Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Facility-based Multi-hazard Asset Resilience Framework – An Application for Combined Earthquake and Flood Risk Assessment for Industrial Properties in British Columbia

Darbandsari, Pedram[1], Guo, Jack[1*], Christopoulos, Constantin[2]

[1] Post-doctoral Fellow, Department of Civil Engineering, University of Toronto, Toronto, Canada
[2] Principal, Kinetica Risk, Toronto, Canada
[1] Professor, Department of Civil Engineering, University of Toronto, Toronto, Canada
[*]j.guo@kinetiacarisk.com (Corresponding Author)

ABSTRACT

The increasing frequency and severity of natural disasters have highlighted the need for disaster resilience planning. While the insurance industry and the catastrophe modelling community have traditionally been major providers of risk solutions and technologies, the focus is usually on parcel level analysis that supports decisions at the scale of hundreds of thousands of assets, where the law of large numbers apply. In the context of critical facilities, the effectiveness of this approach is limited when the size of the portfolio is of the order of 10's to 100's of assets. Furthermore, performance metrics such as continuity of operations and quality of provided services are much more important than simple financial losses. For these users, investing in disaster risk reduction and resilience requires a comprehensive, facility-specific understanding of all hazards and risks, which is difficult given the scarcity of this type of information.

This paper presents a facility-based multi-hazard resilience assessment framework that integrates high-resolution risk assessment with owner-defined interdependencies between individual assets for facility resilience evaluation and planning. The framework combines rational and transparent asset-specific risk and post-disaster recovery analyses under multiple hazards to identify key vulnerabilities and assess options for dealing with their impacts. The framework is implemented in a computer platform, and is applied in this paper to an industry facility in British Columbia exposed to severe earthquake and flood risks to illustrate its use in asset management planning and decision-making.

Keywords: multi-hazard, resilience, asset management

INTRODUCTIONF

Large disasters such as Hurricane Fiona, the flash flood of Toronto and the fire in Fort McMurray are serving as reminders to people that extreme weather events, floods and wildfires are becoming increasingly important for climate change adaptation. Natural disasters like these are traditionally assessed by catastrophe models (CAT models), which have found huge success over the last few decades as risk management tools for the insurance industry. They provide a systematic framework that integrates hazard science, engineering and finance, while consolidating the various sources of uncertainty in highly complex physical situations where the nature interacts with the built environment. However, these models are often tailored to end users such as insurers, reinsurers and governments, who are organizations that have interest in the collective performance of the building stock they insurer or manage. In the context of natural hazards, it is not uncommon to find portfolio sizes of millions or tens of millions of assets. As a result, variabilities of hazard and assets at a finer granularity is often inconsequential to catastrophe modelling as they do not manifest themselves in the global performance of the portfolio. This creates an issue for businesses or individual asset owners with a much smaller portfolio size, as assessments from catastrophe models do not have the resolution to provide actionable asset management decisions. Furthermore, the largest impacts to facilities containing multiple assets are often characterized by disruptions in the ability to provide a predetermined level of service, rather than physical damage. It is not uncommon for such impacts to be uninsurable because they are not well defined and may or may not be tied to physical damage of any individual asset in an insurance policy.

The emerging performance-based engineering paradigm on the other hand, offers a different solution for these asset owners. By developing engineering models of specific assets within a portfolio, a bottom-up risk assessment approach that captures physical and operational features of the assets in question is possible. This practice was pioneered by the earthquake engineering community in the early 2010's with the introduction of the FEMA P-58 standard for seismic performance assessment of buildings, and its core concept of component-based building-specific assessment has been adopted by researchers working on non-earthquake physical hazards such as flood [1-2], and extreme wind [3-6]. Owing to the higher resolution of the risk analysis, a key advantage of this procedure over catastrophe models is that it identifies the causal chain of events leading to property damage and functional disruption, which is extremely useful for helping stakeholders identify and mitigate vulnerabilities. However, the applications to hazard other than earthquake are mostly of academic interest, and there has not been a well-established method for unifying the different hazards for performance-based assessment. Furthermore, even the most current performance-based standards available today for earthquakes will fall short in addressing questions relating to the disruption caused by major natural hazards, as this is not just a question about any individual asset, but the facility as a whole, including the underlying services it facilitates and the interdependencies between its components. Unlike external infrastructure such as electricity and transportation, these interdependencies are within the jurisdiction of the asset owner and stakeholder, and they should fall under the organization's asset management and business continuity plans. For instance, these types of analysis would be well-suited for identifying scenarios for stress testing emergency or business continuity plans. Particularly for black swan scenarios or scenarios that involve cascading effects of multiple hazards. Despite these important uses, the ability to analyze and identify vulnerabilities for such facility is beyond the current building-specific performance-based assessment methodologies. In response to this gap, and to improve the ability for performance-based assessments to capture impacts of natural hazards in a quantifiable and systematic way for decision-making, a multi-hazard framework for physical and operational resilience of multi-asset facilities has been developed, and this framework is implemented into a computer software package MARSP [7]. The present paper provides a working example of a flood and earthquake assessment incorporating such interdependencies using the MARSP platform for an industrial facility in the Greater Vancouver Area to highlight the new information that can be derived from a facility-based multi-hazard resilience assessment.

OVERVIEW OF THE METHODOLOGY

Figure 1 shows a high-level conceptual illustration of the multi-hazard asset resilience assessment framework implemented in the MARSP platform. The framework contains two separate workflows. The first is a unified multi-hazard asset vulnerability analysis tailored to the facility's assets for each specific hazard considered (asset-peril analysis). The second workflow is a facility wide multi-hazard risk simulation with interdependencies (facility assessment). While both workflows play a role in providing high-resolution risk assessment for a multi-asset facility, they are modularized in a way that the running of one workflow does not interfere with the other. These workflows are responsible for developing high-resolution risk results at the asset-peril level, and for aggregating asset-based analyses together into a coherent, correlated, facility risk assessment, respectively. Figure 2 shows screenshots of the MARSP platform showing user interfaces for defining the peril-specific inputs for each building asset, creating a multi-hazard request by integrating hazard events with asset vulnerabilities, and the interface for inspecting results.

