Cost-benefit analysis of liquefaction mitigation strategies

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Abstract

This paper presents a cost-benefit model as part of the options appraisal process to evaluate alternative ground mitigation interventions to reduce vulnerability and/or improve resilience of built assets to earthquake induced liquefaction disaster (EILD) events. The paper presents a review of alternative approaches to cost-benefit analysis and develops forward looking (risk based) and backward looking (impact based) cost-benefit models that can be used by practitioners and policy makers to improve community resilience through better contingency and disaster management planning. The paper customises the models against EILD scenarios and identifies the cost and benefit attributes that need to be assessed if the models are to be effectively integrated into a resilience assessment and improvement framework for improved community resilience to EILD events.

Keywords: cost-benefit modelling; disaster management; community resilience; liquefaction; ground mitigation; contingency planning; built asset management.

1. Introduction

Cost-benefit analysis (CBA) is a well-recognised option appraisal technique to compare the costs and resultant benefits of alternative development/mitigation projects. The technique is particularly useful when government or public institutions are seeking to justify significant investments to improve local infrastructures and community resilience to disasters. The basic idea of CBA is to identify the costs of undertaking development/mitigation projects and compare these to the benefits over time that could accrue from the development/mitigation projects. The benefit to cost ratio (B/C) provides a dimensionless indicator that can inform the business decision on whether development/mitigation projects should be funded. Cost-benefit analysis can be applied at different scales, from assessing development options for individual stakeholders to evaluating the potential net benefit of development options across multiple stakeholder groups. In the LIQUEFACT project, CBA is being used to evaluate the economic viability of different liquefaction mitigation options on both individual built assets (individual stakeholder group) and the wider community (multiple stakeholder groups). This paper reviews alternative approaches to CBA and describes two approaches developed in the LIQUEFACT project to assess alternative ground mitigation options as part of an earthquake induced liquefaction disaster (EILD) resilience assessment and improvement framework (RAIF). Earthquake-induced soil liquefaction occurs when soil strength and stiffness decrease as a consequence of an increase in pore water pressure in saturated cohesionless materials during, and following, seismic ground motion as a result of the applied stress; hence causing the soil to behave like a liquid. (National Academy of Sciences 2016).

2. Cost-Benefit Analysis

Cost-benefit analysis uses the concepts of consumer surplus and externality to evaluate alternative investment opportunities by considering profit (or loss) of investment options for society. When the externality is negative the cost to society is greater than the cost to the individual stakeholder. When the externality is positive the cost to society is less than the cost to the individual stakeholder and as such there is a net benefit to society (Johansson and Kristom, 2016).

The CBA process involves the identification of stakeholder's objectives/outcomes required of a development/mitigation project and the economic evaluation of a range of alternative intervention options (physical, operational, social etc.) to achieve the outcomes. For each option, the project costs are calculated and compared against the estimated benefits to produce a ranked order listing. The results from the ranking list are combined with an assessment of risk and the un-monetarised factors not considered in the CBA to produce a final ranking order of preferred development/mitigation solutions (Johansson and Kristom, 2016).

The cost component of the CBA methodology is calculated by considering both the capital and operating costs associated with an intervention. Capital costs include facilitating works costs, building works costs, construction costs, design and other consultation fees, development costs, risk estimates, inflation estimate and taxes. Capital costs can be estimated from previously completed projects; published data sets or from constructors' quotations. Operating costs include repair and refurbishment costs, utilities costs, disposal costs and facilities management costs. It is generally accepted that the operating cost of a built asset is substantially higher compared to its capital costs (Evan et al., 1985) and as such they must be included when developing lifecycle cost models. Finally, all costs need to be discounted to current value to account for future cash flow projections. Future cash flow is discounted using a discount rate to derive present value estimates that are used to allow direct comparison between the cost of investments and the expected return on that investment over time.

The benefit component of the CBA methodology is calculated by valuing the tangible and intangible benefits associated with an intervention. The International Valuation Standards Council (IVSC) (2016) identifies three main approaches to estimate the value of tangible benefits: the market approach; the income approach; or the cost approach. The market approach provides an indication of value by comparing products with identical or comparable products for which price information is available. The income approach estimates the value of a product by reference to the value of income, cash flow or cost savings generated by the product. The cost approach provides an indication of value by calculating the current replacement or reproduction cost of a product and making deductions for physical deterioration and all other relevant forms of obsolescence.

