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Michael Beer, Ivan S.K. Au & Jim W. Hall (editors)

A Resilience Engineering Framework: Adapting to Extreme Events

Yumei Wang[1] and Qisong "Kent" Yu[2]

[1]Sustainable Living Solutions LLC, Portland, Oregon, USA. email: yumei.wang@comcast.net
[2]SEFT Consulting Group LLC, Portland, Oregon, USA. email: kentyu@seftconsulting.com

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ABSTRACT
In 2011, earthquakes and flooding caused historic insured losses of over USD $126 billion, the highest ever recorded. To save lives, reduce economic losses and improve societal wellbeing, regions should develop resilience engineering frameworks to adapt to possible extreme events. Gap analyses of infrastructure services are required to estimate the restoration time caused by a selected extreme event. Implementation of a resilience engineering framework should adopt performance-based critical infrastructure targets in order to restore services to the Triple 3 Resilience Target: 3 days for emergency services, 3 weeks to restore basic utility services and 3 years to achieve improved critical infrastructure systems. Resilience offices are needed to help lead, coordinate, implement, and track progress focusing on the reliability of critical infrastructure components and interdependencies.

INTRODUCTION
Disasters are on the rise with increasing intensity and frequency of severe storms and flooding and increasing populations. Swiss Re's study revealed that natural and human-caused disasters in 2012 caused economic losses of USD $186 billion with about 14,000 lives lost. Large scale weather events in the U.S. in 2012 contributed to the total insured claims of USD $77 billion, which is the third most

expensive year on record. This 2012 amount is still significantly lower than 2011, when record earthquakes and flooding in the Asia Pacific caused insured losses of over USD $126 billion, which is the highest ever recorded (http://www.swissre.com/media/news_releases/nr_20130327_sigma_natcat_2012.html).

Many regions are prone to extreme events, including earthquakes, tsunamis, hurricanes, and other natural hazards. Among the highest risk regions are those along active plate boundary subduction zones, where earthquake shaking can last for several minutes, tsunamis can strike with only 15 to 25 minutes of warning and coastal lands can experience regional subsidence of one to two meters or more. To save lives and reduce economic losses, society will need to learn from past disasters and develop resilience engineering frameworks to adapt to possible extreme events.

RESILIENCE ENGINEERING

Traditionally, U.S. civil engineers have focused on life safety – but not the actual performance of critical infrastructure systems. Furthermore, lifeline infrastructure systems in different sectors were designed, assessed and/or rehabilitated by their public operators and private owners without coordination and a consistent understanding of their interdependencies on other systems let alone the consequences of their systems' failure on the overall pace of the community recovery. The current thinking by many civil engineers (including the authors) is to break down the "silo" mentality and take a holistic approach to design buildings and infrastructure for physical resilience, which involves being able to withstand an extreme event with minimal disruption and quick recovery. As such, resilience engineering (that is, engineering resilience into structures) may become a new focus in the building code in the future.

Holistic and transparent resilience engineering is needed to ensure a community will quickly recover from an extreme event, also referred to as a disaster. Figure 1 shows the Resilience Triangle graph, which juxtaposes low resilience with a slow recovery time and high resilience with a fast recovery time. In normal conditions, there are gradual improvements to infrastructure services as depicted by the gently upwards sloping “normal condition” line. The resilience triangle, shown in green, depicts minimal service disruption caused by the disaster, immediately followed by quick and efficient recovery to a condition with improved services over the pre-disaster service level.