In the first workflow, a performance-based analysis is used to determine the vulnerability of a given asset under different hazards. It starts with the definition of the hazard intensity levels. The levels cover the range of asset response from zero damage to total loss. Each individual intensity level is then matched to the corresponding intensity measures associated with the hazard. For instance, earthquake ground acceleration, wind gust speed are possible measures. These in turn define the engineering demand parameters (EDP) which are related to component damage and consequences, as well as direct and indirect impacts derived from them. Currently, EDP's are developed through a performance-based approach using engineering simulations of assets subjected to different hazards. For earthquakes, EDP's are derived either from structural dynamic or static analysis, for flood they can be derived from hydrostatic or hydrodynamic analysis, and for wind aerodynamic analysis. The resulting EDP's are stored in CSV format and uploaded to MARSP. Similar to the FEMA P-58 framework [8], a performance model is required for workflow 1. Such model can be automatically created by the MARSP platform given basic building physical and occupancy data by utilizing a combination of RSMeans construction data [9] as well as published hazard-specific fragility functions found in the literature [10]. An automated procedure has been developed for this purpose, to populate building contents and associate them with fragility and consequence functions. The latter are found in a static database of fragilities assembled from the literature and consequence data derived from construction data. The performance model thus generated can then be used to perform component-based loss analysis, which supports the subsequent recovery assessment for each combination of building and hazard. All results obtained from the performance-based analysis are converted into smooth interpolated functions for later use. This process is automatic and is subjected to quality checks to minimize error created by the interpolation process. Furthermore, the stored result preserves the casual relationship between component damage and loss, which means that the cross-correlations of different loss metrics are preserved as well.

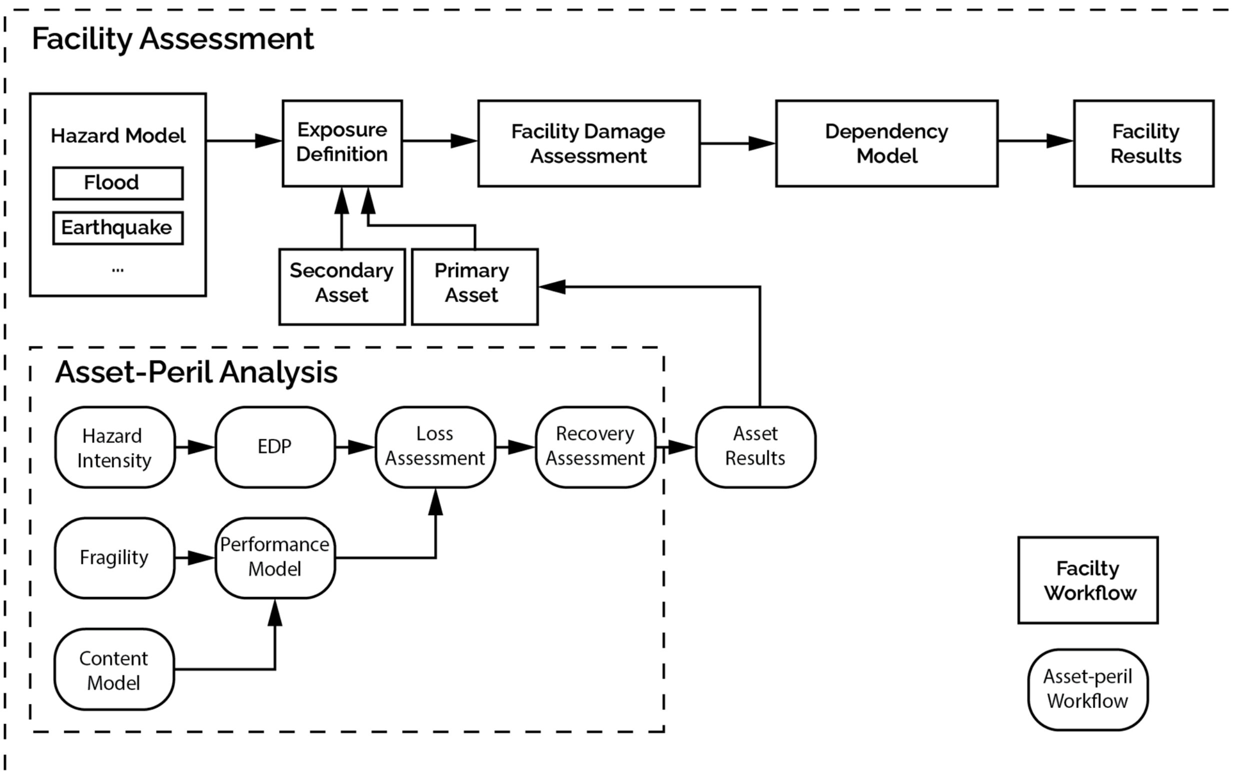

Figure 1. Workflow for multi-hazard facility resilience framework.

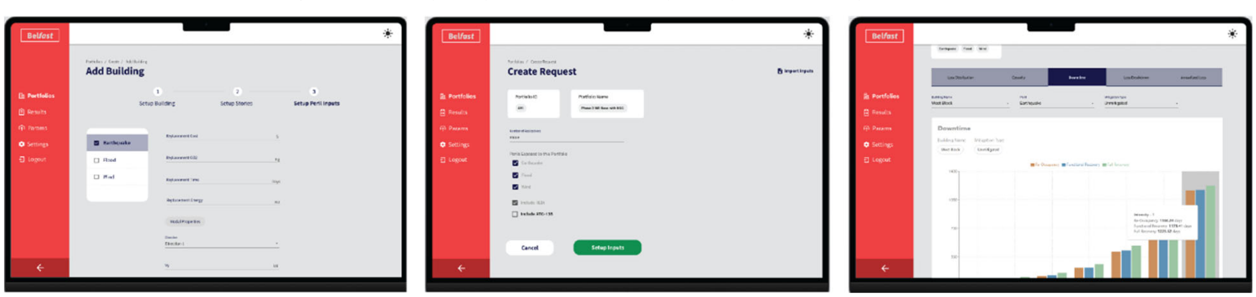

Figure 2. MARSP user interface. From left to right: asset-peril definition, multi-hazard request definition and results viewer

