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Procedia Engineering 212 (2018) 622–628

Procedia Engineering

www.elsevier.com/locate/procedia

7th International Conference on Building Resilience; Using scientific knowledge to inform policy and practice in disaster risk reduction, ICBR2017, 27 – 29 November 2017, Bangkok, Thailand

Earthquake damage estimation systems: Literature review

Kahandawa K.A.R.V.D.[a]*, Domingo N.D. [a], Park K.S. [a], Uma S.R. [b]

[a]*School of Enginnering and Advance Technology, Massey University, Building 106, Gate 4, Oteha Rohe Campus, Private bag 102 904, North Shore, Auckland 0745, New Zealand*

[b]*GNS Science, No 1, Fairway Drive, Avalon 5010, PO Box 30-368, Lower Hutt 5040, New Zealand*

Abstract

Earthquake is an unpredictable natural phenomenon that create a vast amount of damage, affecting communities and their environment. To reduce the effects of such hazards, frameworks like building resilience have emerged. These frameworks target on increasing recovery after such disaster, by introducing new designs, technologies, and components to the building. To calculate the value of such improvements, use of loss estimation systems are essential. This paper compares and contrasts two most widely adopted loss assessment tools available, namely PACT and SLAT. Comparison of these tools mainly focuses on the consequence functions of the two methods. Recommendations are suggested to improve and complement these tools in future use.

Keywords: Earthquakes; Cost Estimation; Time Estimation; Consequence functions; PACT; SLAT;

1. Introduction

Earthquake is a "series of vibrations on the earth's surface caused by the generation of elastic (seismic) waves due to sudden rupture within the earth during the release of accumulated strain energy" (Shah, 2012, p. 96). Depending on the past data, GeoNet (2016) estimates that in New Zealand, an earthquake of low impact, with the magnitude of 4.0 - 4.9, occurs 1 per day in average and high impact earthquakes with magnitude above 7.0 occurs 1 per 2.5 years. These high impact earthquakes cause destruction and damages to the excessive degree (Baocai, 1996). These earthquake damages extend to economic, social, psychological and political areas, requiring rapid rehabilitation and reconstruction (Yaoxian, 1996). Globally,
United States Geological Survey (USGS) Earthquake Hazards Program (2017b) states, from the year 2000 to 2015, earthquake hazards reflected in 801,629 deaths worldwide. In the economic and monetary point of view, the 2010 – 2011 Canterbury earthquakes in New Zealand, 2010 Chilean earthquake, and 2008 Wenchuan Earthquake in China accumulated losses over NZ$ 40 billion, US$ 30 billion, and NZ$ 345 billion in damages to the communities,

10.1016/j.proeng.2018.01.080

respectively (Araneda, Rudnick, Mocarquer, & Miquel, 2010; Marquis, Kim, Elwood, & Chang, 2017; Sun & Xu, 2011). In the event of such earthquakes, rapid recovery and rehabilitations are a priority. According to Yaoxian (1996), this can be achieved through the rapid recovery of economic sectors and financial resources.

Improving the recovering capabilities of organisations, buildings and communities, immediately following an extreme event like an earthquake is a key concept for rapid recovery (Bonowitz, 2009; Pampanin, 2015). Resilience-based earthquake design of buildings is one example in achieving this objective. The framework focuses on improving capabilities of buildings beyond statutory building codes (Almufti et al., 2013; Almufti & Willford, 2014). Objectives of performance-based design and low-damage are also intended to achieve this criterion. In order to achieve these objectives new and innovative technologies should be created and implemented in buildings. The value of these implementations should be calculated, compared and expressed in monetary terms, to increase wider acceptance and implementation (Pampanin, 2015).

