Cost Benefit Analysis to Appraise Technical Mitigation Options for Earthquake Induced Liquefaction Disaster Events

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Abstract

Purpose: Recent earthquake induced liquefaction events and associated losses have increased researchers' interest into liquefaction risk reduction interventions. To the best of the authors' knowledge there was no scholarly literature related to an economic appraisal of these risk reduction interventions. This research investigated the issues in applying Cost Benefit Analysis (CBA) principles to the evaluation of technical mitigations to reduce earthquake induced liquefaction risk.

Study design/methodology/approach: CBA has been substantially used for risk mitigation option appraisal for a number of hazard threats. Previous literature in the form of systematic reviews, individual research and case studies, together with liquefaction risk and loss modelling literature was used to develop a theoretical model of CBA for earthquake induced liquefaction mitigation interventions. The model was tested using a scenario in a two-day workshop.

Findings: Since liquefaction risk reduction techniques are relatively new, there is limited damage modelling and cost data available for use within CBAs. As such end users need to make significant assumptions when linking the results of technical investigations of damage to built-asset performance and probabilistic loss modelling resulting in many potential interventions being not cost effective for low impact disasters. The authors question whether a probabilistic approach should really be applied localised rapid onset events like liquefaction, arguing that a deterministic approach localised knowledge and context would be a better base for the cost effectiveness mitigation interventions.

Originality/value: This paper makes an original contribution to literature through a critical review of CBA approaches applied to disaster mitigation interventions. Further, the paper identifies challenges the limitations of applying probabilistic based cost benefit models to localised rapid onset disaster events where human losses are minimal and historic data is sparse; challenging researchers to develop new deterministic based approaches that use localised knowledge and context to evaluate the cost effectiveness of mitigation interventions.

Key words – Cost benefit analysis, earthquake induced liquefaction, earthquakes, disaster risk reduction

Introduction

Earthquakes cause significant damage to buildings and infrastructure due to ground shaking. In addition, earthquakes can induce secondary hazards such as landslides, liquefaction, tsunami which in turn cause further damage (Daniell *et al.,* 2012 & 2017; Marano *et al*., 2010). This paper is centred on earthquake induced liquefaction, one of the key secondary hazards of earthquakes. Earthquake-induced liquefaction is a phenomenon where soil strength and stiffness in saturated cohesionless soils decrease as a consequence of an increase in pore water pressure caused by seismic ground motion; hence causing the soil to behave like a liquid (National Academy of Sciences, 2016). Liquefaction only occurs in undrained saturated cohesionless soils that are susceptible to deformations due to monotonic, transient or cyclic excitation (Kramer, 2014). Historic events of liquefaction suggest that this occurs in very localised geographic areas, and as such liquefaction risk is also localised and cannot be assessed at the wider regional level. This in turn calls into question the suitability of applying wider area techniques, such as probabilistic based CBA, to the options appraisal of mitigation interventions. This paper explores this issue.

If the ground liquefies, it is less able to support buildings and other structures (UGSC, nd). Depending on the severity of the liquefaction, structures can undergo damage such as stretching, hogging, dishing, racking/twisting, tilting, global and differential settlement (Van Ballegooy, *et al.,* 2014). In addition to damage to buildings and consequential business disruption (Meslem *et al*., , 2021), liquefaction can, in very rare cases, result in death or serious injury to citizens (Daniell *et al.,* 2017; Marano *et al.,* 2010). Analysing losses since 1900 onwards, Daniell *et al.* (2017) reported 3 deaths during the 1995 Kobe event; 2 deaths during the 1964 Niigata; and 16 deaths associated with 1935 Taiwan liquefaction event. Since liquefaction events are rare and localised in nature and cause less severe damage compared to ground shaking early disaster loss modellers' either disregarded liquefaction or assumed its impact was subsumed within wider earthquake loss assessments (Bird *et al*., 2004; Bird *et al*., 2006; Bird and Bommer 2004; Millen *et al.,* 2018; Quigley *et al.,* 2013). However, the damage caused by recent liquefaction events in New Zealand and Italy have questioned the validity of this assumption. For example, observations conducted by researchers (Cubrinovski *et al.,* 2014) found that during the Christchurch Earthquake Sequence (CES), liquefaction, (along with rock falls and slope/cliff instabilities) damaged tens of thousands of buildings, including 20,000 houses of which over 6,000 were damaged beyond economic repair. The CES also disturbed lifelines and horizontal infrastructure over approximately one third of the city. In economic terms, the CES caused around 25 - 30 billion NZ dollars of loss, of which it is estimated that 50% could be directly attributable to liquefaction (Cubrinovski *et al.,* 2012). The impact of liquefaction on losses was also apparent from the relatively moderate magnitude earthquake (around 5.9) in the Emilia Romagna region of Italy in May 2012, which caused significant damage to 12,000 buildings (including old masonry and more modern construction) and horizontal infrastructure (Fioravante *et al.,* 2013; Lombardi & Bhattacharya, 2014; De-Ludovico, 2020). These events also highlighted the limitations of insurance catastrophe models which significantly underestimated the extent and severity of the liquefaction that occurred (Drayton and Verdon, 2013/ cited in Kongar *et al.,* 2017).

Losses due to liquefaction could be reduced by technical interventions to reduce the susceptibility of the soil to liquefaction or by strengthening structures to reduce their vulnerability to ground movement. However, different mitigation options are associated with very different levels of financial investment (Modoni *et al.,* 2019), and they provide different levels of protection to structures and the businesses that operate from them (Dona *et al.,* 2019; Rose and Huyck, 2016). Hence, there is a need to develop a robust business case for liquefaction mitigation.