In the second workflow, a facility-based multi-hazard risk assessment is performed. A facility in this context contains multiple assets which includes buildings, non-building structures, and other infrastructure systems. Since the goal of this analysis is to derive facility level responses that are useful for decision making. This necessitates the inclusion of any inter-asset dependencies into the facility model. These dependencies can be typical utility dependencies such as electric power distribution and telecommunication networks, as well as facility-specific operations such as the distribution of material and products in a manufacturing facility. Currently, MARSP supports user-defined dependencies using template fault trees, which is suitable for well-defined dependence relations that have deterministic outputs given inputs. This workflow is modularized into hazard definition, asset assessment, and dependency impact assessment. Unlike the performance-based asset vulnerability analysis, this workflow subjects all the assets within a facility simultaneously to different hazard events, which are sourced from a hazard module. Rather than generating each hazard separately, the hazard module simply extracts events from existing hazard models that are either commercially or publicly available. The hazard module accepts event catalogues for each peril stored in the OASIS Open Data Standard (ODS) [11] for catastrophe models. Each hazard events can be obtained directly from the stochastic catalogue, or they can be resampled. In addition to hazard, there is an exposure module that defines assets within a facility. Primary assets are analyzed through the asset-peril workflow described above to resolve risk at a high resolution (driven by decision-making needs), and secondary assets are those that need to be captured at a lower resolution such as that permitted by typical vulnerability functions. Example of secondary assets include buildings or infrastructure which impacts the overall resilience of the portfolio, but the damage and loss to these assets themselves are relatively inconsequential compared to their impact on operations or other non-damaged related consequences. Damage assessment can be done by combining the hazard events with the exposure model, with vulnerability results defined either from asset-peril analysis workflow (primary assets) or using an appropriate asset vulnerability function (secondary assets). This module also has the capability to use vulnerability data that are either user-defined or uploaded into the platform. Categorizing the assets is a useful feature for facility assessments that do not warrant a full performance-based analysis, or facilities with mixture of assets requiring different resolutions [12]. Finally, the asset damage and loss results are used as inputs to the interdependency module. As mentioned, this module supports user defined dependences in fault tree format, which are evaluated for each hazard event. In this way, functional dependencies within the facility can be captured as part of the portfolio assessment in a way that preserves the causal relationships and uncertainty propagation.

APPLICATION OF THE PLATFORM TO AN INDUSTRIAL PORTFOLIO

To illustrate the use of the multi-hazard platform for decision-making for facility owners, an application of the platform is described in the following section using an anonymized, and modified distribution facility based on a real facility belonging to a large retailer exposed to flood and earthquake. The location of the facility is in Delta, BC and it consists of a single distribution center with four satellite warehouses, all of which are tilt-up precast concrete structures with steel deck roof supported by open web steel joists (OWSJ). These buildings are connected by paved roads in the same industrial park. To simplify the geometry, all of the building geometries have been made approximately rectangular. A rendered model showing the distribution centre with two of the four warehouses is shown in Figure 3a. For each of the warehouses and the distribution centre, the building is considered available after an event if it is safely occupiable, has inventory that can be shipped, and it has a functional electrical system. For this analysis, the electrical system is considered functional if the main switchgear is functional, and there is a power source either coming from the grid, or the emergency generator. A simple fault tree shown in Figure 3b is used to represent building functionality. This fault tree consists of a simple OR gate and a “fuzzified” AND gate, where the Building Availability variable can take values between 0 and 1 depending on how much of the inventory is available. Finally, a model of the road network showing connections to the major artery highway is also presented in Figure 3c. This model has been simplified to rid of unrelated buildings and highlights the connections between each road segment, which are shown by green numbers and red letters depending on if they run east-west or north-south. The connections between these roads and the warehouses and distribution centres are shown by a small black line. While the road diagram is not shown to scale in the interest of space, it accurately represents the connections between the different segments of roads in real life.

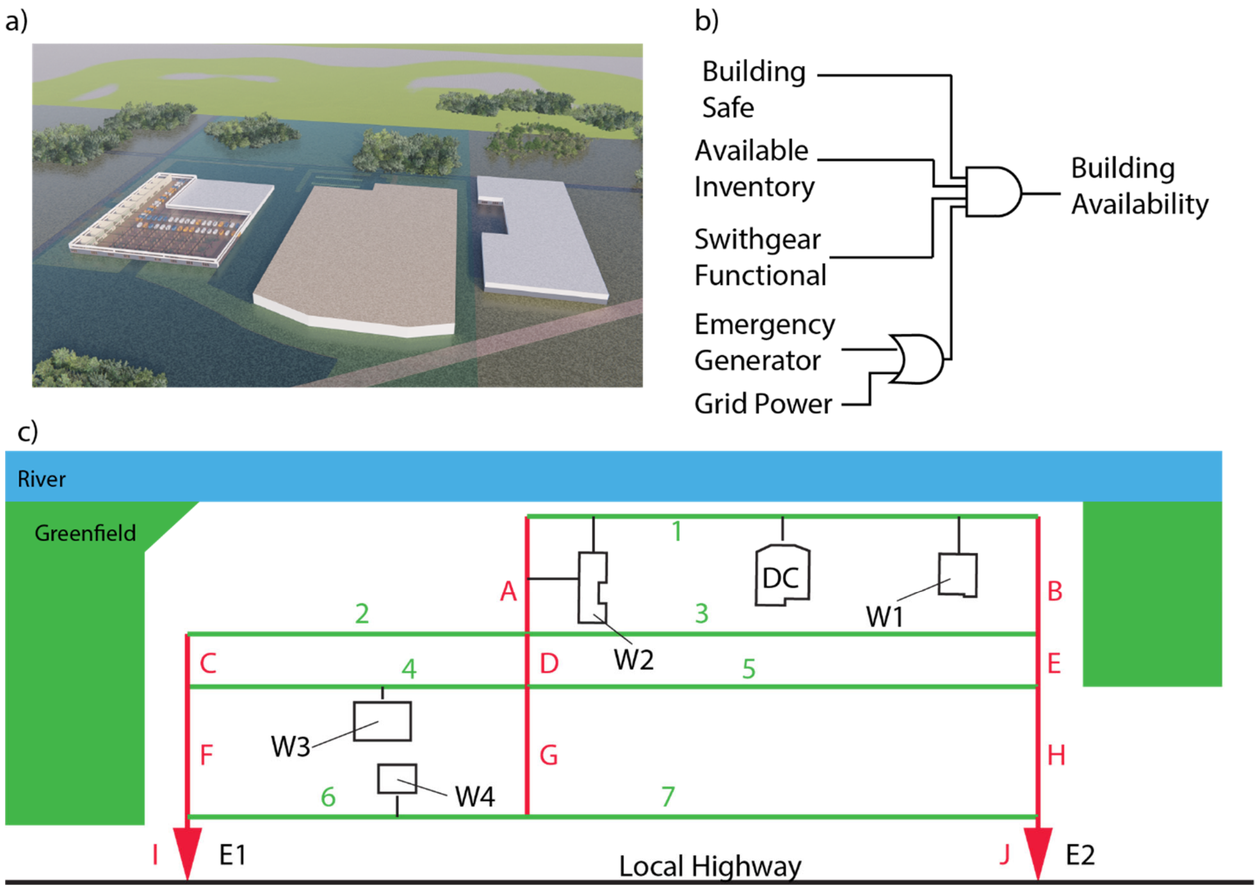

Figure 3: a) Rendered model of the distribution centre and warehouses and b) traffic network