Efficiency calculation using these methods was done at the initial levels of decision making, which is known as seismic loss estimation. Performance Assessment Calculation Tool (PACT), Seismic Performance and Loss Assessment Tool (SLAT), Seismic Performance Prediction Program (SP3), Matlab Damage and Loss Analysis (MDLA), Hazards United States for multi hazards (HAZUS-MH), loss estimation tool developed by Laboratório Nacional de Engenharia Civil (LNEC: National Laboratory for Civil Engineering) (LNECLOSS) are some of the computer tools used for seismic loss estimation (Molina, Lang, & Lindholm, 2010). In order to calculate the value addition of resilience upgrades, the tool used should have building specific seismic loss estimation. In order to use such a tool in New Zealand, it must be calibrated to regional requirements. PACT and SLAT are the probable tools utilised for this task due to its freely available nature of the information. PACT is a freeware tool built in the USA(Hamburger, Rojahn, Heintz, & Mahoney, 2012). It has a database of fragility curves and consequence functions on over 700 components. Yet, due to regional differences, the information cannot be applied directly in New Zealand. Based on PACT, SLAT (B. A. Bradley, 2009) was developed to address the needs of New Zealand earthquakes (B. Bradley, Williams, & Scarr, 2017). But, SLAT is still developing and fragility curves and consequence functions. Which are currently not developed for all the building items.

Both these tools are dependable seismic loss estimation models that can be used in component based probabilistic loss estimation model. Yet, engineers cannot use these systems on a regular basis due to weaknesses like needing significant expert knowledge (Dhakal, Pourali, & Saha, 2016). These weaknesses must be identified and solutions or circumventions must be utilised, for better use of these systems.

The primary aim of this paper is to identify the similarities, differences and shortcomings of these two tools and forward recommend actions to improve these tool for better use.

2. Methodology

In designing new components for buildings, clear and dependable estimations of their effectiveness is crucial. Currently, SLAT and PACT are the leading tools that are used for this purpose in New Zealand. Due to the unpredictability of earthquakes and its subsequent damages, these tools use probabilistic approaches to estimate the repair cost. These tools use fragility curves and consequence functions as well as Monte Carlo simulations to estimate the cost. Due to the probabilistic nature of these tools and their inheriting features, the actual loss may vary significantly from the estimate. Thus, there is a need for analysis of these tools in order identify its shortcoming and improve these systems to suit the needs of New Zealand better.

The primary method used in this research is to analyse these tools in regards its cost estimation functions. This was conducted through a literature review using published information on the tools. There is no exact literature comparing the models. Thereof, user manuals and guides published by the creators were examined and compared. Furthermore, current updates of the tools were compared. The information gained was evaluated with literature in cost estimation. Depending on the evaluation of literature and comparisons, the paper focuses on the characteristics, similarities and shortcomings of the methods. Hence, hypothetical solutions to these problems are recommended in this paper. The results of this paper will provide a foundation for a PhD research into building a Post-earthquake repair cost and downtime estimation model for New Zealand.

3. Literature review and discussion

3.1. PACT

PACT was developed by Federal Emergency Management Agency (FEMA) of United States of America. It is an electronic tool developed to estimate the probabilistic future loss due to earthquakes in the areas of human casualties, building repair or rebuilding costs, rebuild time, and probability unsafe placarding. This tool was developed based on the framework developed by Pacific Earthquake Engineering Research Center (PEER) on performance-based seismic engineering framework. It requires inputs like the ground shaking intensities, feedback from the building to the earthquakes vibrations, fragility functions that expresses the probability of certain damage (a damaged state) occurring in component due to each earthquake intensity, components that are in the building, required cost for repair the stated building, and number of occupant that resides in the building over time. The quantitative input of these requirements will generate the likely consequences of each damage state in terms of downtime, repair cost, casualties, and unsafe placarding. (Federal Emergency Management Agency, 2012c; Harris, Bonneville, Kersting, Lawson, & Morris, 2013)

3.2. SLAT

SLAT is also based on the PEER framework on probabilistic seismic loss estimation mentioned above. This tool was developed by the University of Canterbury in New Zealand. SLAT is used to estimate the expected downtime, repair cost and casualties using similar inputs. But, SLAT does not estimate the probability of unsafe placarding to occur. PACT had much more built-in fragility curves and consequence functions and was a basis for SLAT. SLAT is currently in its development stage and mainly focusing on earthquakes related to New Zealand (B. A. Bradley, 2009).