The intangible impacts are more difficult to value directly and normally rely on proxy measures. There are three main approaches used to value intangible impacts: the revealed preference approach; the stated preference approach; and the subjective well-being/life satisfaction approach. The revealed preference approach quantifies the value of non-market products using market information and behaviour to infer the economic value of an associated non-market impact (OECD, 2006). The stated preference approach uses specially constructed questionnaires to elicit estimates of people's Willingness to Pay (WTP) for or Willingness to Accept (WTA) a particular outcome (Fujiwara and Campbell, 2011), or to offer people choices between "bundles" of attributes from which analysts can infer society's WTP or WTA (OECD, 2006). The Subjective Well-Being/The Life Satisfaction approach attempt to measure people's experiences rather than their preferences through direct measures of well-being, such as life satisfaction (Fujiwara and Campbell, 2011).

Whilst in many cases the costs associated with development/mitigation options appear easier to estimate than the benefits of such interventions care must be taken to avoid, or at least minimise, optimism bias and risk. Optimism bias (the proven tendency for appraisers to be too optimistic about key project parameters) and risk perception (uncertainties that arise in the design, planning and implementation of an intervention) are known to have a significant impact on cost estimates which if unaccounted for can undermine confidence CBA models. As such CBA models should include a sensitivity analysis and, where interventions have significant direct effects on markets, compliance costs should be estimated using general equilibrium analysis which captures linkages between markets across the entire economy (U.S. Environmental Protection Agency, 2010).

3. CBA in Disaster Mitigation

The generic approach to CBA has been adapted to assess the efficiency and benefits of mitigation interventions that seek to reduce disaster impacts. Figure 1 presents the five basic steps of CBA for disaster mitigation according to Smyth et al. (2004).

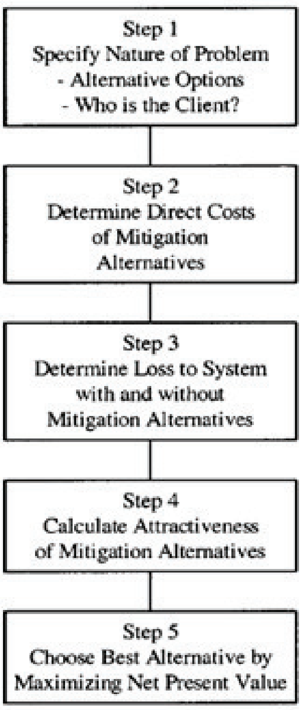

Figure 1. Steps of CBA for disaster mitigation. Source: Smyth et al. (2004).

As with the generic approach to CBA there are a number of practical issues associated with the quantification of tangible and intangible benefits that have to be addressed if the technique is to be successfully applied to disaster scenarios.

In disaster mitigation CBA the costs represent the expenditure needed to retrofit or refurbish an asset whilst the benefits are related to avoided damages (to assets and people) due to the improved performance of retrofitted assets. The cost of retrofitting assets are compared with future benefits quantified in terms of equivalent annualized values discounted to present-day that could be realised in the future if a disaster occurs.

Whilst there are many different approaches to developing CBA models for disaster mitigation (Kull et al., 2013; Jonkman et al., 2004; NIST, 2013;) White and Rorick, 2010; Wethli, 2014; Mechler, 2005, Mechler et al, 2014) the assessment of losses to a system are complicated by the uncertainties in the timing, location, and severity of future disasters events.

White and Rorick (2010) present three theoretical approaches to CBA based on the comparison of the impact of disasters with and without disaster risk reduction (DRR) mitigations. The first approach adopts either backward-looking (impact) or forward-looking (risk) methods to assess the cost and benefits of DRR mitigations. The former uses a comparison between the impact of a given disaster in a community with DRR mitigations and a hypothetical community without DDR mitigations while the latter suggests a comparison of the realized impacts in a community without DRR interventions to the hypothetical impacts with DRR mitigations. The second approach is a comparative approach where the impact of DRR mitigations are compared in two different communities stricken by disasters of the same magnitude. The third approach is a before-and-after approach that compares impact data from the same community for similar disasters occurring before and after a DRR mitigation programme. However, whilst there is evidence of the economic effectiveness of CBA in DRR there are also numerous limitations with their existing application to disaster management, including a general lack of sensitivity analyses and the absence of meta-analysis linking theoretical solutions to empirical findings (Shreve and Kelman, 2014).