As the main logistic hub in western Canada, the facility is responsible for distributing goods to the retail locations in the region via road traffic. The shipments of goods depart from the Distribution Centre (DC) to retail destinations via the local freeway. There are two ramps to the freeway that are connected to the DC. Goods that are not in stock in the DC are delivered to the DC from one of the warehouses in the vicinity. Flooding of earthquake damage of the road network or the warehouses of distribution centre can therefore impede this operation. Furthermore, the operations of the DC and the warehouses depend on the availability of electric power, either coming from the local grid or from onsite emergency diesel generators (EDG) and fuel. As part of the effort to assess the adequacy of the current insurance risk transfer strategy, the metrics of interest to the portfolio owner are direct physical damage to building structures and inventories, as well as the business interruption (BI) caused by such damage. In addition, it is crucial for the owner to understand if there are scenarios that are not be covered under current insurance policy and other risk mitigation plan. To develop this type of information, a multi-hazard facility model was created in the MARSP platform, using high-resolution vulnerabilities derived from asset-specific multi-hazard analysis.

Each of the five building structures, namely, the distribution centre and warehouses, are first analyzed using a performance-based approach for earthquake and flood. This procedure is similar to the PEER framework for earthquake risk assessment described in the FEMA P-58 standard where structural and performance models for the distribution centre and warehouse buildings are used to quantify damage at the component level. A structural model for each building is developed for earthquake analysis using the simplified approach proposed by Koliu (2018) for rigid wall flexible diaphragm structures as illustrated in Figure 4. In this approach, a 1-D model is used to capture the main engineering demand parameter, building drift, which is the diaphragm drift at the mid-length of the building. Before using the 1-D models to develop the earthquake demands, it is compared to a 2-D model, which shows a more intuitive representation of the actual building as illustrated in Figure 4a.

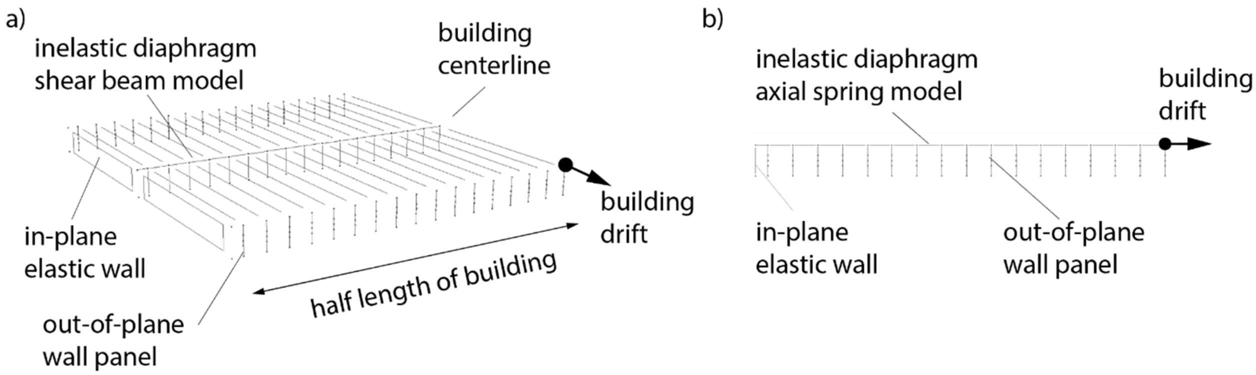

Figure 4: Earthquake structural model for warehouse and distribution centre a) 2D model used for validation b) 1-D model used for nonlinear time history analysis

Due to the inherent flexibility of the roof diaphragm in these buildings, its dynamic response is expected to be dominated by the flexing and shearing of the diaphragm with constraints between applied at the boundary by in-plane walls along its ends, and out-of-plane flexure of walls along its length. Hence, the building drift at the centre of the diaphragm will occur in the direction perpendicular to the longest dimension of the building. Furthermore, the nonlinear behaviour will concentrate in the shear response of fasteners between roof decks. The model shown in Figure 4 captures half of the length of the building. The combined nonlinear shear response of the fasteners and the linear flexural and shear response of the decks are captured in the elastic shear hinge element in the 2-D model and by inelastic bar elements in the 1-D model. The out-of-plane resistance in the walls are simulated by column elements along the length of the building. The in-plane resistance of the shear wall at the end of the building is captured by a single elastic column at the end with in-plane properties. This model hence assumes that nonlinearity only occurs in the fasteners and in the out of plane walls. The 1-D models are used to perform nonlinear dynamic analysis to obtain engineering demand parameters for performance assessment. Seven suites of ground motions were selected and scaled to the NBC 2015 target spectrum. These ground motions consist of crustal, interface and in-slab records. The scaled spectra are shown in Figure 5.