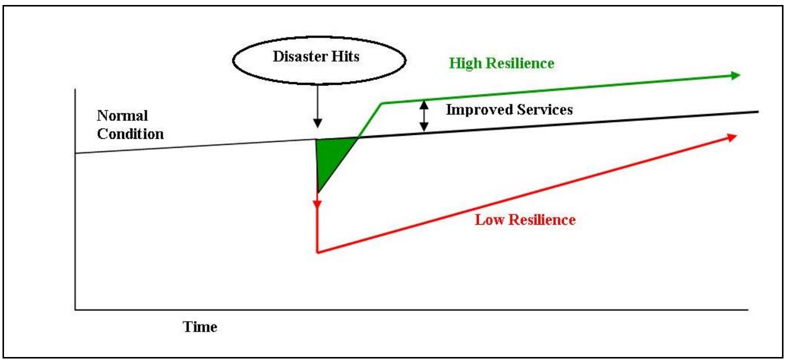

Figure 1. Resilience Triangle (modified from Wang et al., 2013).

Critical facilities and infrastructure systems (e.g., hospitals, emergency response, power, and transportation) need to be operational and functional during and after an extreme event to support other aspects of community resilience. Additionally, the remaining buildings and infrastructure systems need to be restored within a specified period of time, if damage does occur, to minimize disruption to the community, expenditures for repair and rebuilding, and economic impacts. Resilience of the built environment depends upon the post-event capacity of each facility and infrastructure system, when considered in the context of the community, to maintain acceptable levels of functionality during and after disruptive events and to recover full functionality within a specified period of time (McAllister, 2013).

RESILIENCE ENGINEERING FRAMEWORK

The proposed resilience engineering framework addresses extreme events and involves several phases: identifying the possible extreme events, conducting gap analysis of the critical infrastructure services for a given event, determining viable strategies for reducing the impact of such event, involving stakeholders to develop action plans to improve the community resilience, implementing the plan, and tracking the progress using resilience metrics.

The purpose of the resilience engineering framework is to reduce the impact from both frequently occurring disasters, such as 100-year floods, and extreme events, such as 2,500-year earthquake ground motions. Reducing the impact involves enhancing life safety, reducing property losses, and quickening the recovery process. In order to improve the recovery process, critical infrastructure that modern advanced society relies upon must be reliable in normal conditions and can be restored within a reasonable timeframe during extreme event conditions.

Triple 3 Resilience Target

To support a healthy vital economy, many infrastructure services are needed. Emergency services, involving fire, police, hospital and emergency operation centers are needed. Utilities, involving electricity, natural gas, water, waste water, and telecommunications are essential. Transportation services, involving highways, ports, airports, rail, and liquid fuel supplies are needed.

Immediately after an extreme event, the functionality of certain infrastructure services will likely be compromised. The Triple 3 Resilience Target, proposed herein, aims to provide three tiers of services after an extreme event: 1) Recovery of emergency services for immediate needs within 3 days in order to provide a base level of protection for people. 2) Recovery of basic infrastructure services to the near pre-disaster service level within 3 weeks in order to recover from the disaster and restore normal living conditions. This will likely involve temporary fixes to systems to regain operability but lack the required engineered upgrades. 3) Modern upgrades to infrastructure systems to better than pre-disaster system levels, including substantial improvements to older damaged components that did not meet current design levels (Figure 2).

To simplify, the Triple 3 Resilience Target is:

- 3 days: restore emergency services
- 3 weeks: restore to pre-disaster service levels
- 3 years: improve infrastructure to a new norm