Cost Benefit Analysis (CBA) is often used as a methodology to develop business cases and option appraisals for the impact of wide area disaster events such as earthquakes (ground shaking), flooding, volcanic eruption, hurricanes and tsunamis. Based on these studies, it is often claimed that every dollar invested in disaster (any) mitigation results in two to four dollars in benefits in the form of avoided losses (Mechler, 2005; World Bank and United Nations, 2010). Whilst there is significant research and examples into CBA for earthquake risk mitigation options appraisals (e.g. Smyths *et al*., 2004; Kappos and Dimitrakopoulos, 2008; Vitiello *et al*., 2017; Martins, 2018), application of CBA for secondary impacts such as liquefaction is extremely limited (Jones *et al*., 2019). Bird and her colleagues (reported in Bird *et al*. 2004 a; Bird *et al*. 2004 b; Bird and Bommer 2004) identified 3 approaches used by loss modellers to estimate specific damage associated with ground failure. Firstly, some loss modellers disregard liquefaction effects, assuming shaking as the predominant cause of damage. Secondly, some modellers adopt a simplified approach, where ground shaking intensity is increased for susceptible soils, effectively subsuming the effects of liquefaction into stronger (amplified) ground shaking. (eg: Bommer et al., 2002). This is the primary approach used by insurance loss modellers (kongar *et al*., 2017) where data from past events are used to determine the amplifier (Quigley *et al*., 2013). Thirdly, some modellers use a detailed in situ geotechnical data to evaluate the probability of liquefaction; the expected permanent ground deformation and, according to the foundation type, relate this to the expected building damage (Bird *et. al*., 2006). In particular, Bird *et al*. (2006) developed a hybrid approach to estimate damage to buildings based on observations from the Marmara earthquake. They presented a framework to guide on suitable liquefaction damage assessment solutions based a building’s foundation type and the mode of ground deformation (e.g. uniform vertical deformation, differential lateral deformation). However, whilst this approach is suitable for assessing damage on a single site, the volume of data (soil and building) required to make an assessment across a wide geographical area makes it less applicable to insurance modellers (Kongar *et al*., 2017).

Finally, whilst this paper has outlined a number of generic approaches to modelling CBA for disaster events the authors could find no specific examples of how liquefaction induced damage levels could be converted in monetary losses to support liquefaction risk mitigation options appraisal. This paper addresses this gap in knowledge by exploring the application of the CBA technique to appraise technical interventions to reduce liquefaction related losses as part of a resilience assessment and improvement framework (Jones *et al.,* 2021). The main objective of the paper is to discuss the potential issues faced by researchers and practitioners seeking to develop CBA methodologies for liquefaction risk mitigation option appraisal. The findings would also enhance built environment professionals limited knowledge in applying CBA for disaster mitigation decision making (Amaratunga *et al*., 2018).

The research presented in this paper is based on the work of the LIQUEFACT project (Work Packages 5 and 6 (WP5&WP6). LIQUEFACT was a project, funded by the EU within the H2020 Research and Innovation programme. Eleven EU and UK research and industry partners worked together within the LIQUEFACT project to investigate the effectiveness of a range of mitigation actions to improve business (including critical infrastructure) and community resilience to earthquake induced liquefaction events. WP5 developed set of tools to link technical solutions developed in other work packages of the project with business and community solutions. WP6 developed an easy-to-use software (Liquefaction Reference Guide - LRG) to facilitate statistical calculations and modelling associated with the assessments on the feasibility and cost-benefit relationships of selected mitigation techniques. Further details of the projects and its results are available on the project 's website (Liquefact, nd).

Literature review

Cost benefit analysis

Cost Benefit Analysis (CBA) is a widely used option appraisal technique adopted worldwide in many fields. The technique emerged from welfare economics in Europe in the 1840s (Mishan and Quah, 2007). It was used to estimate the consequence of an economic activity on an unrelated third party (primarily society) through an assessment of consumer surplus and externality. The CBA approach is now widely used to explore costs and benefits of interventions across a wide range of disciplines such as environmental policy, transport planning, healthcare, and disaster mitigation projects

(Wanigarathna *et al*., 2018). In simple terms, during this analysis, all costs and benefits associated with each intervention, are identified, quantified, monetized and aggregated to net present values (NPV) (Mechler, 2016) to derive a benefit to cost ratio (B/C ratio). If the NPV of total benefits exceeds NPV of total costs for a particular intervention, the intervention could be considered as net beneficial. In disaster risk mitigation CBAs, cost refers to the cost of planning, design, maintenance and disposal of mitigation interventions, whilst benefits refer to avoided losses due to the implementation of mitigation interventions. Wethli (2014); Hawley *et al*. (2012); Mechler (2005); and Mechler (2016) provided review of CBA applications for disaster mitigation interventions. In their analysis of CBA studies for a range of technical and non-technical disaster mitigation interventions, Wethli (2014) summarised that mean benefit cost ratios for structural interventions to limit damage from earthquakes, floods and tropical storms as 3.1, 11.1 and 5.1 respectively. Mechler (2016) in his review of 52 benefit cost studies for a range of disaster mitigation interventions across a number of disasters, concluded that disaster risk mitigation investments (39 out of 52) would lead to a B/C ratio of close to 4 (3.7). None of these key reviews have considered any examples related to liquefaction risk mitigation interventions.

Disaster risk mitigation decision makers use two key approaches to CBA. At a regional level, CBA can take a *backward-looking approach* in which past events and their impacts (losses) are used as the basis to estimate the potential future impacts (losses) for a similar region (Mechler, 2005). During this approach, historical base loss data is adjusted to the predicted severity of the disaster and the vulnerability of the buildings, infrastructure, and community of the region. Accuracy of such analysis is therefore dependant on the ability to predict hazard risks, vulnerability of the built assets, and resilience of businesses and communities of the region being assessed in comparison to base historic events. The backward-looking approach is used as the basis for widely used earthquake loss assessment methodologies such as the FEMA methodology, the HAZUS-MH Earthquake Model (HAZUS-MH 2003) and the SELENA RISe earthquake loss assessment model (NORSAR/ICG, nd) Whilst the backward-looking approach is generally considered suitable for CBA modelling of widespread, large scale disaster events its aggregated nature doesn’t model well the situation at the local or organisational scale. In this case a *forward-looking approach* that can accommodate a more complex and interrelated resource scenario has been developed. Several researchers have provided examples of forward looking CBAs for technical interventions across a range of disasters, such as earthquake (Smyths *et al.,* 2004; Kappos and Dimitrakopoulos, 2008; Kunreuther and Michel Kerjan, 2012); and floods (Kull, 2008; Mechler *et al.*, 2014; Burton and Venton, 2009). HAZUS-MH Earthquake Model later added the Advanced Engineering Building Module (AEBM) (FEMA, 2010) to guide forward looking CBAs at individual building level.