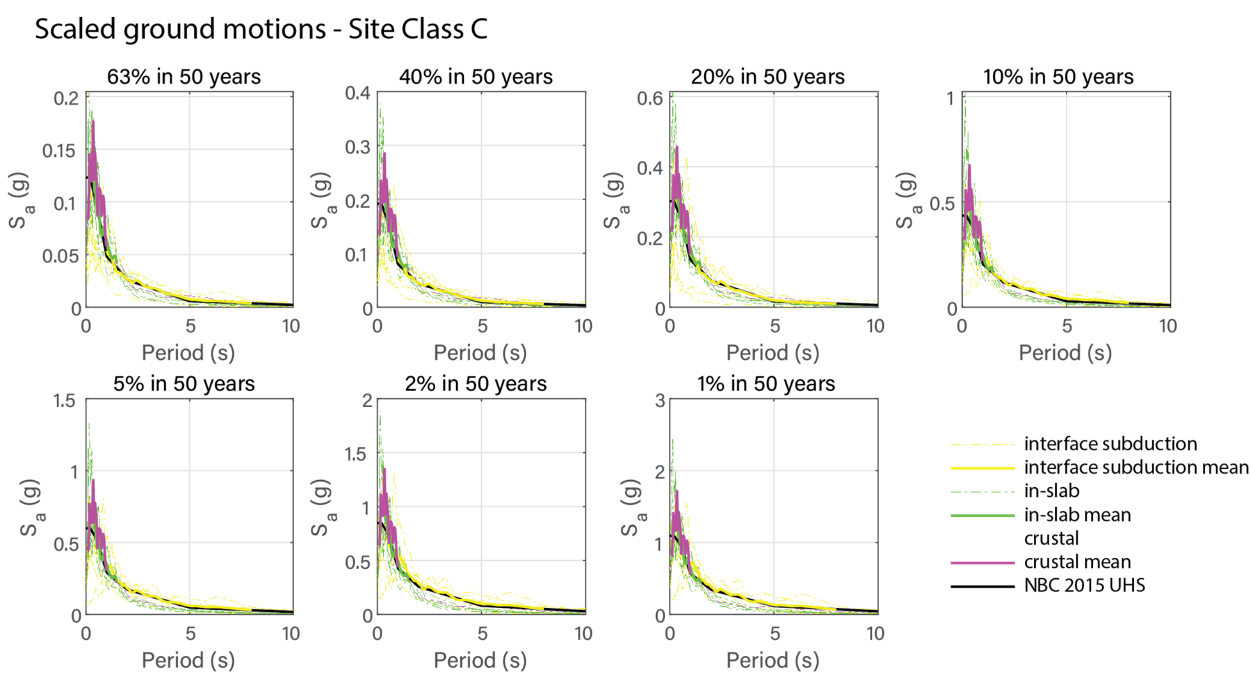

Figure 5: Ground motion used for time-history analysis of warehouses and distribution centre.

An earthquake performance model was built initially using the FEMA P-58 normative quantity estimator, accessed through the MARSP platform. The contents are adjusted to match the flood contents with additional tilt-up building seismic fragilities for in-plane wall, out-of-plane wall, deck to wall anchorage developed using the method in FEMA P-58. A building specific seismic risk assessment is performed at each intensity, and the results in terms of building collapse, building direct loss, inventory loss, loss of emergency diesel generator, loss of switch gear and wiring at each intensity are evaluated to allow the creation of vulnerability surfaces (intensity measure vs. percentile loss) for earthquake.

For flood assessment, no explicit structural model is considered for the buildings in this analysis. Instead, it is assumed that buildings contain vents that allow water infiltration and the equalization of water pressure. A performance model for flood-prone building contents and components was created using the MARSP platform where occupancy-specific contents from RSMeans are generated and automatically matched to a database of flood fragilities developed from available literatures. As mentioned above, the earthquake performance model is adjusted with the generated flood contents to preserve internal consistency. Similar to the seismic analysis, 7 flood intensities are chosen to cover the full range of building damage from no damage to total loss. The inundation depth for these are 0.02m, 0.07m, 0.48m, 1.10m, 1.60m and 2.37m, respectively. Similarly, building-specific flood risk analyses enable the definition of vulnerability surfaces for flood given inundation depth.

Figures 6 show sample direct loss vulnerability curves for the distribution centre under earthquake and flood, parameterized by the hazard intensity measure. Vulnerability surfaces are form by applying cubic splice interpolations of the vulnerability curves conditioned at each intensity. For earthquakes, the intensity measure shown in the spectral acceleration at 0.2 s for a reference class C site. Note, that these acceleration values should be interpreted as labels for the intensity and are not the actual accelerations experienced by each building. This process is generally applicable to other response parameters, such as casualty and downtime.

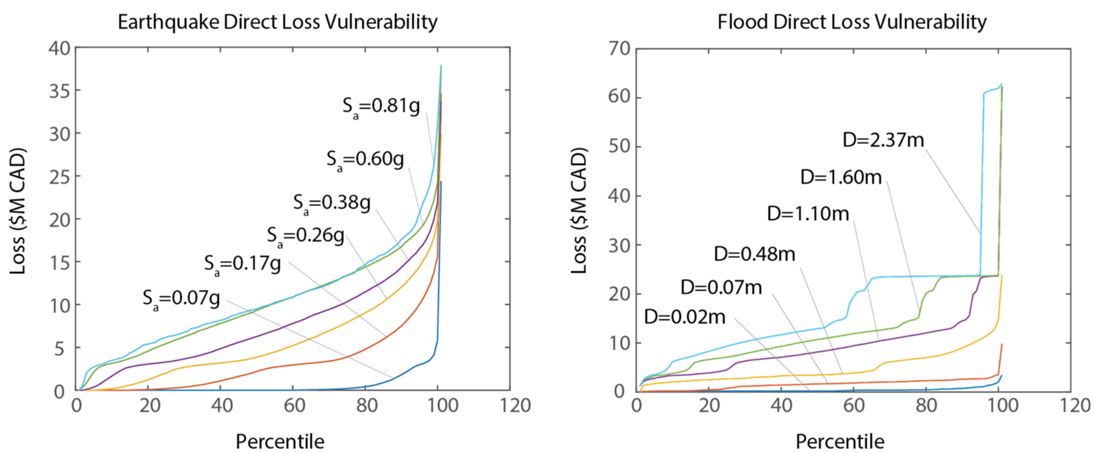

Figure 6: Sample direct loss vulnerability functions for earthquake (as functions of $S_a(0.2)$) and flood (as functions of inundation depth)

Figure 7 shows a breakdown of loss contributions for each component system for earthquake and flood for the distribution centre at three levels of increasing intensities from left to right. It can be seen that the main cost drivers in the buildings during a flood are electrical system and interior partitions. On the other hand, the primary driver of damage during an earthquake are the storage racks and structural components under larger shaking. Even under moderate earthquakes, the racks can be damaged and the contents in the racks can experience significant shaking and fall onto the floor. In very large earthquakes, the buildings can also experience total loss due to either excessive residual deformations in the building or structural collapse.

For the entire facility containing all of the buildings and contents, building-specific vulnerabilities shown in Figure 6 are used to define joint probability distributions of all metrics of interest in a facility risk assessment using workflow 2 in MARSP. The exposure model consists of the distribution centre and warehouses as primary assets, while roads are considered secondary assets. This process channels earthquake and flood stochastic events data for each site to perform facility simulation. The 6th generation national seismic hazard model as implemented in OpenQuake [13], and the AON Impact Forecast Canadian flood model [14] are selected as hazard sources for this analysis. For both earthquake and flood, the facility model is subjected to a 300,000 year stochastic event set.