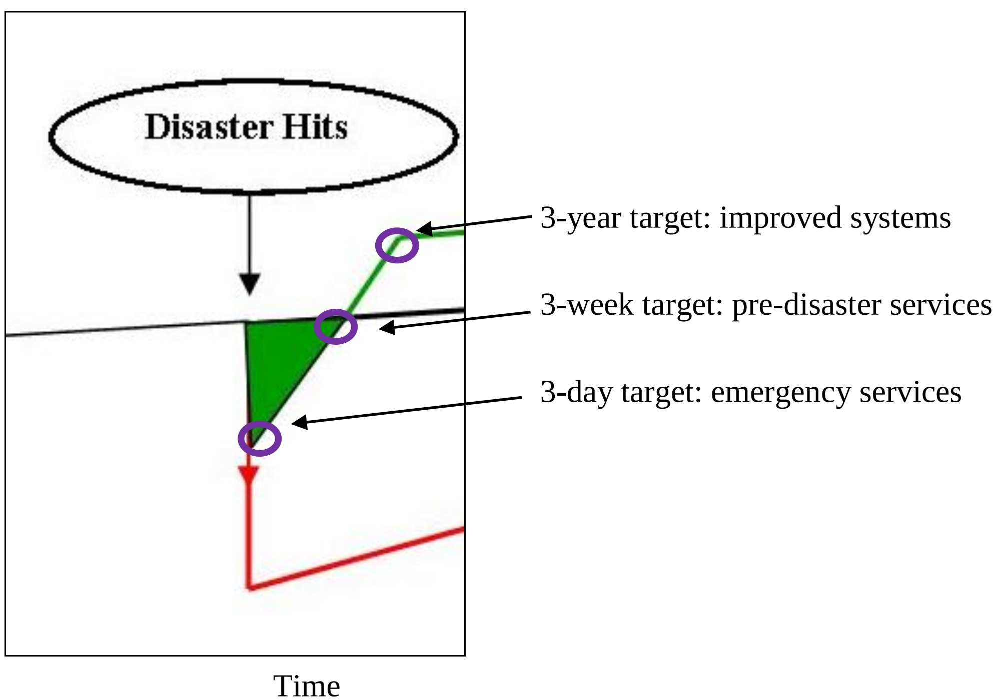

Figure 2. Triple 3 Resilience Target: 3 days for emergency services, 3 weeks to restore services to the

pre-disaster level, and 3 years to improve critical infrastructure systems to provide a new higher service level. It is a close up of the resilience triangle.

A resilience engineering framework, which should integrate the newly proposed Triple 3 Resilience Target, is guided by the Critical Infrastructure Pyramid (Figure 3). The framework should address the potential impacts to people, communities and businesses, which are supported by ensuring reliable critical infrastructure, which is built into the environment that serves as the base of the pyramid. An important relationship exists between the health and well-being of people, communities and businesses and the resilience of the critical infrastructure upon which they rely.

Furthermore, the framework should dovetail into multiple existing plans, including long term community master plans involving business development, transportation, emergency response and recovery, natural hazard mitigation, sustainability and climate change and land use planning. A successful framework should focus on maximizing life safety and business continuity, thus reliable critical infrastructure services are important. Performance metrics on multiple scales, including the component, system, and multiple system level, are needed to measure the resilience of the critical infrastructure.

Building resilience in a modern city is a complex process that involves many critical infrastructure systems. This process of “climbing the resilience ladder” from lower to higher resilience may involve many stakeholders over decades. Before the disaster, a combination of planning, preparing and mitigation should take place with the goal of achieving the Triple 3 Resilience Target. Systems that depend on components with low levels of engineering design may require engineered mitigation that improves the reliability of the overall system performance. Mitigation actions conducted before the extreme event should reduce the needed response and recovery after the extreme event.

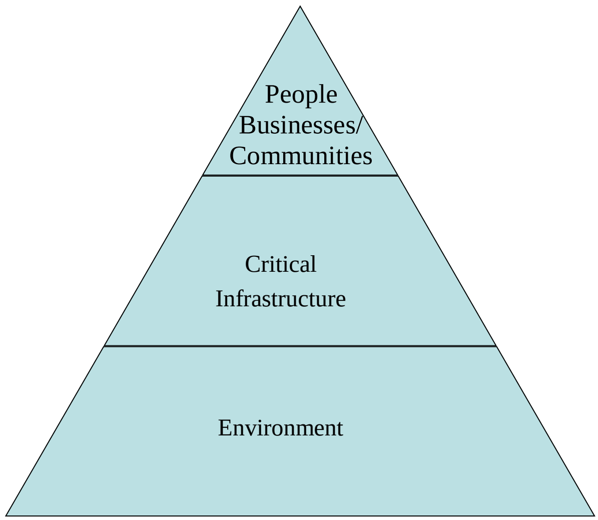

Figure 3. Critical Infrastructure Pyramid showing the environment as the foundation, and critical infrastructure as supporting people, communities and businesses.