CBA for liquefaction

This section discusses CBA literature and liquefaction literature to establish how the forward-looking CBA approach could be adopted by individual organisations during liquefaction mitigation intervention appraisal. Many previous researchers (e.g. Smyths *et .al*., 2004; Kappos and Dimitrakopoulos, 2008; Martins, *et al.,* 2016) have identified consistent steps for conducting CBAs. The literature review presented here is based on 5 key chronological steps for conducting a forward-looking CBA for disaster mitigation interventions. These are: 1) specifying the nature of the problem; 2) determining loss to the system without mitigation interventions; 3) identification of mitigation interventions and estimating the direct costs of the different mitigation interventions; 4) modelling the application of interventions and estimating benefits of mitigation interventions; and 5) calculating the cost/benefit ratio for each intervention.

Step 1 –Specifying the nature of the problem of liquefaction

Earthquake induced liquefaction hazard risk is linked with the probability of an earthquake occurrence, its magnitude, and the susceptibility of the local soil to liquefy. Liquefaction susceptibility is associated with the type of soil deposits found near the surface and directly below the properties being assessed (USGS, nd). The knowledge of earthquake occurrence probability is considerably advanced through the use of hazard maps such as USGS National Seismic Hazard Maps (for US); The 2013 Euro-Mediterranean Seismic Hazard Model (for Europe); The New Zealand National Seismic Hazard Model (NSHM) to estimate earthquake risk for a given region. However, local liquefaction hazard maps are still underdeveloped with only a few databases having collected and published historic data on liquefaction triggering locations during previous earthquake events (NASEM, 2016). Some of these includes: USGS maps for USA; The Italian Catalogue of Earthquake-Induced Ground Failures (CEDIT); The DALO database and more recently the GIS-based catalogue of historical liquefaction occurrences in Europe developed by the LIQUEFACT project (Lai *et al*., 2018). Where macro scale liquefaction hazard maps have been developed these could provide indicative liquefaction risk probabilities for larger regions. The liquefaction potential index (LPI) by Iwasaki *et al*. (1984), conditional probability of liquefaction (Hazus, 2003), Liquefaction Severity Number (LSN), by Tonkin and Taylor (2013) can then be used to estimate the extent of liquefaction hazard risk at a particular location based on local soil investigation data. Finally, whilst structural vulnerability entails complex calculations, building owners and users could get an overview of structural vulnerability by mapping their building to typical building typologies that reflect structural form and design code compliance.

Step 2 - Estimation of losses without mitigations:

Disasters cause economic losses (such as damage to building, infrastructure, and business interruption), environmental losses (damage to watercourses, eco systems and habitats), social losses (deaths and injuries, increase in crime, family violence etc), and heritage losses (such as damage to cultural, historic and world heritage assets) (De Grove *et al*., 2015). Previous research (e.g., Kappos and Dimitrakopoulos, 2008; Martins, 2016; Paxton *et al*., 2015) have applied three sequential steps for loss estimation. They are: 1) estimation of physical damage to properties and infrastructure, 2) estimation of other direct consequential damage resulting from the building damage, and 3) conversion of damage into monetary values.
Based on field observations, centrifuge experiments, and numerical simulations researchers have developed damage estimation methodologies for structures with shallow foundations subjected to liquefaction (i.e., Liu and Dobry, 1997; Karamitros *et al*., 2013; Bray and Dashti ,2014). However, these methodologies could only be used when the scenario specific structural and soil characteristic data is available. This said, structural damage modelling has been enhanced through the availability of generic fragility curves and these could be used to model damage related to liquefaction as well. Fragility curves (a structural modelling technique) in now widely used to model the probability of a structure exceeding a given damage state under a given scenario (hazard level, susceptibility condition and structural vulnerability) (Da Fonseca *et al*., 2018). The results can be presented either in graphical form or as a predicted damage state (% probabilities of minor damage through to collapse) or as a mean damage ratio.

Deaths and injury rates are then estimated for each building damage state based on widely used norms such as the FEMA methodology for casualty estimation (HAZUS-MH (2003), or research-based models such as the casualty estimation model of Coburn and Spence (2002). For example, Paxton *et al.* (2015) assumed that collapsed buildings would result in 10% occupant fatality. Liquefaction would rarely cause large-scale deaths or serious injury (Daniell *et al*., 2017), thus incorporation of such losses should be considered on a case-by-case basis. Even though researchers have attempted to model the business interruption resulting from building damage (Cremen, *et al*., 2020; Dona, *et al.,* 2019), these are rarely used in forward looking CBA studies. For example, based on previous case studies of actual earthquake damage, FEMA's loss estimation tool (HAZUSTM MH MR4, 2003) provides approximate number of days a business will have to close for recovery for three damage states. Such information could be used to estimate business interruption.

The damage states are then converted to monetary values associated with repair costs, casualties and business interruption. Building repair costs could be estimated based on published cost data such as price books, or other cost databases such as FEMA P-58 component repair estimate database and estimating tool (FEMA, 2018), (http://www.geradordeprecos.info/). However, many researchers have followed a simplified methodology to estimate the repair cost by multiplying the mean damage ratio or damage cost functions computed for the properties and the building replacement cost (e.g. Paxton *et al*., 2015; Martins, 2018; Ramirez *et al*., 2012). Other researchers have assumed that the repair cost for rebuilding at the collapse or significantly damage state would be assumed as 100% replacement cost, since rebuilding is more economical in such cases (FEMA P-58 (FEMA 2012), Smyths *et al*., 2004). On top of the building repair costs, additional cost related to relocation during the repair period such as property rental and mobilisation cost should be added. There is no generic approach to calculate contents damage, they need to be evaluated based on the value and type of contents contained within individual buildings. Recent advancement in knowledge related to the assessment of business downtime and business interruption losses (see works of Cremen *et al*., 2020; Ortiz *et al*., 2021) may be adopted in liquefaction mitigation CBAs. If any deaths or injuries are predicted these can then be monetised based on techniques such as average earning potential method (Erdurmus, 2005), or country specific courts awards approach (as in Kappos and Dimitrakopoulos, 2008).