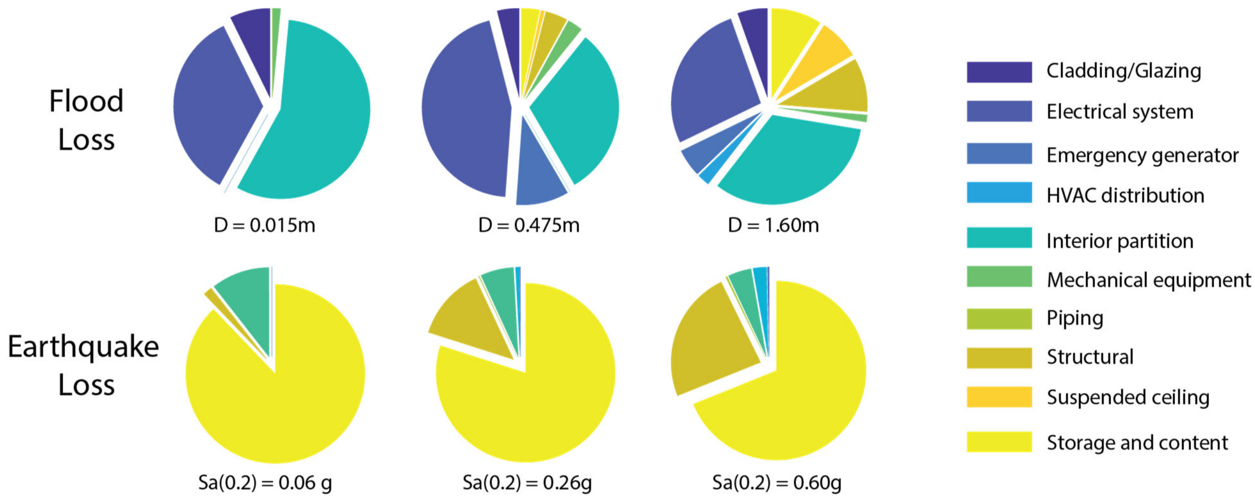

Figure 7: Breakdown of losses at different hazard intensities for a) flood and b) earthquake

Figure 8 shows the facility loss exceedance probability curve (EP curve) for the case where only property damage is considered, and for the case when additional "assumed" business interruption loss is included. Based on the event tables, the average annualized earthquake and flood loss are $1.45 million and $208,000, respectively, indicating that from a direct physical loss perspective, earthquake risk will dominate. Expressed in loss ratios, these amounts to 0.28% and 0.04% of the portfolio replacement cost, respectively. Based on this, investment in earthquake risk mitigation, particularly in the protection of inventory and seismic strengthening of the storage rack system seem to have to most impact on risk reduction. However, this risk does not incorporate the direct business interruption losses that can occur if recovery time of the facilities are factored in.

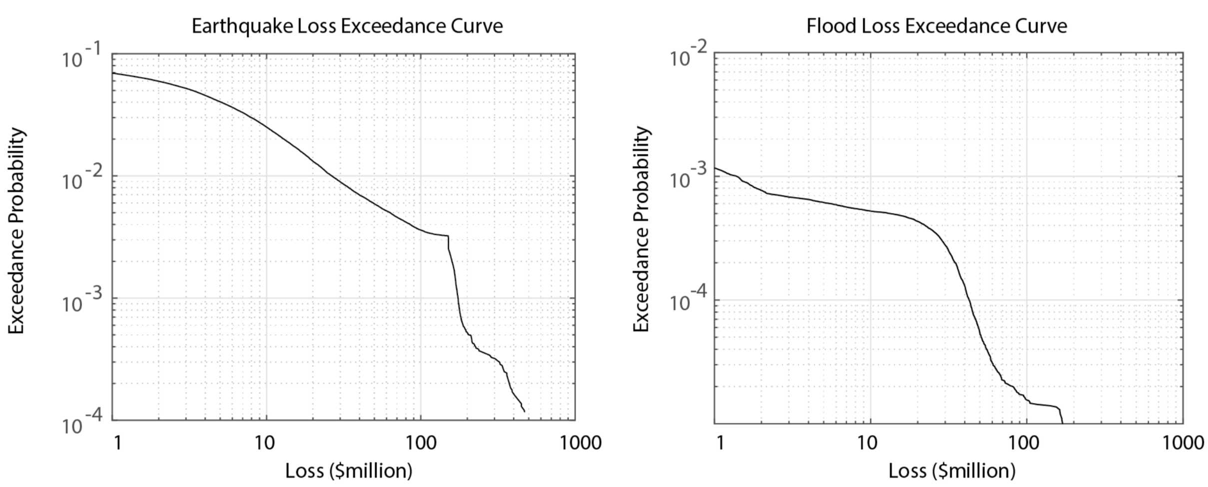

Figure 8: Loss exceedance curves for the entire distribution facility for earthquake and flood

One of the key usages of the MARSP analysis is to assist asset owner in capturing facility-specific business impacts, particularly for cascading consequences due to interdependencies between the facility assets and the surrounding infrastructure, that may not be adequately addressed by the existing risk management strategy, despite having property and business interruption insurance coverage. Specifically, there are conceivable scenarios where the hazards may not necessarily incapacitate the assets physically, but nonetheless severely disrupt the operations of the facility. These scenarios may not trigger business interruption insurance, but nonetheless cause severe impact to business operations. A specific scenario that is investigated is the ability of the facility to continue to fulfill its distribution role by making shipments of goods to the retail nodes from its distribution centre via road transport. Since the facility buildings and the paved roads connecting them to the local major transportation arteries are all subjected to flood and earthquake hazards, the ability to ship out goods would also depend on the functional states of these roads. In these situations, it is assumed that the facility will continue to operate to some capacity as long as safety, power and inventory are available (even though part of the facility may require repair). To capture these scenarios, a facility-based fault tree that represents its functional dependencies for distributing goods via road traffic is developed and applied as part of the facility analysis in workflow 2. A schematic of this fault tree is shown in Figure 9.