3.3. High-level comparison between SLAT and PACT

There is no exact literature comparing SLAT and PACT. In comparison, this two software have many common characteristics. These tools use PEER framework on performance based seismic loss estimation using probability. Both tools require similar input and output requirements such as ground shaking intensities, the reaction from the building to the earthquakes vibrations, component fragility functions, required cost of repair for the stated building, and occupancy over time. Based on the inputs they produce a cost for repairing damages, downtime of the building and casualties, which are produced by assigning different damage states in fragility curves for each component and assigning consequences to each damage state. Consequence functions use the same structure, using upper quantity, lower quantity, maximum cost, minimum cost and dispersion to express cost variations (B. A. Bradley, 2009; Federal Emergency Management Agency, 2012c).

The information collected for PACT is from USA and SLAT from New Zealand (B. A. Bradley, 2009; Federal Emergency Management Agency, 2012c). Therefore, fragility curves and consequence functions cannot be globally used. This is due to the fact that, behaviour of building components and its behaviour will depend on the standards and practices utilised for its construction. For repair cost, consequence functions factors like location, material costs, labour costs and other environmental factors will affect its figure in addition to regional standards and practices (Ashworth & Perera, 2015).

Though SLAT was developed based on PACT, there are some main differences that can be identified in the two systems. When considering the inbuilt data bases, PACT provides a larger number of built-in fragility curves and consequence function than SLAT. These inbuilt data of both software are specific to its region, PACT is suitable for United States region and SLAT is suitable for New Zealand region. In the software distribution point of view, PACT is provided in a downloadable '.exe' format as well as spreadsheets of the inbuilt data. SLAT provides a web-based interface where users can input data and retrieve the output through server processed information. The inbuilt data in PACT is provided as spreadsheets, with clearly detailed user manuals enable the users to understand the processes and data used. On the other hand, SLAT has black box method in processing data through servers and the provided user manuals require additional knowledge to understand the processes thoroughly. Thus, PACT has more transparency than SLAT.

Both systems use classification systems to identify and categorised fragility curve according to the component types. PACT uses NISTIR 6389 standard classification system. This classification system is based on the UNIFORMAT II classification system. This system has six main categories and four sub levels. Currently, SLAT doesn't use any standard classification system. It uses a unique classification system which has three main categories and one sub level (B. A. Bradley, 2009; Federal Emergency Management Agency, 2012c).

When comparing the inbuilt population models, PACT provided models for ten different types of buildings depending on its usage. These include commercial offices, healthcare, hospitality, residential buildings. SLAT has no indication of such population models. On the other hand, loss assessment functions in PACT is limited to buildings were as SLAT has included functions for bridges as well. Inbuilt consequence functions of PACT are provided in detailed breakdowns and can be updated by the user, but, these functions in SLAT cannot be updated by the user and input data on cost is limited to cost of demolition and collapse by the web interface. These differences are expressed in the following Table 1.

Table 1. Differences between PACT and SLAT

Differences	PACT	SLAT
Standard number of fragility	Over 700	Less than 100
Inbuilt data suitability	For USA	For New Zealand
Software availability	.exe program and spreadsheet	Currently a web interface
Understandability	Has provided a clear and detailed user manuals and inbuilt functions can be identified through the spreadsheets provided	Web interface provides black box method data processing systems and user need additional knowledge to understand and use the system
Classification	Uses a standard NISTIR 6389 classification system.	Simple and unique classification system used
Categories and sub levels of the classification system	6 main categories and 4 sub level	3 main categories and 1 sub level
Number of inbuilt population models for different types of buildings	10	No indication of such models
Types of structures	Buildings	Buildings and Bridges
Updating consequence function	User can update the consequence functions and Detailed breakdowns are provided	Cannot be updated by the user