Literature reveals a number of issues associated with the current loss estimating processes used within CBAs. Mechler (2016) in his systematic review claimed that availability of fragility curves is limited and generating bespoke fragility curves are often fraught with complications. Further, Crowley *et al*. (2005) claimed that due to the number of assumptions involved in desk-based loss estimates, accuracy could be significantly reduced. Recent research (e.g. Del- Vecchio *et al*., 2018; Eleftheriadou *et al*., 2016) has compared actual damage caused by recent earthquake disaster events with their desk based damage estimates and found significant inaccuracies in damage estimates. Inaccuracies are reported for damage modelling as well as converting damage states into monetary losses. Fragility curves primarily predict response of structural components undergoing set forces. Hence, the accuracy of damage estimates could be dependent upon the details of non-structural components within buildings. Examining a few selected buildings Del Vecchio *et al*. (2018) reported significant levels of underestimation in damage when using pre-existing fragility functions, which did not consider the level of infills and partitions within buildings. Del Vecchio *et al.* (2017) investigation into the L'Aquila earthquake, Italy found similar inaccuracies related to estimating losses associated with predicted damage repair costs. Similar detail comparison does not exist for liquefaction loss modelling. It is claimed that availability of fragility curves for building damage by soil liquefaction is limited (De Fonseca *et al*., 2018), hence such comparisons would be difficult.

Step 3 - Identification of mitigation interventions and estimating the direct costs of alternative mitigation interventions

Technical interventions could substantially reduce damage to structures caused by liquefaction. They aim at either reducing the site susceptibility to liquefaction through improving the soil or enhancing the capacity of structures to prevent their collapse if the ground should liquefy (Flora *et al*., 2020). Some techniques improve the strength of the soil, usually by densification of the liquefiable soil via compaction (see Hayden and Baez, 1994); stabilization of the soil skeleton (Boulanger and Hayden, 1995); by improving drainage capacity (Mitchell *et al*., 1995; Hausler and Sitar, 2001); or desaturation of the liquefiable soil (Shi *et al*., 2019). Alternatively, improvements to the structure could be achieved through the addition of pile foundations to transfer the structural loads to deeper non liquefiable soil layers (Flora *et al*., 2020). The choice of mitigation methods and the selection of proper strengthening techniques will depend on the extent of liquefaction of the local site and the level of damage that could be avoided (Flora *et al*., 2020).

Direct cost of mitigation options includes estimated costs related to the capital expenditure on local soil investigations, planning, design and implementation/construction of the technical interventions and their maintenance costs (such as inspections, repairs, security) incurred throughout the mitigation's economic life. These costs could often be obtained from construction organisations implementing technical mitigations (as in Smyths *et al*., 2004), vender literature or other published cost data (as in Martins 2018; Liel, 2011) or similar estimating tools such as cost estimating tools of the Geo Institute (Geoinstitute, nd) . Timing (the year which the cost needs to be incurred) of these costs should also be determined during this step.

Step 4 – Modelling the application of mitigation interventions and estimating benefits of mitigation interventions

End users should short list mitigation interventions based on the results of steps 1,2 and 3 . Mitigation interventions would either change the hazard risk profile or improve the structural stability to withstand the hazard. The next step is to repeat the loss assessment calculations for each mitigation alternative by updating the hazard risk profile and/or structural details of the system. In Smyths *et al.* (2004) study, they changed the structural characteristics of the building under investigation for 3 structural improvement alternatives. A similar method could be adopted during the modelling of liquefaction mitigation interventions associated with structural improvements. This means that each alternative mitigation intervention would need to have its own accompanying fragility curve. For example, in this case of soil improvement interventions, hazard risk profile for the building site could be changed to apply the intervention. Specific CBA examples of applying hazard risk changing interventions could not be found within the literature review conducted for this research. Step 2 could then be repeated to assess new (reduced) losses when each of the selected mitigation alternative is applied. The difference between the antecedent loss calculated at step 2 and the reduced losses calculated at this step is the avoided damage by each intervention, hence is considered as the total benefit of each intervention.

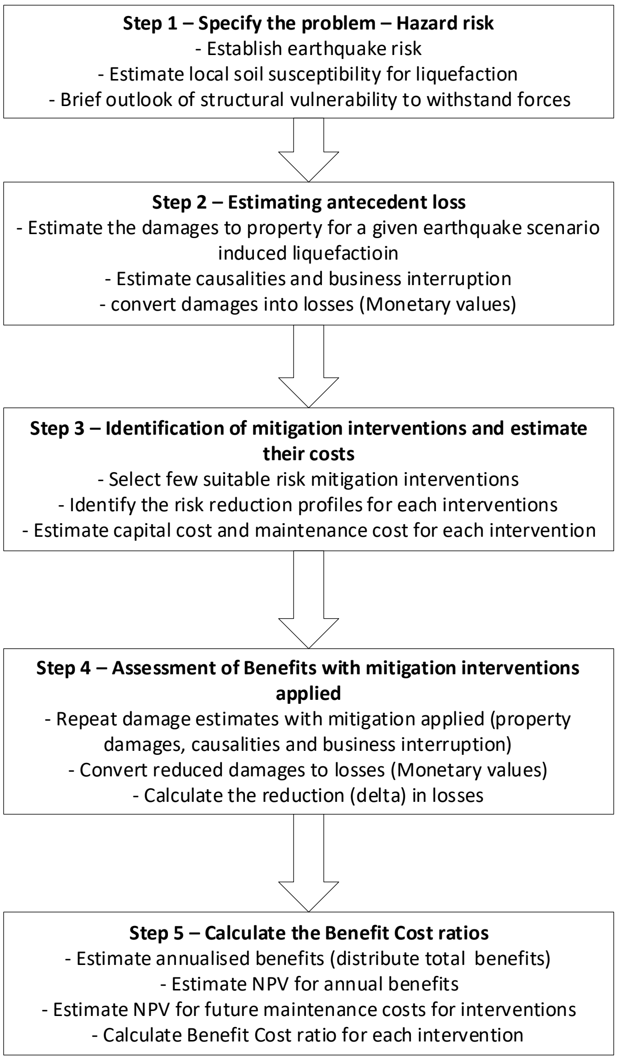
Step 5: Calculating of cost/benefit ratios

None of the benefits would be realised unless an earthquake induced liquefaction event occurred. Therefore, using a Poisson distribution model of earthquake occurrence and equivalent annualised avoided losses needs to be calculated (see the works of such as Leil and Deierlein, 2013; Smyth *et al*., 2004). All the benefits and costs that are expected to occur in the future, throughout the economic life of the building are discounted to estimate NPV using a suitable discount rate. Discount rates used in earthquake scenarios could be considered as reasonably accurate for its secondary perils such as liquefaction. FEMA 227 (1992) recommends discount rates between 3–6% for earthquake CBAs. Other researchers have used similar percentages (e.g. Pesaro *et al*. (2016) - 4%; Paxton *et al*. (2015) - 3-5%). Researchers often recommend the need for conducting a sensitivity analysis for the discount rate.