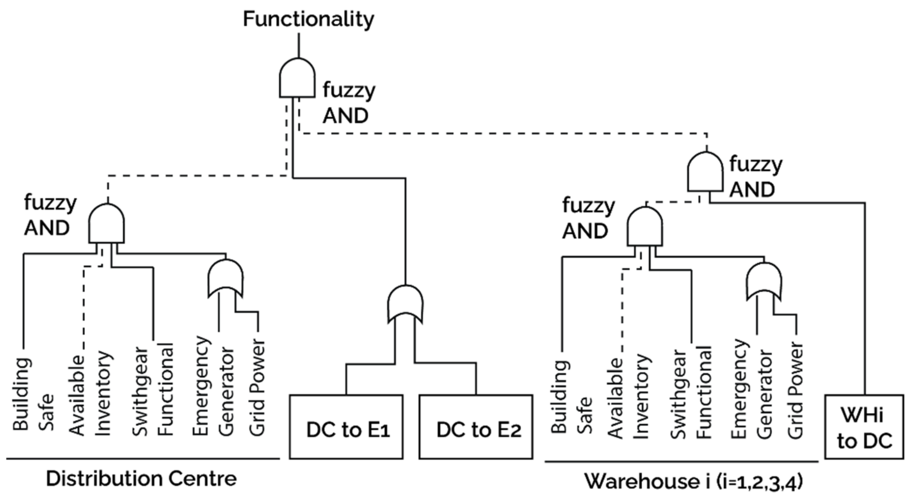

Figure 9: Fault tree used to model functionality of portfolio for the ability to distribute goods via road traffic

The operation in question is defined as the ability for the facility to send goods via road traffic to the local highway. There are two entrances to the highway connected to the local traffic grid, called E1 and E2. The roads are two-way streets connecting the warehouses and the distribution centre. Each segment is evaluated independently for earthquake (failure due to lateral spread) and flood (accumulated water halts traffic completely). The fragility functions used for modelling road failure is based on the HAZUS earthquake manual for lateral spreading [15], and [16] for traffic speed reduction due to inundation. The roads are partitioned into cells with a dimension of roughly 30m, and a segment of the road is considered available if all the cells are neither flooded nor damaged from an earthquake. Traffic between two locations is thus possible if there is at least one available route, consisting of multiple road segments. Under this definition, the functionality of the facility is dependent on the availability of traffic connecting the warehouse to the distribution center, and between the distribution centre and the entrances E1 and E2 to the local artery. These variables are evaluated using a connected graph model, which is evaluated for connectivity every time an event occurs that causes some damage to the road segments (and the buildings). If the buildings are connected to the target locations after damage has been accounted for.

In addition to the availability of road transport, the distribution centre itself must be at least partially functional, which means the building needs to be safe for occupants, must have power and must have undamaged inventory that can be shipped. Similarly, for goods that must be fetched from one of the surrounding warehouses to the distribution centre, both the warehouse and distribution centre must be partially functional. Finally, the AND gates in this fault tree are “fuzzified” in the sense that the inventory available in each of the distribution centre and warehouse contribute to the total function in a proportional manner. Hence, the outputs and inputs of these fuzzified AND gates (shown as dotted lines) can take values between 0 and 1. In the actual implementation, the fuzzified input values take values between 0 and 1, while the standard Boolean inputs/outputs can only take values of 1 or 0. The final Functionality variable represents the proportion of the facility’s original functionality in terms of its ability to fulfill distribution orders.

Table 1 summarizes the degree of function in the facility immediately after a damaging earthquake and flood event. The mean, median and 90th percentile, deemed worse case scenario, are shown. The degree of function represents the fraction of pre-event capability for distribution of goods retained by the facility. In this table, the percentile results are functions of the entire facility including buildings and road infrastructure. The results shows that the median functional disruption is higher for earthquake than flood, but the impact of these are minor. The primary reason for this is because there are generally a lot more earthquake events in the stochastic catalogue (although most do not cause any serious damage) than floods (floods that do not produce a positive inundation in the assets are excluded) and hence given that an earthquake event happen, there is a higher probability that the facility will continue to function and that the local roads are available. When looking at the worst case (90th percentile damage) scenarios, the operational disruption risk caused by flood is actually much higher due to its impact on the surrounding road network. Specifically, there is almost a 30% chance that the facility will not be functional even if all of its building assets are because of the failure in the transportation grid, leading to segments of roads being flooded and cannot be used. Figure 10 illustrates two specific damage footprints, extracted from the 90th percentile simulations showing the damage to the facility buildings and the availability of the roads. This figure highlights that the scenario for earthquake damage is caused by moderate damage to properties and buildings, while that for flood is caused by flooded roads blocking road traffic. These are scenario that would require additional risk mitigation measure to address, and it emerges solely from the interdependencies of the facility operations.

Table 1. Facility function in terms of capacity to make shipment

	Earthquake	Flood
Mean	92.7%	69.8%
50th percentile (median) damage	99.6%	100%
90th percentile damage	93.6%	0.0%
Availability of Routes	97.2%	72.0%