3.4. Limitations and drawbacks of SLAT and PACT

Some limitations of these systems and their inbuilt fragility curves and consequence functions are expressed in the guides and user manuals of the tools. Some of these limitations expressed apply to both tools. Furthermore, Redi framework has also expressed some limitations. (Almufti et al., 2013; B. A. Bradley, 2009; B. Bradley et al., 2017; Federal Emergency Management Agency, 2012a, 2012b, 2012c)

One drawback of these systems is that they do not factor in sudden cost increases due to high demand (B. A. Bradley, 2009). Major hazards cause damages to larger region instantly. Due to these damages, a sudden need for construction materials, labour and professionals can be seen during the post-earthquake recovery stage. This rapid increase in demand cannot be catered by the standard supply of construction industry. Which will cause a rapid and unexpected increase in construction cost. The construction cost increase of 40% and 20% after 2010-2011 Christchurch earthquake and 1992 Hurricane Andrew are few examples (Almufti et al., 2013). This sudden increase in cost of construction is referred to as loss amplification. Not accommodating this phenomenon will vary the estimates indefinitely.

The tools limited to component downtime rather than targeting the whole building. There are many factors affecting downtime other than separate downtime of each component. First, impeding factors, which the time delay from the event of the earthquake to start of repair, like time to complete building inspection, mobilisation of contractors, ordering and receiving components that required a substantial amount of time to be delivered. Secondly, repair sequence, which directly affects the total time required to repair. These items are not considered in the tools. (Almufti et al., 2013)

These software does not consider the effects of aftershocks. Major earthquakes are accompanied by a series of small shocks which are known as aftershocks (USGS Earthquake Hazards Program, 2017a). These aftershocks can damage the buildings further. Thereof effects of aftershock should also be considered (Jordan, Lander, & Black, 1965). When accompanying the effects of aftershock to a model, current damaged state of the building should be considered. But this damaged states and effects of aftershocks are not considered by PACT or SLAT. They only consider the building at its original state and does not consider the effects of aftershocks (B. A. Bradley, 2009). But, FEMA, (Federal Emergency Management Agency, 2012c) has expressed that an additional damage state for residual drift ratio has been added to accompany the effects of aftershocks in PACT tool.

These tools only generate estimates for full recovery of buildings, but there are stages of recovery for building in the event of an earthquake. Almufti et al. (2013) describe three of such recovery stages. Re-occupancy, when the building is used only for shelter, functional recovery, when the building can be used for the specified primary use, and full recovery, when the building is repaired to its original pre-earth state. Different stakeholders like building occupants, building owners and government officials, require the repair cost required to attain these stages. This because some buildings might not be fully repaired and might only be partially repaired. These two tools are not equipped to estimate repair cost need to gain the Re-occupancy and functional recovery stages. This can be expressed as a limitation of the tools.

There are many dynamic factors affecting the cost of construction. These include the size of the project, locations, fluctuations, labour costs, material cost, market conditions, overheads and profits (Ashworth & Perera, 2015). Due to the interrelation during component repair, cost per component should include a global cost component like preliminaries. These factors are lacking in these models. Ashworth and Perera (2015), further express that, to keep the models accurate, cost feedback is important. The system must be developed so the cost functions can be updated. Which was expressed by Ashworth and Perera (2015) through the following. See Fig. 1. The unaccounted nature of these variables makes the predictions of these models imprecise.