In summary, Figure 1 outlines the CBA framework for the appraisal of liquefaction mitigation interventions.

Research methods

A pragmatic research stance in combination with ‘scenario-testing’ (Ramirez *et al*., 2015) through a desk study was adopted for this research, for the following reasons. First, scenario testing is similar to the approach taken in real practice-based CBA applications, where desk-based CBAs are used to appraise options before they are implemented. Secondly, this is a commonly used methodology within similar academic research. Several disaster mitigation CBA researchers have conducted desk-based studies into hypothetical buildings in their widely cited works (e.g. Ramirez *et al* 2012; Paxton *et al*., 2015; Smyth *et al*., 2004). This methodology has been used to evaluate individual asset level interventions, for example, Paxton *et al*. (2015) evaluated the benefit cost ratio for three earthquake retrofitting interventions by applying them to a hypothetical two-storey building in downtown Victoria.



Step 1 – Specify the problem – Hazard risk
- Establish earthquake risk
- Estimate local soil susceptibility for liquefaction
- Brief outlook of structural vulnerability to withstand forces

Step 2 – Estimating antecedent loss
- Estimate the damages to property for a given earthquake scenario induced liquefactioin
- Estimate causalities and business interruption
- convert damages into losses (Monetary values)

Step 3 – Identification of mitigation interventions and estimate their costs
- Select few suitable risk mitigation interventions
- Identify the risk reduction profiles for each interventions
- Estimate capital cost and maintenance cost for each intervention

Step 4 – Assessment of Benefits with mitigation interventions applied
- Repeat damage estimates with mitigation applied (property damages, causalities and business interruption)
- Convert reduced damages to losses (Monetary values)
- Calculate the reduction (delta) in losses

Step 5 – Calculate the Benefit Cost ratios
- Estimate annualised benefits (distribute total benefits)
- Estimate NPV for annual benefits
- Estimate NPV for future maintenance costs for interventions
- Calculate Benefit Cost ratio for each intervention

Figure 1: CBA Process model for Liquefaction Risk Mitigation

Thirdly, scenario testing is claimed as a strong scholarly research methodology to produce interesting research in addition to their use during the planning purposes (Ramirez *et al*., 2015). This methodology could help stakeholders to explore the functioning of proposed research outputs (Ravera, *et al*., 2011) and to propose 'new research needs' for the studied disciplines (Thompson *et al*., 2012). The research presented in this paper adopted a scenario-based methodology to investigate the application of the CBA to appraise technical interventions to reduce liquefaction related losses, with the intention of testing the availability and usefulness of the 'state of the art' of knowledge related to earthquake induced liquefaction risk modelling, structural vulnerability analyses and economic analyses (as collated through the LIQUEFACT project) during the mitigation intervention decision making process.

The liquefaction CBA model was developed as part of a wider resilience assessment and improvement framework that used an action research methodology to develop, test and refine

LIQUEFACT project tools within a built asset management model (Jones *et. al*., 2021). The CBA tool was developed and tested during a two-day workshop (16-17 April 2019) during which the impact of earthquake induced liquefaction on a hypothetical hospital scenario was modelled; and the alternative soil mitigation options evaluated, using the LIQUEFACT-LRG software (Meslem *et al*., 2021). The workshop was structured around the CBA process model (Figure 1) and involved detailed discussions between researchers to explore the useability of the CBA from an end-user perspective (each researcher took a different end-user perspective depending on their research background). In particular the scenario explored the level and detail of data input needed to support the development of the CBA and the usefulness of the output produced by the CBA to support optional appraisal decision making. The workshop was audio-recorded and individual researchers took detailed notes and photographs of critical stages in the CBA process. Further details of the experimental methodology can be found in Morga *et al*. (2020). The next sub sections present further details of the scenario, workshop, and data analysis.

Theoretical model of CBA for liquefaction – The theoretical model presented in the previous section was developed through a literature review. First, literature related to CBA applications in general was analysed to explore how CBA techniques were applied in disaster mitigation intervention appraisals. Valuation approaches to costs and benefits (avoided losses) were explored via actual case studies presented in scholarly articles and various reports. These were then combined with the literature related to liquefaction risk and loss modelling to develop a theoretical model of CBA for liquefaction mitigation option appraisal. This model was then verified based on reviews and the comments from the wider LIQUEFACT research community and the project's international advisory group during internal project meetings.

Scenario, data and assumptions

A scenario-based method was then adopted to test the theoretical model against a detailed hypothetical example. The scenario used here is an enhanced version of a healthcare scenario used in the development of the resilience assessment and improvement framework (RAIF) in which the CBA analysis is located (see Jones *et al*., 2020 for further details) and first used to validate the data analysis software [LRG]. The healthcare scenario was proposed by the project partners and the international advisory group and used throughout the LIQUEFACT project to verify and validate the tools developed by the different LIQUEFCAT research teams. A hospital scenario was chosen because it provided a level of complexity in terms of different building typology, location and use, whilst providing a level of continuity in terms of built asset management portfolio planning. In addition, the CBA research team had significant previous experience in healthcare built asset related research that enhanced the realism of the scenario. For the CBA workshop the generic hospital scenario, which had been developed earlier in the LIQUEFACT project, was enhanced in terms of its contextual details, to investigate, how CBA could be used to evaluate liquefaction risk mitigation interventions of a range of built assets across a number of locations.

The hypothetical scenario entailed a set of contextual information (location, structural vulnerability, hazard risk) assumed for a primary healthcare provider with 9 care provision buildings within a region susceptible to liquefaction. It was assumed that these 9 buildings were located in four campuses. The table 1 below provides the details assumed for the buildings considered within the scenario. Further assumptions were made as an when needed during the workshop. For example, end users will first make a high level estimate the liquefaction hazard risk for each of their buildings based on regional level macro zonation maps. An assumption was made that any buildings located in a very low liquefaction zone was not analysed further in the scenario. Table 2 presents details of the other key assumptions made during the CBA analysis.

