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MOVING TO RESILIENCE AND ROBUSTNESS AND IMPLICATIONS FOR ENGINEERING DESIGN

NORB DELATTE[1] and MARK MILKE[2]

[1]*Civil and Environmental Engineering, Oklahoma State University, Stillwater, USA*
[2]*Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand*

Recovery of the city of New Orleans from Hurricane Katrina in 2005 and recovery of Christchurch, New Zealand from the earthquakes of 2011 are used as case studies for examining the changing nature of engineering design. While in both cases the loss of life was considerable, each event was followed by several years of severe economic disruption. The examination highlights that the high indirect costs of civil engineering failure along with the unpredictable nature of extreme events increasingly require adaptive solutions. Design could change from a process that happens once over a 50-year lifespan to a process where re-design is considered every 10 years, each time evaluating new information. Design as an adaptive process will require revisiting issues such as design contracts, the separation of design from construction and operation, and education of engineering design.

Keywords: Natural disasters, Flooding, Earthquakes, Building codes, Life safety.

1 INTRODUCTION

The first Canon of the Code of Ethics of the American Society of Civil Engineers begins by stating, “Engineers shall hold paramount the safety, health and welfare of the public.” In the case of large-scale natural disasters, the profession has been better at preserving “health and safety” than in preserving “welfare.” Traditionally, civil engineering design has focused on life safety, with less attention on large-scale resilience and robustness. This has tended to be satisfactory for individual structures and facilities. However, large-scale natural disasters require a different approach. In particular, adaptation to climate change and stronger and more frequent natural events will hasten changes to design procedures. This paper examines two cases: recovery of the city of New Orleans from Hurricane Katrina in 2005 and recovery of Christchurch, New Zealand from the earthquakes of 2011. The paper then briefly analyzes some of the implications of moves towards resilience and robustness on the engineering design process.

2 HURRICANE KATRINA – NEW ORLEANS, USA, 2005

The failure of the levees and the flooding of New Orleans, Louisiana during Hurricane Katrina (August 2005) was not only an engineering disaster but also crippled the region for many years to come (ASCE 2007, Delatte 2009). The catastrophic failure of New Orleans’s hurricane protection system represents one of the nation’s worst disasters ever: “A storm of Hurricane Katrina’s strength and intensity is expected to cause major flooding and damage. A large proportion of the destruction from Hurricane Katrina was caused not only by the storm itself, however, but also by the storm's exposure of engineering and engineering-related policy failures" (ASCE 2007).

While the immediate impact was at least 986 deaths in Louisiana and an estimated $135 billion in property damage, the depopulation of the city was long lasting. The population decreased by over half, from 484,674 before Katrina (April 2000) to an estimated 230,172 after Katrina (July 2006). By July of 2015, the population was back up to 386,617 – 80% of what it was in 2000, with an increase of only 4 percentage points in the prior three years (The Data Center 2016).

Following the disaster, the Chief of Engineers of the U.S. Army Corps of Engineers, Lieutenant General Carl A. Strock, ordered a thorough investigation. The investigation team was termed the Interagency Performance Evaluation Taskforce (IPET). He also requested that ASCE form an external review panel to assess IPET's work. Many other teams of investigators also assessed the performance of the levee system.

In 2009, the IPET report summarized the consequences that were still felt four years after the event: "Approximately 80% of New Orleans was flooded, in many areas with depth of flooding exceeding 15 ft. [5 m] The majority, approximately two-thirds overall in areas such as Orleans East Bank and St. Bernard, of the flooding and half of the economic losses can be attributed to water flowing through breaches in floodwalls and levees. As of December 2005, the National Hurricane Center reported that there were approximately 1300 fatalities in Louisiana directly related to the forces of Katrina, a significant majority within New Orleans. Over 70% of the fatalities were people over age 70. The poor, elderly, and disabled, the groups least likely to be able to evacuate without assistance, were disproportionately impacted. Direct property losses exceeded $20 billion, and 78% of those losses were in residential areas. There was an additional loss of over $7 billion in public structures and utilities. The indirect consequences were equally disastrous. The breakdown in New Orleans' social structure, loss of cultural heritage, and dramatically altered physical, economic, political, social, and psychological character of the area are unprecedented in the United States. In themselves, these create a formidable barrier to recovery. Where water depths were small, recovery has been almost complete. In areas where water depths were greater, significantly less recovery or reinvestment has taken place" (USACE 2009a).