In an effort to address the weaknesses identified with DRR CBA and to develop operational tools to translate the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) into practice, the Joint Research Centre of the European Commission developed "the guidance for Recording and Sharing Disaster Damage and Loss Data" (EU expert working group on disaster damage and loss data, 2015). The guidance identified that losses should be recorded against four key types of "affected elements": Social; Economic; Environmental; and Heritage (Figure 2). These categories have been used to assess the losses associated with the EILD event CBA.

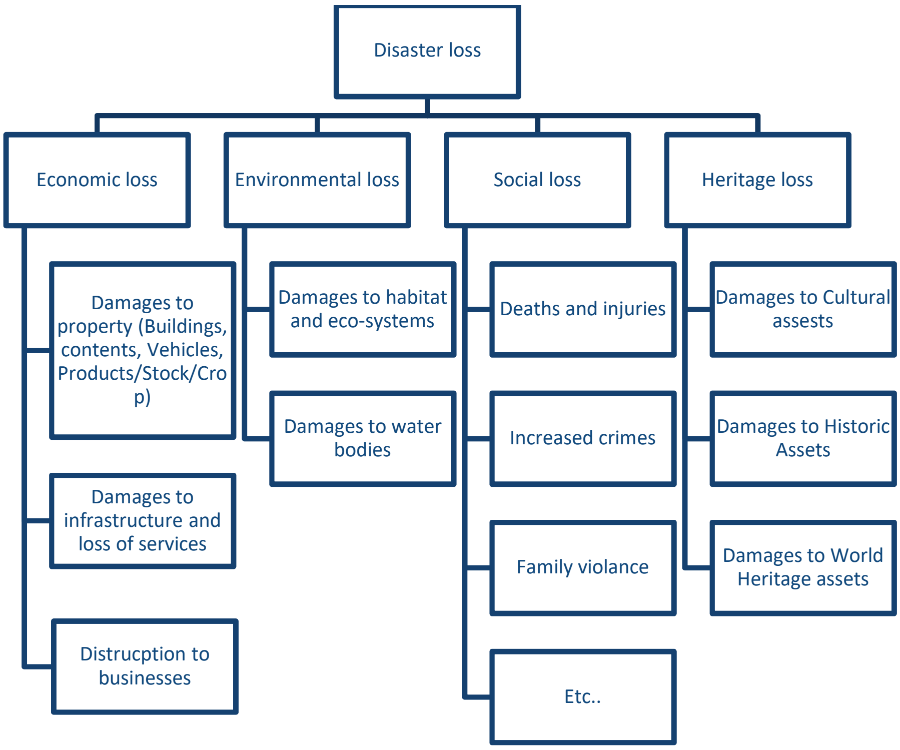

Figure 2. Summary of loss categorisation provided in The guidance for Recording and Sharing Disaster Damage and Loss Data (EU expert working group on disaster damage and loss data, 2015).

4. CBA applied to Earthquake Events

Cost-benefit analysis has been used to assess the effectiveness of mitigation interventions to reduce earthquake associated losses at both the individual building/assets and city/regional level.

At the building/asset level Goda et al (2010) used CBA to investigate the efficiency of different types of seismic isolators to mitigate seismic risk applied to two identical buildings located in Vancouver. Their CBA model considered both the initial construction cost and the repair/re-construction costs associated with post event damage but did not include mortality or morbidity costs and as such represented only the tangible costs of earthquake events.

Kappos and Dimitrakopoulo (2008) applied CBA to the assessment of the economic feasibility of retrofitting a portfolio of domestic buildings in the city of Thessaloniki. Thier CBA model used a series of hazard curves based on probabilistic models and vulnerability analyses to develop fragility curves to examine the cost effectiveness of retrofitting actions to the urban pre-1959 reinforced concrete designed housing. The CBA model used local and international datasets to assess replacement and retrofit costs for a range of building typologies with the building damage being calculated as the product of the replacement cost times the area of the building times the mean damage factor derived from a damage probability matrix that describes the vulnerability of the building. In addition to the physical cost of damage to the buildings the CBA model also considered indirect losses including human fatality.