Table 1: Initial details of the scenario assumed for the workshop

Building	Structure system (Materials)	Building height	Foundation System	Earthquake design code
S1	Concrete	Medium	Shallow	Pre-code
S2	Concrete	Medium	Shallow	Low-code
S3	Masonry	Low	Shallow	Low-code
S4	Steel frame	Medium	Shallow	Low-code
S5	Concrete	Medium	Shallow	Pre-code
S6	Masonry	Low	Shallow	Low-code
S7	Masonry	Low	Shallow	Pre-code
S8	Steel frame	Medium	Shallow	Low-code
S9	Steel frame	Mid rise	Shallow	Medium-code

In particular, for each step of the theoretical model of CBA for liquefaction, discussions were held in relation to: information which the end user need to input in order to proceed with the CBA and the usefulness/adequacy of the existing liquefaction related knowledge and the results produced by the LRG software to arrive at meaningful results and decisions. The 2-day face to face workshop attended by the researchers from the WP5 and WP6 of the LIQUEFACT project. The workshop was held at the Anglia Ruskin University and was attended by all the member of the research team from the WP5. This included a professor in facilities management, 3 senior lecturers who have significant experience in research into healthcare building design and asset management, disaster damage modelling and construction economics. The main full-time researcher from the WP 6 was a senior research engineer who has extensive research experience in seismic damage and loss modelling and was the main developer of the data analysis software used for this research. These researchers were considered as the best available participants for two further reasons. Firstly, they were researchers involved in the LIQUEFACT project, thus familiar with the LIQUEFACT scientific outputs and related literature. Thus had a strong understanding of the state of art knowledge of the liquefaction hazard risk modelling and asset damage modelling.

Table 2: Data and assumptions used within the workshop

CBA input requirements	Data and assumptions
Client and the project	Hypothetical healthcare organisation scenario explained above
Earthquake risk	475 year earthquake return period was assumed as the probability, for earthquakes larger than M6.5, M6.5 and M7 and above considered for magnitude.
Regional liquefaction risk	Macro zonation maps for liquefaction provide an indicative risk (very low to very high risk). Buildings within low-risk regions (S2, S6, and S9) were removed from the further analysis.
Local liquefaction risk /soil susceptibility data	Soil investigation test data gathered from an area within Emilia Romagna, which underwent earthquake induced liquefaction were adopted at this stage. See Figure 2 for existing local liquefaction risk data collated by the LIQUEFACT project
Structural vulnerability	Most suitable pre-existing fragility curves were selected from LRG, based on the assumptions related to structural details presented within the Table 1 above were used.
Building replacement cost	Since the scenario was not meant to be location specific and did not have floor areas defined a set of reasonable value of building replacement costs were assumed based on the experience. Taking a similar approach to CBAs for other disasters (such as FEMA P-58, Symth *et al*., 2004), the LRG assumes that if a building is predicted to experience greater than 50% then it is it is more economical to rebuild than repair, hence the LRG consider the loss as equivalent to the total replacement cost.
Content damage and business interruptions	Based on LRG developer’s previous experience, it was assumed that low, moderate, high, and complete building damage states will result in 20%, 50%, 85% and 100% contents losses and 0% 15%, 100%, and 100% business interruption losses.
Capital and maintenance cost of mitigation interventions	These data were not available at the time of this workshop, industry partners who developed mitigation interventions were unable to compute the costs during the LIQUEFACT project, prior to market testing of these innovative interventions.

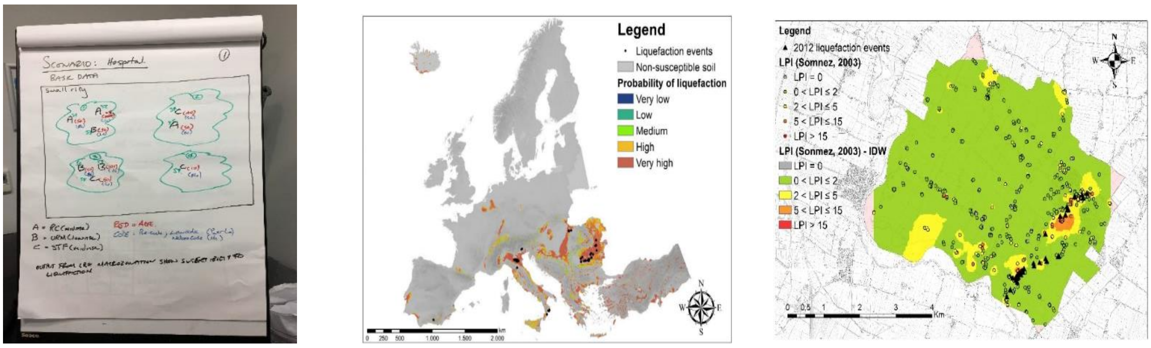


Figure 2 – Start point of the scenario (Left) and Liquefaction risk map (Source – Lai *et al*., 2019) (Right)

Secondly, researchers from the WP5 lead the overall LIQUEFACT project and had acted as stakeholders (potential users) in regular intervals to test the compatibility of output produced within various work packages to form the final outputs. The second role in particular was helpful to distinguish between CBA issues related to weaknesses/flaws of outputs of LIQUEFACT and real issues of conducting CBA for liquefaction mitigation option appraisal by the end-users when former flaws are reinstated. This research reports the later type of issues only. Further details of this workshop could be found at Morga *et al*. (2020).

Detail of the data analysis

The LRG software (Meslem *et al*., 2021) was used as the primary data analysis software for the workshop. As a part of the LIQUEFACT project, the LRG was developed by NORSAR, the developer of a widely used earthquake loss assessment software solution (SELENA–RISe Open Risk Package). The LRG was underpinned by a range of methodologies, procedures and models developed by the other LIQUEFACT consortium partners as part of the LIQUEFACT project to support the RAIF and CBAs for liquefaction mitigation interventions. Using the outputs from the LIQUEFACT project partners, the LRG was built with embedded Liquefaction hazard maps, structural vulnerability models for typical structures, liquefaction mitigation techniques and a CBA methodology developed by the authors. In addition, the LRG was also embedded with a range of publicly available maps, vulnerability data (ground shaking fragility models), and test data. The LRG software was previously validated as a part of the LIQUEFACT project. The data produced by the LIQUEFACT project partners and embedded within the LRG were also verified and validated previously. Jones *et al*. (2020) provides details and evidence of these activities.