Disaster recovery is an expensive proposition. Money is needed for both immediate relief and for rebuilding, and typically the immediate relief needs are more pressing. Following Katrina, "Of the $120.5 billion in federal spending, the majority — approximately $75 billion — went to emergency relief, not rebuilding. Philanthropic giving, while more than double the giving for either the 2004 South Asian Tsunami or 9/11, was only $6.5 billion. Meanwhile, private insurance claims covered less than $30 billion of the losses" (The Data Center 2016).

3 EARTHQUAKE SEQUENCE – CHRISTCHURCH, NEW ZEALAND, 2011

The Canterbury Earthquake Sequence (CES) in 2010-2011 involved four major events—4 September 2010 (Mw=7.1), 22 February 2011 (Mw=6.2), 13 June 2011 (Mw=6.0), and 23 December 2011 (Mw=5.9)—along with thousands of associated aftershocks. The 4 September event and its aftershocks were near the town of Darfield, 30 km west of Christchurch. There were no fatalities and only two serious injuries (Wood *et al.* 2010). PGAs were in the range of 0.3 g to 0.8 g and PGVs exceeded 1 m/s. On 22 February 2011, Christchurch City was hit more directly, with the epicenter in hills just outside of the city and relatively shallow at 5-6 km depth. The earthquake caused 185 deaths, 8,600 injuries, and widespread physical damage to buildings and lifelines. The highest PGA recorded was 1.41g (Bradley and Cubrinovski 2011). The CES, in particular, the February earthquake, caused unprecedented levels of liquefaction throughout the southern and eastern suburbs of Christchurch alongside the Avon River (Yamada *et al.* 2011). The liquefaction resulted in settlement, lateral spreading, sand boils, and a large quantity of ejected silt mud and water ponding on the ground surface. The impact on horizontal and vertical infrastructure in these areas was severe. The CES resulted in widespread damage to buildings and infrastructure across the whole Canterbury region. Roughly 90% of the damage was within Christchurch City (Liu et. al. 2013). A financial loss of $30 billion (20% of New Zealand's annual gross domestic product) has been estimated (Parker and Steenkamp 2012).

The high rate of insurance in New Zealand (commercial buildings, residential land and buildings, and municipal infrastructure had high rates of cover relative to elsewhere in the world) meant that 80% of the economic loss was on the insurance industry (Bevere and Grollimund 2012). There were hundreds of thousands of insurance claims and extensive impact on insurers and re-insurers around the world (Parker and Steenkamp 2012). Residential housing presented an extreme case where government-led insurance paid practically all costs. Nguyen and Noy (2019) estimate that an application of the Japanese insurance system in Christchurch would have paid roughly 25% of what was paid to NZ residents, and for California's systems, only 12%.

Another intriguing result was the relationship between insurance and the fate of multi-story commercial buildings. Kim *et al.* (2017) analyzed a select set of 203 multi-story reinforced concrete buildings within the Christchurch central business district. Of these, 138 were demolished and 65 were repaired. Of the 138 demolished buildings, only 3 were deemed unsafe to re-occupy, while another 10 were demolished because of conflicts with newly planned large civic projects. Kim *et al.* (2017) found little relationship between the amount of damage to a building and a decision to demolish rather than repair. A series of interviews indicated that the decision was mostly motivated because of specific wording in commercial insurance policies that made a cash payout and a rebuild preferred over a slow and uncertain process of negotiating how much insurance would pay towards repair.

To manage infrastructure damage in Christchurch City, an alliance agreement was developed by three funding agencies and five commercial providers (Liu *et al.* 2013). The Stronger Christchurch Infrastructure Rebuild Team (SCIRT) was in charge of the damage assessment, rebuild design, and reconstruction delivery for the impaired roads, fresh water, and sewerage and stormwater networks in Christchurch with a budget of NZ $2.2 billion (approximately US $1.5 billion) and a roughly five-year timeline.

A significant issue during SCIRT's operation was the extent that they could or would "build back better". It would make no sense to replace a busted sewer pipe with a pipe in a pre-quake state (say, showing 40 years of wear). On the other hand, the insurers and the central government of New Zealand would not pay for a situation where Christchurch would have all new infrastructure that would in turn mean very low maintenance costs over the next 50 years relative to what they would have paid without the CES. The compromise solution meant that SCIRT would indicate the additional cost to "build back better", and the city would have the choice to on whether or not to pay for that additional work.

Both the horizontal and vertical infrastructure experiences in Christchurch have led to a great deal of consideration on adding resilience and robustness in civil engineering construction. For residential houses, the sizeable expense of, often minor, repairs on tens of thousands of houses has pushed the insurance and house construction industry into investigating new methods of construction to make houses more resilient to events well within their structural design limits (Pourali *et al.* 2017).