MAGNITUDE 9 EARTHQUAKE CASE STUDY

The extreme event for the Pacific Northwest, U.S., is a magnitude 9 Cascadia earthquake on the Cascadia subduction zone, a major plate boundary fault. The Cascadia fault has conditional probability of generating a magnitude 8 or larger earthquake of about 40 percent in the next 50 years. Based on 10,000 years of Cascadia earthquake history preserved in the geological environment, 75% of the time intervals between Cascadia megaquakes have already been exceeded for the southern margin of the Cascadia fault. If a megaquake has not occurred by the year 2060, then 85% of all the known intervals between earthquakes will be been exceeded (Goldfinger et al., 2012). This case study includes the 2013

Oregon Resilience Plan: Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami, which was developed by the Oregon Seismic Safety Policy Advisory Commission (OSSPAC) at the direction of the Oregon Legislature immediately after the 2011 Tohoku Japan earthquake and tsunami disaster (OSSPAC, 2013). The planning process was largely driven by civil engineers (including the authors), and included about 170 contributors from industry, government, and the private sector.

Results from gap analyses of five critical infrastructure sectors, including critical buildings, energy, transportation, water and waste water, and communications, reveal extreme vulnerabilities and extensive recovery times for restoring basic infrastructure services. Table 1 shows the expected recovery times for critical services in two geographic zones: the coast, which is lightly populated and would experience strong earthquake shaking and partial tsunami flooding; and, the valley which is moderately populated and would experience moderate earthquake shaking. As shown on Table 1, row 1, basic water services are expected to be down for over 36 months on the coast and between 6 and 12 months in the valley, and so on.

Table 1. Expected Timeframes to Restore Infrastructure Services (based on OSSPAC, 2013)

Critical Services	*Coast (months)*	*Valley (months)*
Water	*36 +*	*6 – 12*
Waste Water	*36 +*	*36 +*
Healthcare	*36 +*	*18*
Highway (Tier 1)	*12 - 36*	*12 – 36*
Fire	*36 +*	*2*
Police	*36 +*	*4*
Schools	*18*	*18*
Communications	*6 - 12*	*6 - 12*
Electricity	*3 - 6*	*1 - 3*
Fuel	*No Info*	*No Info*

Steps to develop order of magnitude cost estimates for priority recommendations along with benefit cost analyses are underway for certain infrastructure, such as the highway system. At the direction of the Legislature, a task force was created to develop a resilience implementation plan by October 2014. Implementing and tracking progress would be the next phases of the resilience engineering framework.

RESILIENCE ENGINEERING CHALLENGES

Resilience engineering challenges on the global level relate to the need for: 1) widespread regional critical infrastructure gap analyses from extreme events; 2) improved models for system interdependencies; 3) cost-effective intermediate solutions to enhance service reliability; 4) resilience metrics at multiple scales; and 5) integration with sustainability efforts. Due to the long term, complex nature of building resilience in a community, establishing Resilience Offices, such as within the Governor's or President's Office, is needed. The Resilience Office would help promote, prioritize, lead, coordinate, track and report on resilience engineering efforts.

CONCLUSIONS

In order to adapt to extreme events, such as a magnitude 9 Cascadia earthquake in the Pacific Northwest, engineers need to move the performance goal beyond life safety to resilience. Resilience engineering frameworks should be developed focusing on achieving reliable critical infrastructure services. Long range action plans should achieve the Triple 3 Resilience Target to meet immediate needs in 3 days, basic needs in 3 weeks, and modernized infrastructure with improved services in 3 years. Resilience Offices should be established to lead and coordinate resilience efforts and track progress towards the Triple 3 Resilience Target.

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