities and home to many military personnel, as well as a number of resort hotels. The bridge was built in the 1960s with the support of Governor Edmund G. Brown, a champion of bridge-building as a tool of economic development. Various local groups were opposed to building a bridge, including Coronado residents who protested the bridge because they feared it would destroy the small-town character of the island. In addition, the Navy initially opposed a bridge because it might interfere with ship movement in and out of San Diego Harbor. They later softened their opposition, but insisted on at least 200 feet clearance over the main shipping lane. In order to accommodate this height without making the bridge too steep, engineers designed the bridge with a 90 degree curve in the middle to increase its length.

Figure 5. The San Diego-Coronado Bridge. Photo by Michael Foley, http://www.flickr.com/photos/michaelfoleyphotography/414187007/. Reproduced under Creative Commons license.

Because the shipping lanes were closer to the San Diego side, the highest portion of the bridge was built on the San Diego side. As a result, the bridge touches down at the edge of Coronado, but extends approximately a quarter of a mile inland on the San Diego side. In addition, approach ramps connecting the bridge to Interstate 5 take up a great deal of real estate on the San Diego side. This was made possible, in part, by the low property values on the San Diego side and the lack of any organized opposition to the bridge in that area. But the bridge actually ran right through the center of a thriving neighborhood on the San Diego side, an area known as Barrio Logan because of its largely Hispanic population. A wide swath of the neighborhood was leveled in order to make way for the bridge and the approach ramps. In contemporary accounts, however, this is never mentioned; Barrio Logan was invisible in the media and was seen by the bridge builders merely as a "path of least resistance," to quote one of the architects involved in the project. As this suggests, the sociopolitical settlements that enable infrastructure projects to proceed typically include certain interests and exclude others; in this case, the Department of Transportation, the Governor, the Navy, and Coronado residents were part of the settlement, and Barrio Logan residents were not.

By the late 1960s, however, Chicano political activism was on the rise nationally, and was becoming particularly important in California. The Barrio Logan community, which had already suffered through numerous policy and infrastructure projects that threatened its integrity, was in the midst of a political awakening. The pivotal moment came when the state announced plans to build an enormous California Highway Patrol station on the already desolate land under the bridge and approach ramps. The community, which had had an unhappy relationship with police, found this unacceptable. As a result, a group of several hundred residents came together to occupy the construction site for twelve days, preventing construction from proceeding and demanding that a community park be built instead. The state backed down, and entered into negotiations with the city of San Diego that eventually resulted in the establishment of what became known as “Chicano Park.”

Figure 6. Chicano Park in 2006. Photo by Steven Jareb, http://www.flickr.com/photos/sjareb/294952844/. Reproduced under Creative Commons license.

The park became a focal point of community activity, but remained a noisy and sometimes gloomy place, dominated by the gray concrete of the bridge structure. Partly to combat this gloominess, a loose coalition of local artists conceived the idea of painting murals on the approach ramp columns in the park. Over next thirty years, at least 40 brightly-colored, symbolically-dense murals were painted on the columns by artists from San Diego and throughout the Southwest. The Barrio Logan community had entered into the settlement of interests around the bridge, indeed with a very direct interest in the structure itself. This was a process of repair, restoring Barrio Logan as a community in the aftermath of the destruction the building of the bridge had brought.

Figure 7. "Colossus" mural, Chicano Park. Photo by Nathan Gibbs, http://www.flickr.com/photos/nathangibbs/401116523/. Reproduced under Creative Commons license.

Figure 8. "Why Us" mural, Chicano Park. Photo by peyri, http://www.flickr.com/photos/peyri/1013337551/. Reproduced under Creative Commons license.