The workshop identified a number of critical issues related to the development of CBA for liquefaction, not least the complex nature of the level of risk and quantifying the losses associated with the various mitigation interventions. Due to the detailed and complicated nature of the benefit analysis in particular, results are reported in a narrative style following the same chronological steps in the theoretical model of CBA for liquefaction.

Findings and discussions

Issues related to specifying the problem (Liquefaction risk)

Existing regional level liquefaction maps (Macro zonation maps) only provide some indication of the possibility of liquefaction within a large region. Since the liquefaction risk is based on local soil conditions, identifying the risk to each building is complicated. Therefore, even if a building is located within a liquefaction prone zone, precise risk of liquefaction cannot be determined unless there has been a historic liquefaction event very close by or a local soil investigation has been undertaken at the building location. Consequently, there is a high chance that the user would have to invest money on conducting soil investigations to provide soil susceptibility data, for the LRG to model the Liquefaction risk for the building(s) being analysed. Further, end users would have to select an earthquake scenario (earthquake return period and magnitude) to trigger liquefaction which could also be difficult to identify. Alternatively, end users could conduct liquefaction risk analysis against different earthquake scenarios (e.g. most likely or most severe), and proceed with loss analysis scenarios.

Issues related to antecedent loss analysis

This section explores issues with estimating damage levels and converting them into predicted losses. As Liquefaction does not cause significant deaths or serious injuries (Daniell *et al*., 2017; Marano *et al*., 2009; Green and Bommer, 2019) the LRG does not include such estimates as part of its loss assessments. Further, there is no prudent methodology that could be integrated into the CBA to estimate other social losses such as increases in crime, family violence or environmental and heritage losses specific to liquefaction disasters. Hence, the LRG focus did not estimate such losses.

Estimating potential building damage levels (Antecedent damage level)

The LRG uses building typology data (e.g., construction material, structural system etc.) provided by the end users to identify a pre-existing (typical) fragility curve (damage modelling function) for the building (s) to estimate damage status (e.g. probabilities of non, low, moderate, high, collapse damage levels) and Mean Damage Ratio (MDR) for each building against each earthquake scenario. However, whilst using a typical fragility function reduces the modelling effort required by the end-user, it could undermine the accuracy of damage estimates as it would not take account of any variation of building (s) from the standard typologies. This could be particularly true for old buildings and non-typical buildings, where there could be a lack of knowledge about their structural details or structural changes that may have occurred over time. Whilst accuracy can be improved through the use of bespoke fragility functions (generated by specialist consultants and uploaded in the LRG software), this would be significantly expensive for the end-user.

Estimation of losses (prior to and after mitigation (Antecedent loss)

Building damage related losses

The building damage related loss was calculated by multiplying the Mean Damage Ratio for each building by the building replacement cost estimated by the end-user. The replacement cost could be sourced through local knowledge of new building rates or through published cost data (as in Martins, 2018; Paxton *et al*., 2015; Ramirez *et al*., 2012) which could be adjusted to account for location and other building morphological factors such as height and architectural and structural design (Ramirez *et al*., 2012; Ashworth and Perera, 2015). The possible short-term increase in local construction prices due to the demand surge immediately following a disaster (Ruddock *et al*., 2010; Wedawatta *et al*., 2018; Ortiz *et al*., 2021; Kahandawa *et al*., 2021) should also be considered. However, the causes and evidence of liquefaction damage repair cost escalations following CES (Kahandawa *et al*., 2021) shows that the extent of such factors may be difficult to predict accurately. Further, since the nature and extent of liquefaction depends on local soil conditions, it is difficult to estimate other associated costs such as additional external works, cost of demolition and clearing of debris in a forward-looking liquefaction mitigation CBA. This may result in a significant underestimate of reinstatement costs as reported by previous researchers (Vecchio *et al*., 2018; Leil and Deierlein, 2013).

Content and business interruption loss estimating

Whilst there are a number of methodologies for estimating potential contents damage and business interruption resulting from disaster events, these methodologies were considered too complicated (based on previous experience by the LRG development team - see Meslem *et al*., 2021) to be incorporated within forward looking CBA exercises. As such a simplified approach using loss coefficients is used in the LRG (Meslem *et al*., 2021). By default, the LRG assumes that low, moderate, high, and complete building damage states will result in 20%, 50%, 85% and 100% content losses and 0% 15%, 100%, and 100% business interruption losses.

Content loss = mean building damage ratio* content damage coefficient * total value of contents within the building

Business interruption loss = mean building damage ratio * business interruption coefficient * total value of the business

Whilst the use of generic loss coefficients can provide a high-level estimate of potential content and building interruption losses, they do not consider the wider contextual circumstances that are known to affect individual organisations (Cremen *et al*., 2020; Kolks, *et al*., 2019). However, developing bespoke coefficients is a complicated task requiring significant resource and involving several probabilistic assumptions, which may be beyond the organisations' capability or knowledge. For example, predicting the business interruption caused by factors such as management effectiveness or supplier dependency throughout the economic life of a building is difficult in the short term, an almost impossible in the long term. Also, even though liquefaction generally causes less sever building damage than ground shaking, recent historic events show that liquefaction can cause significant business interruption without causing major damage buildings (Wedawatta *et al*., 2014; Ortiz and Reinoso, 2019, cited in Ortiz *et al*., 2021). As such, modelling business interruption based on building damage alone could be misleading and further research is required to understand the relationship between business interruption and regional liquefaction hazard risk. Work of Cremen (2020), Dormady *et al*. (2019) provides good frameworks for this purpose. However, business interruption caused by certain external factors such as critical infrastructure system failures and supply chain failures (Kolks, *et al*., 2019) could be difficult to predict due to the localised nature of a liquefaction hazard. Finally, the value of the business could be difficult to estimate for small scale organisations.