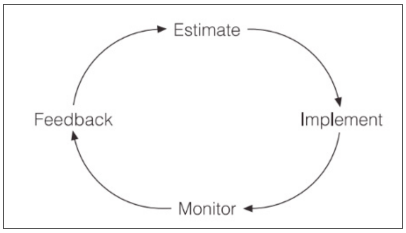

Figure 1 – Cost feedback (Ashworth & Perera, 2015)

3.5. Recommendations

These tools are freeware and based on the same principles and use the same type of data to generate results. Due to the complementary nature of the two methods, data and information from one model can be analysed and used in the other. Since many consequence functions are currently inbuilt in PACT, SLAT tool can adapt this information to improve its database. Thus, in-depth analysis is advised to check the suitability of such adoption. A standard model could be developed for such transition. Classification systems play a vital role in item identification when developing such transition model. SLAT currently has no standard classification system. It is recommended to use a standard classification system that is similar to NISTIR 6389 so that information between the tools can be shared.

FEMA (2012b) suggests a methodology to quantify the cost using a "Bills of Materials" concept. This concept implies breaking down the cost into required material, labour, and equipment categories. It could be adopted in the tools for updating the cost in the bottom-up method. This process can be utilised to identify data redundancies, eliminate unaccounted items and double counted items, and keeping the cost up to date.

4. Conclusion

PACT and SLAT tool are two freeware that used in the earthquake-related loss estimation through performance based probability estimates. These tools have been built using the same PEER framework, which allows the tools to be compared. It can be concluded that PACT software has more to offer than the SLAT due to its higher number of fragility curve, and consequence functions, higher transparency and user friendliness. On the other hand, SLAT's server based processing and web user interface allow the user for up to date utilisation of the tool. There are some limitations in these systems like not considering loss amplifications, downtime impeding factors, interrelations between components in cost consequence functions, and not updating consequence functions.

Due to the similar nature of the tools, the information gained in either party can be used to complement each other. Thus, to improve these tools to predict up to date, realistic, and accurate cost estimates some recommendations can be prescribed. These are upgrading the models to share information between the tools, adopting similar classification systems between the tools, and utilising a bottom-up cost estimation system.

References

Almufti, I., & Willford, M. (2014). The REDi^{TM} rating system: A framework to implement resilience-based earthquake design for new buildings. In E. E. R. Institute (Ed.), *10th U.S. National Conference on Earthquake Engineering, Frontiers of Earthquake Engineering, July 21-25* (pp. 4567–4577). Anchorage, AK: Earthquake Engineering Research Institute. https://doi.org/10.4231/D3P26Q437

Almufti, I., Willford, M., Delucchi, M., Davis, C., Hanson, B., Langdon, D., … Mote, T. (2013). REDi ^{TM} Rating System. Retrieved March 27, 2017, from publications.arup.com/publications/r/redi_rating_systemtions

Araneda, J. C., Rudnick, H., Mocarquer, S., & Miquel, P. (2010). Lessons from the 2010 Chilean earthquake and its impact on electricity supply. In *2010 International Conference on Power System Technology* (pp. 1–7). IEEE. https://doi.org/10.1109/POWERCON.2010.5666023

Ashworth, A., & Perera, S. (2015). *Cost Studies of Buildings* (6th ed.). Oxon, England: Routledge. https://doi.org/10.4324/9781315708867

Baocai, L. (1996). Exploration of Restoration and Reconstruction in an Earthquake-Stricken Area. In F. Y. Cheng & Y. Y. Wang (Eds.), *Post-Earthquake Rehabilitation and Reconstruction* (pp. 229–234). Elsevier. https://doi.org/10.1016/B978-008042825-3/50026-0

Bonowitz, D. (2009). Resilience Criteria for Seismic Evaluation of Existing Buildings: A Proposal to Supplement ASCE 31 for Intermediate Performance Objectives. In *Improving the Seismic Performance of Existing Buildings and Other Structures* (pp. 477–488). Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/41084(364)44

Bradley, B. A. (2009). *User manual for SLAT : Seismic Loss Assessment Tool version 1 . 14*. Christchurch, New Zealand: Department of Civil Engineering, University of Canterbury.

Bradley, B., Williams, A., & Scarr, J. (2017). OpenSLAT Web Application. Retrieved May 31, 2017, from http://openslat.canterbury.ac.nz/

Dhakal, R. P., Pourali, A., & Saha, S. K. (2016). Simplified seismic loss functions for suspended ceilings and drywall partitions. *Bulletin of the New Zealand Society for Earthquake Engineering*, *49*(1), 64–78.