Retrofit and Chicano Park

When the Coronado bridge finally came up for retrofit in the mid-1990s, Caltrans officials and engineers, as well as the San Diego-based engineering firms designing the retrofit, were aware that the murals could pose a problem, but did not appear to have been aware of the depth of the community's commitment to the artwork and the degree of political difficulty that could attend any disruption of the park. In order to get ahead of the issue, Caltrans held public meetings early in the design process, but at the meetings presented a range of possible retrofit measures, most of which would have had a significant impact on the murals — including completely replacing the columns, encasing them with steel jackets, and thickening the existing columns in the lateral direction. Decades of community mistrust of Caltrans came to the surface immediately, and community activists began to dig in their heels for a fight. Some questioned whether the bridge really needed to be retrofitted at all. An artists' group sent out a newsletter demanding "no retrofit, not now, not ever!" A mural was painted in Chicano Park with the prominent message "No Retrofitting" (Figure 9). In sharp contrast to the invisibility of the Barrio Logan community during the building of the bridge, local politicians and newspapers soon took up the cause of preserving the murals. Clearly, the power structure in the city and state had changed considerably since the 1960s, and a political showdown was in the works.

Figure 9. "No Retrofitting" mural, Chicano Park. Photo by jessicavk, http://www.flickr.com/photos/jessicavk/2558525919/. Reproduced under Creative Commons license.

Seeing that discussions were not going well, San Diego-based Caltrans environmental planners, who saw themselves as having a better grasp on local politics and concerns about the retrofitting, began to take a much more aggressive role in courting community leaders, holding numerous additional public meetings throughout the course of the retrofit development. At the same time, Caltrans historians and archaeologists who developed the required environmental impact documentation for the project had come to the conclusion that the murals probably qualified for inclusion in the National Register of Historic Places, further complicating matters. Indeed, the existence of laws like the National Environmental Protection Act (NEPA) are one reason why the political processes surrounding infrastructure have changed so significantly since the time when the Coronado Bridge was initially built, and are a key point of leverage for communities like Barrio Logan.

The turning point in the retrofit struggle came from the engineering side. Frieder Seible, a structural engineering professor at UC San Diego and a key Caltrans consultant, was on the peer review panel overseeing the retrofit design. Realizing that their relationship with the community was on shaky ground, local Caltrans officials approached Seible to explain the technical issues to community leaders. Seible brought the activists to UCSD to tour the structural engineering laboratory, where he explained the reasons for the retrofit and showed them large-scale test specimens of bridge columns that had been put through simulated earthquakes. This apparently made a big impression, and convinced many of the skeptics present that retrofit was actually needed.

Seible worked both sides of the problem, however. Using his position on the peer review panel, he pushed Caltrans to require a more detailed analysis of the approach ramp columns in the design process, including testing sample columns at the UCSD lab. When this analysis was completed, and with new data on soils at the site, the designers concluded that retrofitting work could be limited to only the footings of the columns. In other words, almost all the work could be done below the existing ground level, sparing the murals.

This story illustrates a number of the points raised above about sociotechnical repair. The Coronado Bridge was the object of a complex settlement of sociotechnical and political interests, a settlement that had only grown more complex in the years since it was built. Retrofit was a transformational repair that Caltrans engineers and officials entered into with trepidation, knowing that it would threaten key interests and possibly arouse powerful opposition. Although initially caught somewhat off guard by the intensity of the opposition to retrofitting, they updated their strategies and pulled together a classic example of "heterogeneous engineering" – John Law's term for the way engineers often tackle the social and technical aspects of design problems as an integrated whole. In this case, the heterogeneous engineering involved working through local political channels, community relationships, and professional engineering networks in order to pull together resources as diverse as soil assessments, community activist groups, local politicians, and engineering laboratories. In the end, these resources were assembled into a new settlement of interests, in which engineering design criteria, political interests, community identity, and aesthetic concerns were reconciled in a newly meaningful way. In the terms of social constructivist analysis of technology, the controversy reached closure. The bridge was retrofitted and the murals of Chicano Park have gone on to become an even more prominent and valued cultural resource in San Diego.