Padgett et al. (2010) developed a risk-based seismic lifecycle CBA to evaluate alternative retrofit mitigations to non-seismically designed bridges as part of a seismic upgrade programme. Padgett et al's approach again used probabilistic seismic hazard models combined with fragility curves of the as-built and retrofitted bridges across a range of damage scenarios and retrofit options to compare the expected costs of damage before and after a retrofit program. The CBA model considered the cost and benefits over the service life of the bridges (an assumption of 50 remaining years life was used for all bridges) but did not include the costs of ongoing maintenance during the remaining service life period.

In the previous examples CBA were used to assess losses and evaluate mitigation interventions at the structural serviceability and ultimate limit states. However, in many modern buildings (increasingly used by the critical infrastructure providers) failure at the functional limit state can have a significant impact on service delivery, and in turn total loss assessment, and failure to address this aspect is a significant weakness in most CBA models (Kanda and Shah, 1997). Addressing the business-related aspects associated with EILD events is a key aspect of the LIQUEFACT project.

5. CBA applied to EILD events

The LIQUEFACT project has developed a CBA methodology to evaluate liquefaction risk management strategies at the community, single built asset and critical infrastructure levels.

Unlike disaster events that affect a wide geographical area, EILD event impacts are generally localised, affecting individual sites and/or assets and as such the traditional disaster CBA model has been customised to reflect localised hazard, exposure and vulnerability assessments. In LIQUEAFCT CBA is applied at two levels. Firstly, CBA is used as part of the options appraisal process to identify the most appropriate liquefaction mitigation option at an individual asset (or collection of assets) at the site level. At this level the cost of a mitigation option is set against the perceived benefit to the asset owner/operator in terms of avoiding the costs (both direct and indirect) associated with loss of performance or failure (full and/or partial loss of performance over time) of the asset following an EILD event. Secondly, the CBA for those individual assets within a region that are critical to support community resilience to an EILD event are aggregated to provide an assessment of the overall CBA for the region of the mitigation interventions applied to the individual assets.

The CBA model developed by LIQUEFACT follows a four stage approach similar to that developed by Mechler (2014).

- Stage 1: Estimate the risk in the antecedent condition without soil liquefaction risk management strategies being implemented. This requires estimating and combining liquefaction hazard, exposure and vulnerability.
- Stage 2: identify possible soil liquefaction risk reduction / mitigation measures and their costs, which, for hard infrastructure projects, consist of design, construction and maintenance.
- Stage 3: Analyse the risk reduction associated with each mitigation option: estimate the benefits of reducing liquefaction risk.
- Stage 4: Calculate the economic efficiency of the measures. A measure can be defined economically efficient if the benefits exceed costs.

In operationalising the above two frameworks have been developed. The forward-looking CBA framework (risk-based approach) combines data on hazard and vulnerability to assess antecedent risk and reduced risk after mitigation. Whilst this approach is mathematically rigorous, its application can be problematic in situations where data and resources available to undertake the assessment are limited. The backward-looking framework (impact based-approach) uses past damage to assets to assess the risks associated with the disaster event and quantify potential future damage states that history suggests would exist should such an event occur again. Both the forward and backward looking CBA frameworks have been integrated into the RAIF (LIQUEFACT D1.3[1]) and an initial validation of the approach has been performed through a detailed review of literature and in discussions/interviews with practitioners and academics.

6. Impacts and costs associated with EILD events

Natural disasters result in a range of impacts that affect social, economic, environmental and heritage elements. Further, the impact can occur as a direct result of the disaster event or over time as indirect or macroeconomic effects (Mechler, 2005). The expected range of impacts associated with EILD events include:

- Social: household structure; furnishings, fixtures and fittings; temporary housing; increased rents; loss of income; reduced purchasing power; mortality and morbidity rates; service loss/reduction; reduced well-being; lower living standards; increased poverty.
- Economic: loss/damage to public assets; service disruption; consequential loss to businesses; ejecta clean-up; repair and reconstruction; post event survey; reduction in skilled labour; disruption to supply chain logistics; unemployment.
- Environmental: pollution control and clean-up; decontamination.
- Heritage: damage to historical assets; business closure; reduced tourism; loss of natural habitat; impacts on biodiversity.