For commercial buildings, the response in Christchurch has been towards resilient buildings, including fuse-like damper systems to reduce repair costs (Rodgers *et al.* 2016). Although the direct additional cost of resilience additions might not be justifiable when considering the probability of damaging events and the cost of the building, greater consideration than before the earthquakes has been given to the indirect costs for commercial entities of a demolish/rebuild path.

A new appreciation for the cost of damage to non-structural building components (fittings, cladding, and furniture) and the cost of business disruption is the driver in Christchurch for additional robustness and resilience in building construction. While a path exists for these costs to be factored into decisions related to resilience/robustness for buildings (through insurance), the same does not yet exist for horizontal infrastructure. It is not clear how a city government in New Zealand can factor in the indirect costs of failure (e.g., health costs from failed sewers) into decisions to pay extra for resilient infrastructure.

4 IMPLICATIONS AND CONCLUSIONS

The United States and New Zealand are two of the richest countries in the world. If such severe economic and societal disruptions are possible in those countries, how much greater are the risks in other parts of the world? In these cases, while there was considerable loss of life, the survivors were faced with serious economic and societal disruptions. It is important to learn from those events and to adapt to the future (ASCE 2015). We present a number of thoughts on implications with the intention of stimulating discussion rather than providing results of any specific research.

The need for greater resilience and robustness, as supported by these two case studies, indicates that redesign and retrofit design will become more common in the future. As risks are reassessed, redesign will lead to better outcomes. The challenge will be society providing new and appropriate contractual pathways for redesign and retrofit design.

Past experiences such as those from Katrina and Christchurch will push society increasingly towards acceptance of robust and/or resilient design approaches. While engineers might accept a need to move from 'fail-safe' designs to 'safe-to-fail' designs, that can only happen if clients and contracts recognize the long-term benefits of resilient approaches (New Zealand Ministry for the Environment 2017).

One reason that there has been little push for redesign/retrofit in the past is that there has been no reduction in the great uncertainty that decision-makers face when making design decisions. The growth of structural monitoring and smart infrastructure has changed this. Increasingly, redesign/retrofit can be worth the cost because new data can reduce uncertainty in decisions.

A major part of the challenge with design in the face of climate change is uncertainty about future demand loads, and about the technology options engineers will have in the future to solve problems. New knowledge and technology will create opportunities for new robust/resilient design options, and the construction industry and its clients are increasingly seeing resilient design choices as a way to keep options open rather than locked in obsolesce.

Civil engineering design has a history of thinking in terms of 100-year design lives. This is unlike the design process in other engineering branches where re-design and retrofit are well accepted, and products are design as a platform that can be redesigned and repurposed into the future. Climate change in particular will push civil engineers into changing their view of the design product to be more like that of other engineers.

The combination of risk reassessment, monitoring, and new technology seems likely to push civil engineering design into the following cyclical process: design → monitor/change → redesign → monitor/change → redesign (Gibbs 2015). This will apply not only to buildings but also to roads, sewers, bridges, etc. The push for resilience is likely to continue recent movement away from the three separate stages of civil infrastructure (design, build, operate/maintain), and towards seeing infrastructure construction as part of integrated infrastructure service provision.

Perhaps we are in the middle of a change in what civil engineering design means without recognizing it. Perhaps the process and discipline are changing, but is it happening quickly enough and are our institutions adapting? For example, a change away from design as a discrete event to a process indicates a need for new contracting arrangements for design services. This change also implies a need for changes in engineering education where the traditional design course is modified to focus on monitoring, redesign, and infrastructure service provision.

The book ***Flexibility in Engineering Design*** (de Neufville and Scholtes 2011) provides a valuable set of signposts for a move in the direction of resilient civil engineering design processes. It emphasizes the consideration in design of variability, uncertainty analysis, Bayesian updating, and decision tree approaches. How many universities today would tie these concepts tightly to engineering design? How many practicing design engineers are ready to adapt to a world where those subject areas are central to improved design practice?

There is recognition of a need to design and build infrastructure (vertical and horizontal) with resilience, robustness, and a capacity for adaptation. Acceptance of these precepts will likely change the nature of civil engineering design. A robust, resilient, and adaptive design is one that is able to be tuned when faced with new information on risks and one that is able to be modified to incorporate new techniques. To provide value to society in changing times, civil engineering designs must be seen as resilient and adaptable. So too must the engineers themselves be ready to adapt.

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