It should be noted that this particular repair story is atypical in some ways. Certainly many infrastructure design and retrofit projects, particularly involving prominent structures like bridges, involve negotiations between local interests. However these interests are usually focused around general architectural qualities (for bridges), the services the infrastructure provides, and its socioeconomic impacts on different communities. It is rare for the embeddedness of infrastructure in a local community take such concrete symbolic and aesthetic form as it did in the case of the Coronado Bridge and Chicano Park. But the explicit symbolism of the murals serves as a useful metaphor for the way interests are embodied in infrastructure. Infrastructure is a canvas on which communities project their fears, hopes, and interests in political power, investing the material world with potent cultural meanings. For this reason, the idea of sociotechnical repair, with its focus on how order and meaning are restored in social life, is a particularly apt framework for understanding infrastructural problems.

Conclusion

In conclusion, I would like to gesture in the direction of relevance to broader concerns in social studies of technology and infrastructure policy. In the sociology and philosophy of technology, the concept of technological determinism has always loomed large. Technological determinism refers to the idea that technology in some sense drives its own evolution, and in the process also serves as an exogenous driver of social change. Early work in the social constructivist analysis of technology focused a great deal of its energy on undermining technological determinism, emphasizing the "interpretive flexibility" of technology and showing how the material form of technology is shaped by competing interest groups. More recent work, particularly on infrastructural technologies, has attempted to grapple with the apparent "obduracy" of technology in this context – its frequent unwillingness to conform to our shifting interpretations of it. The concept of sociotechnical repair contributes to this train of thought because it provides a language for describing how technology is stabilized in relation to social interests. It emphasizes that technology is not a static thing, but is embedded in shifting networks of sociotechnical relations. These networks could not remain stable but for the often invisible routine repair and maintenance work that attends all technological artifacts, and the institutional mechanisms that enable these to occur. Still, eventual breakdown is inevitable, and when it occurs, the obduracy of technology is revealed to be a product of a complex, heterogeneous network of relations between material things, technical knowledge, and political power. The extensive interpenetration of infrastructures in all of these dimensions is what makes them so resistant to change. We could always level our infrastructure and start over again, and someday we may, but this would rightly be regarded as a terrible disaster because of the thorough upending of social life as we know it that it would entail.

I now return to the question posed at the beginning of the paper: why has it been so difficult for the United States to devote sustained resources to maintaining and upgrading its national infrastructure? This is obviously a complex question, and the answer involved many different factors. However, this discussion of infrastructural repair suggests one significant contributing factor: repairing, retrofitting, or upgrading existing infrastructure is not necessarily any easier or more straightforward than building new infrastructure. In fact, in many ways it may be more difficult because these processes are so constrained by the obduracy of existing structures, and by the potential for upsetting fragile settlements of interests around them. In addition, a new set of environmental regulations have been put into law since our last major round of infrastructure building in the 1960s. By ensuring that interests that might previously have been excluded are given voice, they greatly expand the range of interests that must be involved in the settlement of infrastructure decisions. This is undoubtedly a positive change, but it makes it more difficult to engage in the kind of audacious, bulldozing system building that created much of our current infrastructure in the United States. If infrastructure repair truly is a national priority, infrastructure policy should take these constraints into account, and could include incentives to encourage local agencies to overcome the additional difficulties posed by work on existing infrastructure.

References

This paper is, in part, based on the author's doctoral thesis, *On Shifting Ground: Earthquakes, Retrofit, and Engineering Culture in California* (University of California, San Diego, Department of Sociology and Science Studies Program, 2000). Much of the narrative is based on interviews and participant observation with engineers at Caltrans, engineering firms, and UC San Diego, as well as informal conversations with one of the muralists. A complete set of references is available in the thesis. In addition, this paper builds on collaborative work with Christopher Henke on the concept of sociotechnical repair, including our paper "Maintenance and Transformation in the U.S. Nuclear Weapons Complex," *IEEE Technology and Society Magazine* 27 (2008):32-38. See also Henke's book *Cultivating Science, Harvesting Power: Science and Industrial Agriculture in California*. (Cambridge, MA: MIT Press, 2008).