In addition to the cost elements the CBA model needs to assess the benefits associated with alternative mitigation options. Two approaches to mitigate liquefaction have been investigated in LIQUEFACT: reducing the site susceptibility to liquefaction (through ground densification, stabilisation, dissipation and desaturation); and/or enhancing the capacity of assets to reduce the damage caused by liquefaction (structural modifications, change of use, or change of operating procedures).

For each of the above the costs associated with retrofitting alternative mitigation options to existing built assets are calculated (see section 2) and compared to the costs associated with loss of performance/functionality for the individual asset owner and the wider community. Two resilience toolkits are being developed that assess the impact that the loss of performance of assets will have on individual asset owners and the wider community (LIQUEFACT D5.1[2]) The associated costs and benefits are discounted to current value to account for future cash flow and a sensitivity analysis is performed by varying the input variables to the resilience toolkits.

7. Integrating CBA in Built Asset Management Planning

The final stage of the CBA process is to integrate the CBA models into the RAIF and develop built asset management plans for improved resilience to EILD events. Whilst this work is ongoing an initial 10 step framework has been developed,

1) Define the characteristics of the building or asset under consideration;
2) Identify the susceptibility of the building or asset to an EILD event;
3) For those buildings or assets at risk of physical damage assess the impact that different damage states have on the performance / functionality of the building or assets;
4) Identify a range of mitigation options (both physical and operational) that can reduce the impact on both the building/asset owner and the wider community;
5) Calculate the cost (capital and operating) of implementing each mitigation option through reference to existing cost databases or contractors estimates;
6) Calculate the benefits in terms of avoidable losses without mitigation at the organisation and community levels using the resilience scorecards;

[1] Available at: https://zenodo.org/record/1342687#.XAVKh0x2taQ

[2] Available at: https://zenodo.org/record/1887913#.XAY3rkx2taQ

7) Combine 5) and 6) for each mitigation option using a hybrid version of the forward and backward looking CBA frameworks to derive loss-frequency curves and develop a rank order list based on the B/C ratio;
8) Compare the economic and social benefits associated with each mitigation option and evaluate the impact of including each as part of the maintenance/refurbishment life cycle of the building or asset;
9) Instigate full technical design procedures for those mitigation options that form part of the next maintenance/refurbishment cycle;
10) Develop disaster management and business continuity and resilience plans to manage the impact that an EILD event will have on building asset performance for any mitigation options that have been deferred future application.

8. Conclusions and Next Steps

The LIQUEFACT project aims to develop a more comprehensive and holistic understanding of the earthquake soil liquefaction phenomenon and the effectiveness of mitigation techniques to protect structural and non-structural systems and components from its effects. The LIQUEFACT project will evaluate the mitigation techniques against the potential improvements that could accrue to community resilience in regions prone to EILD events. This paper provides an introduction to CBA as it is applied to the valuation of mitigation interventions that seek to reduce the impact of disaster events on individual buildings/assets and the wider community. The paper has outlined the basic principles of a CBA and drawn attention to the issues that need to be considered when assessing both the costs and benefits associated with a mitigation intervention. The paper has reviewed the role of CBA in the project development cycle and discussed alternative theoretical approaches that have been developed by researchers studying disaster management and disaster risk reduction mitigation. In reviewing these theoretical approaches the paper has considered both the benefits and limitations of applying CBA in disaster management and disaster risks reduction and, whilst it acknowledges that the limitations are significant, concludes the benefits of using CBA to inform business decisions, outweighs the limitations. The paper also outlines a bespoke hybrid LIQUEFACT CBA framework that can be applied to the evaluation of alternative mitigation interventions that seek to reduce the impact that EILD events have on individual buildings/assets and the wider community. In developing the LIQUEFACT CBA framework the paper has considered the specific characteristics of EILD phenomenon and explained how these are addressed within the LIQUEFACT CBA framework. Finally, the paper explains how the LIQUEFACT CBA framework is integrated into the LIQUEFACT RAIF to support a 10 step model that will be used to validate the LIQUEFACT CBA, RAIF, LRG through a range of use-cases currently being developed in the LIQUEFACT project. Further details of the CBA modelling can be found in LIQUEFACT Deliverable 5.3[3].

9. Acknowledgment

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