Issues related to modelling application of mitigation and estimating the reduced losses

As discussed within the literature, mitigation interventions would either change the hazard risk profile or improve structural stability to withstand the hazard. This research considered, 3 specific liquefaction mitigation techniques (vertical draining, horizontal draining and induced partial soil saturation) developed and tested by LIQUEFACT partners (Flora *et al*., 2020). Unlike widely tested earthquake risk mitigation interventions, these liquefaction risk mitigation interventions are innovative and still being developed and commercially tested. As such they do not yet have validated risk reduction profiles and/or damage modelling data that can be used in loss estimates. Therefore, damage modelling software (LRG in our case) and forward-looking CBAs can currently only consider a limited number of existing mitigation techniques, many of which are not suitable for retrofitting (e.g. vibro compaction). Alternatively, users could proceed with the analysis by selecting the level of risk reduction they would like to achieve (e.g., reduce risk from very high to low) and identify a suitable mitigation intervention later if they decide to adopt mitigation activities.

Estimating the cost of mitigation interventions

Our experience was different to that of previous researchers who used secondary data for estimating cost of mitigations for other disaster (e.g. Martins, 2018; Liel, 2011). This research revealed several issues related to costing liquefaction risk mitigation interventions. Firstly, since the liquefaction risk mitigation techniques are relatively new, local historic cost data was not available to use as the basis of cost estimates. Secondly, since some of the techniques are being developed in laboratory environments, actual on-site implementation requirements and subsequent cost considerations are difficult to estimate. This was confirmed by the LIQUEFACT project partners who developed three specific mitigation techniques. Once these techniques are available commercially, specialist local contractors would be able to provide cost estimates for individual projects. Thirdly, it is unlikely that published retrofitting unit rates (such as FEMA or Geo Institute retrofitting cost estimating tools) will be available for ground improvement techniques since they may require bespoke designs and the cost of working underneath an existing building are affected by a very large number of parameters (as explained by Lehtonen and Kiiras, 2010). In addition, these costs would be further affected by the site-specific circumstances (e.g. access, proximity of other buildings, tenancy etc.) which can only be determined on a building by building basis (Morga *et al*., 2020). Finally, details of maintenance requirements and maintenance cost data is not available for innovative mitigation techniques, which will again reduce the accuracy of whole-life cost estimates.

Issues related to calculation of benefit to cost ratio

The difference between the antecedent loss and the reduce loss is equivalent to the monetary value of benefits derived from implementing the mitigation intervention. However, in reality these are potential benefits, that would only be realised if an earthquake similar to that modelled in the LRG occurred. For example, many researchers in their scenario analyses consider that the earthquake return period for Europe is 1 in 475 years. As such there is a chance that benefits of the mitigation interventions may not be realised during the economic life of a building. Therefore, in order to avoid over estimation of benefits, Poisson distribution model of earthquake occurrence was used to estimate annualised benefits (see works of Smyth *et al*., 2004; Kappos and Dimitrakopoulos, 2008). All annual costs and benefits estimated could then be discounted to NPV using a suitable discount rate to create a common ground for comparison.

Since the cost of mitigation interventions could not be estimated, real benefit cost ratios were not established as a part of this research. Instead, CBAs were developed using hypothetical data to estimate mitigation intervention costs. It was evident that significant changes to building structure through retrofitting of technical mitigations would invariably cost more than the expected benefits

(benefits to cost ratio <1). There are two key reasons for this result. Firstly, negligible causalities associated with liquefaction disasters resulted in total benefits accruing solely from avoided building repair costs. Since the statistical value of a life is very high compared to the value of physical properties, removing causality related losses from the CBA analysis, resulted in a relatively low estimate of losses. This result is similar to the findings of Smyth *et al.* (2004) and Leil and Deierlein (2013) who found that earthquake 'mitigations start to make sense' only when fatalities are expected and included in CBAs. Secondly, use of a Poisson distribution model to calculate probabilistic annual benefits resulted in a drastic reduction of total net benefits over the economic life of a building. However, in reality, if a liquefaction hazard occurs within the economic life of a building, the owner would suffer the whole loss as opposed to the significantly low probabilistic annualised loss. This suggests the need for an alternative risk-based approach for probabilistic allocation of benefits within CBAs.

Implications

This paper investigated issues of applying a contemporary approach to CBA to earthquake induced liquefaction. When mitigation interventions are expensive, probabilistic assessed benefits are likely to be lower than deterministic assessed intervention costs. Similar issues could be expected when CBA are applied to other localised rapid onset disaster events that occur with little or no warning and result rare human losses (such as landslides). The findings presented in this paper suggest two directions for further research. Firstly, more research is required to develop new deterministic based approaches to evaluate the cost effectiveness of mitigation interventions, that integrate attitudes to risk into the CBA process (e.g., better understand issues around willingness to pay and willingness to accept and how these affect capital investment decisions). Secondly, more research is needed to evaluate a range of operational mitigation interventions around resilience (physical and societal) and risk transfer, including potential change in use or relocation of critical built assets (e.g., planned relocation of a hospital from a highly susceptible location to less susceptible location) and a wider use of insurance cover against liquefaction or earthquakes.

Conclusions

Cost benefit analysis (CBA) is a widely used option appraisal technique for disaster mitigation decision making. This paper discussed the application of a forward-looking probabilistic cost benefit analysis approach to evaluate technical mitigation options for earthquake induced liquefaction disaster events. Even though a significant level of methodological guidance and examples are available on how to conduct CBAs for disasters such as flooding and earthquakes, there are a number of limitations when it is applied to earthquake induced liquefaction. Firstly, due to the lack of widely available data, liquefaction risk mitigation CBAs require a significant effort and resources to gather accurate input data such as site-specific hazard risk, soil susceptibility and structural vulnerability data as well the costs of designing and implementing bespoke mitigation interventions. Therefore, mitigation option appraisal using CBAs could be significantly expensive, time consuming for SMEs and in some cases may be abandoned. Secondly, for low frequent and medium impact disaster events such as liquefaction, current probabilistic benefit estimation method CBAs would show that significant changes to structures via technical mitigations are costlier than their benefits. Further research is therefore required to establish methodological alternatives that incorporate a wider risk-based approach for allocation of benefits within CBAs. This research has shown that CBA for disaster mitigation entails a highly detailed analysis of costs and benefits of mitigation interventions, and as such it can be a strong decision support tool if sensibly applied. Further, irrespective of the highly assumptive nature of the benefits to cost ratio, CBA analyses would still be beneficial as it provokes thoughts and increase private clients' awareness on holistic hazard risks.

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