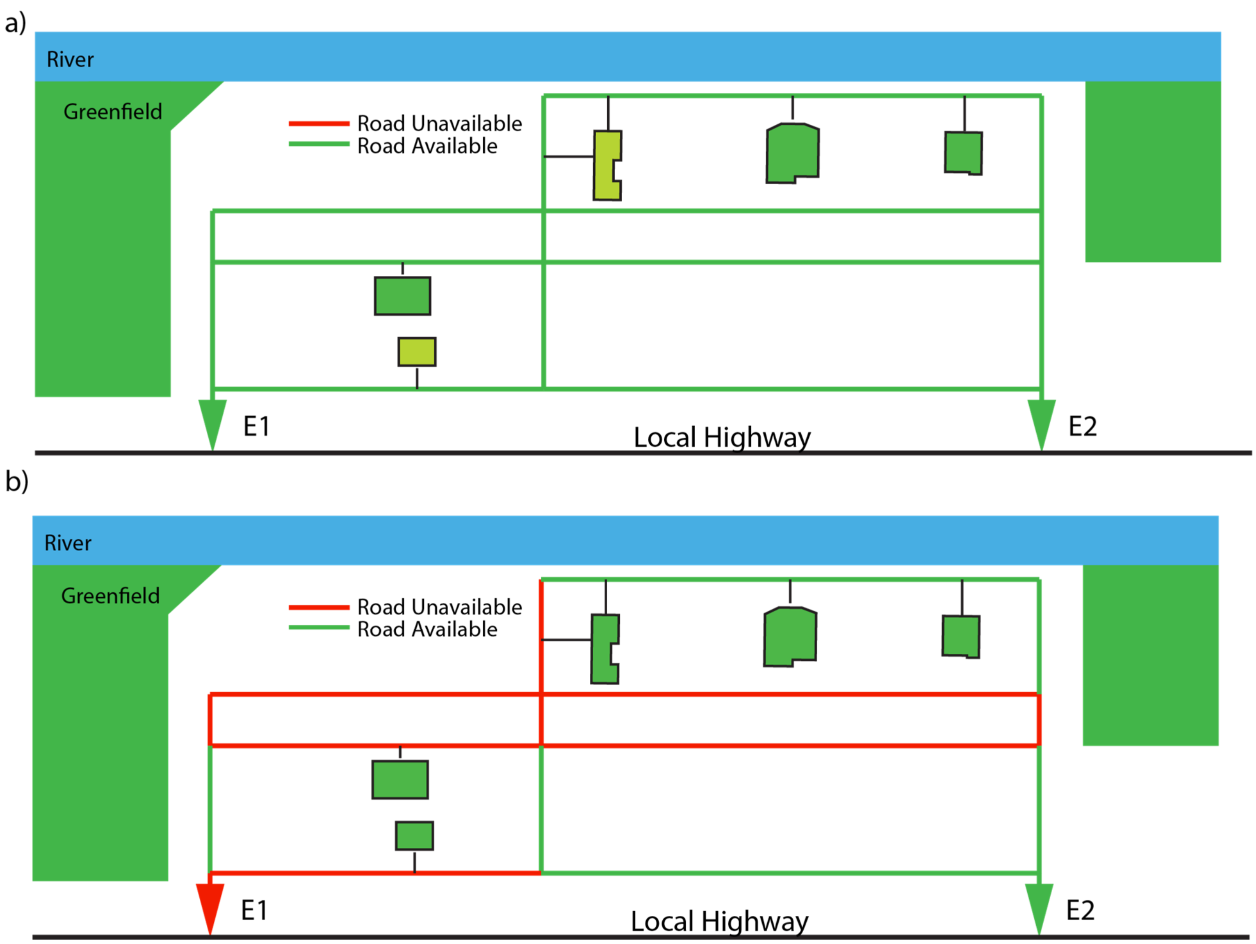

Figure 10: 90th percentile scenarios for functional disruption of facility for a) earthquake and b) flood

CONCLUSION AND FURTHER DEVELOPMENT

This paper describes a multi-hazard study of a multi-asset facility using a software platform that integrates the asset-specific risk assessment with explicit interdependency modelling. The MARSP platform uses an expanded version of the FEMA P-58 risk assessment methodology, with changes made to accommodate for non-earthquake fragilities, content models and recovery process. An important feature of this methodology is the ability to capture causality in a loss scenario due to its ability to resolve losses at the component level, and using these component-based results as inputs for network models that captures cascading losses due to interdependencies between components or subsystems in an asset to functionality measures of the entire facility. The study examined a very specific usage case where the ability of the distribution facility to ship goods via road transport to the local traffic artery in the events of floods and earthquakes. While the purpose was to identify any potential gaps in the existing risk management strategy, the methodology itself can be useful for developing other critical risk management information such as, but not limited, to the identification of loss scenarios for business continuity planning and the evaluation of the benefit-cost of investing in physical risk mitigation or even relocation.

Currently, the MARSP platform supports user-defined interdependencies between any of the modelled components within a multi-asset facility through a fault tree template. However, there are many situations where the interdependencies are much more difficult to define, or the information required to define them is difficult to assess and verify. In these situations, it is essential to capture the uncertainties in the network model itself. Further, it is also important to be able to develop template network models that are applicable to large classes of facilities without the need to fine tune the dependences between individual components or assets for higher level facility assessments. These elements are currently being developed and validated jointed by the researchers.

ACKNOWLEDGMENTS

The authors would like to express their gratitude towards Dr. Rachid Ouche and Dr. David Bristow for their insightful suggestions and discussions on the modelling of dependencies, which was crucial to the work presented in this paper.

REFERENCES

[1] Nofal, O. M., & van de Lindt, J. W. (2020). Understanding flood risk in the context of community resilience modeling for the built environment: Research needs and trends. *Sustainable and Resilient Infrastructure*, *7*(3), 171–187. https://doi.org/10.1080/23789689.2020.1722546

[2] Nasiri, H., Mohd Yusof, M. J., & Mohammad Ali, T. A. (2016). An overview to flood vulnerability assessment methods. *Sustainable Water Resources Management*, *2*(3), 331–336. https://doi.org/10.1007/s40899-016-0051-x

[3] Ciampoli M, Petrini F., and Augusti G. (2011) Performance-based Wind Engineering: Towards a general procedure. *Structural Safety*. 33, pg 367-378.

[4] Suksuwan, A., and Spence, S. M. J. (2018). Performance-based Multi-hazard Topology Optimization of Wind and Seismically Excited Structural Systems. *Eng. Structures* 172, 573–588. doi:10.1016/j.engstruct.2018.06.039

[5] Gardoni, P., and LaFave, J. M. (2016). "Multi-hazard Approaches to Civil Infrastructure Engineering: Mitigating Risks and Promoting Resilence," in *Multi-hazard Approaches to Civil Infrastructure Engineering* (Berlin, Germany: Springer), 3–12. doi:10.1007/978-3-319-29713-2_1

[6] Ouyang Z., and Spence SMJ (2020) "A performance-based wind engineering framework for envelope systems of engineered building subject to Directional wind and rain hazards." *Journal of Structural Engineering.* 146(5): 04020049, DOI:10.1061/(ASCE)ST.1943-541X.0002568.

[7] Kinetica Risk (2022) *MARSP*. Software

[8] ATC (2018) *FEMA P-58 Seismic Perofrmance Assessment of Buildings Vol 1 – Methodology.* Redwood City, California.

[9] Gordian (2022) *RSMeans.* Software

[10] Kinetica Risk (2022) "Multi-hazard Platform for Resilience and Strategic Planning of Real Assets – Review of Multi-hazard Resilience Methodology – Vol 1.*" Milestone Report for Canadian Safety and Security Program (CSSP).*

[11] OASIS (2023) *Open Data Standard.* https://github.com/OasisLMF/ODS_OpenExposureData

[12] Jeswai K., Guo J., and Christopoulos C. (2022) "Seismic risk assessment and mitigation analysis of large public school building portfolios in Metro Manila." *Earthquake Spectra.,* 38(3), https://doi.org/10.1177/87552930221086304.
[13] Natural Resources Canada (2020) *Input File Sixth Generation seismic-hazard model of Canada.* Natural Resources Canada, Ottawa, ON.
[14] AON (2022) *Impact Forecast Canada Flood Model.*
[15] FEMA (2022) *Hazus Earthquake Model Technical Manual – Hazus 5.1.*
[16] Pregnolato M., Ford, AC., Wilkinson S., Dawson R. (2017) "The impact of flooding on road transport: A depth-disruption function." *Transportation Research.* Vol 55., p. 67-81.