Federal Emergency Management Agency. (2012a). PACT 3.1 - software. Washington, DC. Retrieved from https://www.fema.gov/media-library/assets/documents/90380

Federal Emergency Management Agency. (2012b). *Seismic performance assessment of buildings: volume 4 (FEMA P-58-4) methodology for assessing environmental impacts* (Vol. FEMA P-58-). Washington, DC. Retrieved from https://www.fema.gov/media-library/assets/documents/90380

Federal Emergency Management Agency. (2012c). *Seismic Performance Assessment of Buildings Volume 1 - Methodology (FEMA P-58-1), prepared by the Applied Technology Council for the Federal Emergency Management Agency* (Vol. FEMA P-58). Washington, DC. Retrieved from https://www.fema.gov/media-library/assets/documents/90380

GeoNet. (2016). Earthquake Facts and Statistics - Earthquake - GeoNet. Retrieved February 18, 2017, from http://info.geonet.org.nz/display/quake/Earthquake+Facts+and+Statistics

Hamburger, R. O., Rojahn, C., Heintz, J. A., & Mahoney, M. G. (2012). FEMA P58 : Next-Generation Building Seismic Performance Assessment Methodology. *15th World Conference on Earthquake Engineering*, *10*, 10.

Harris, J., Bonneville, D., Kersting, R. A., Lawson, J., & Morris, P. (2013). *Cost Analyses and Benefit Studies for Earthquake-Resistant Construction in Memphis, Tennessee*. *NEHRP Consultants Joint Venture* (Vol. NIST GCR 1). Retrieved from http://www.nehrp.gov/pdf/NIST GCR 14-917-26_CostAnalysesandBenefitStudiesforEarthquake-ResistantConstructioninMemphisTennessee.pdf

Jordan, J. N., Lander, J. F., & Black, R. A. (1965). Aftershocks of the 4 February 1965 Rat Island Earthquake. *Science*, *148*(3675), 1323–1325. https://doi.org/10.1126/science.148.3675.1323

Marquis, F., Kim, J. J., Elwood, K. J., & Chang, S. E. (2017). Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand. *Bulletin of Earthquake Engineering*, *15*(2), 731–758. https://doi.org/10.1007/s10518-015-9772-8

Molina, S., Lang, D. H., & Lindholm, C. D. (2010). SELENA ? An open-source tool for seismic risk and loss assessment using a logic tree computation procedure. *Computers & Geosciences*, *36*(3), 257–269. https://doi.org/10.1016/j.cageo.2009.07.006

Pampanin, S. (2015). Towards the “Ultimate Earthquake-Proof” Building: Development of an Integrated Low-Damage System. In *TR News* (pp. 321–358). https://doi.org/10.1007/978-3-319-16964-4_13

Shah, A. J. (2012). Earthquake Disaster Management : Indian Perspective. In *2nd International Conference on Management, Economics and Social Sciences* (pp. 96–98).

Sun, C., & Xu, J. (2011). Estimation of Time for Wenchuan Earthquake Reconstruction in China. *Journal of Construction Engineering and Management*, *137*(3), 179–187. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000277

USGS Earthquake Hazards Program. (2017a). Earthquake Glossary. Retrieved March 26, 2017, from https://earthquake.usgs.gov/learn/glossary/?term=earthquake

USGS Earthquake Hazards Program. (2017b). Earthquake Statistics. Retrieved March 25, 2017, from https://earthquake.usgs.gov/earthquakes/browse/stats.php

Yaoxian, Y. (1996). Decision-Making for Recovery and Reconstruction Following a Strong Earthquake. In *Post-Earthquake Rehabilitation and Reconstruction* (pp. 59–68). Elsevier. https://doi.org/10.1016/B978-008042825-3/50009-0