Reliable Quantification and Mitigation of Catastrophe Risk for Industrial Facilities

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SUMMARY:
Recent natural catastrophe events have shown that along with residential and commercial construction, industrial facilities can also be seriously impacted by earthquakes, tsunamis and other natural catastrophes. This exposure results in monetary losses associated with direct physical damage of industrial facilities, which can be substantial given the concentration of value at one geographic location for such facilities. This physical damage loss, however, often pales in comparison to the associated monetary loss from direct business interruption and, as observed after the Tohuku earthquake, from contingent business interruption by affecting global supply chains. Thus, it is imperative that the performance of these facilities, in terms of monetary loss potentials, be reliably quantified such that informed pre-catastrophe decision making can substantiate the development, evaluation and selection, communication, and implementation of appropriate physical and financial risk mitigation measures. This paper summarizes a methodology for developing reliable quantitative measures of seismic loss potentials associated with industrial facilities and illustrates the application of the methodology through a case-study. The primary components of the methodology are engineering-based component-level vulnerability functions for components typically observed at industrial facilities, a weighting of the vulnerability functions based on valuation of the component classes to derive facility-level vulnerability functions, an option for inclusion of a network model to better capture the business interruption loss potential, and cost-benefit evaluations to evaluate various mitigation measures.

Keywords: industrial facilities, loss potentials, mitigation, vulnerability, components

1. INTRODUCTION

In the recent past, earthquake events have resulted in severe monetary losses associated with direct physical damage (denoted as PD) and business interruption (denoted as BI) to numerous industrial facilities throughout the world. Notable examples are the Tupras refineries in Turkey that were damaged by the M7.4 Izmit Earthquake in 1999 (PEER, 2000), the Kashiwazaki nuclear power plant in Japan that was damaged by the 2007 M6.6 Niigata Chuetsu-Oki Earthquake (IAEA, 2007), among many other such examples (e.g., NIST 1997, Eshghia et al. 2005, Suzuki, 2006, Cruz et al. 2010). Given the typically high PD and BI value associated with these facilities and their importance in global supply chains, it is imperative that the performance of these facilities, in terms of monetary loss potentials, be reliably quantified such that informed decision making can occur pre-catastrophe to develop, evaluate and select, communicate, and implement appropriate physical and financial risk mitigation measures.

The loss potentials for these industrial facilities depend on many factors including the type of industrial facility (e.g., pharmaceutical, petrochemical, high-tech manufacturing), its construction and maintenance characteristics, its operational network, reliance on third-party vendors, internal and externals lifelines, among many others, which make reliable risk quantification a difficult task. Also, there is a paucity of facility-level historical loss data that inhibits a reliable statistical definition of the loss potentials, as opposed to that for residential and commercial construction. These complexities necessitate an engineering-based approach to evaluate the risk potentials for such facilities.

Industrial facilities also pose a unique challenge in that these facilities are comprised of many different types of components (Figure 1), which may exhibit markedly different seismic vulnerability, and these components may be present in different proportions (in terms of value) even within similar facilities. Figure 2 shows the value distribution of two power generation facilities. Both facilities are coal-fired thermal generation facilities located close to one another; however, as can be seen in the figure, the specific configuration of each plant dictates the value proportions of their constituent components. The distinct value distributions influence the facility-level seismic vulnerability as different components have different relative vulnerabilities to seismic ground motions. These considerations point to the need for a component-level evaluation of the seismic vulnerability of industrial facilities.

Figure 1. Example of components observed at industrial facilities. All exhibit different seismic vulnerability.

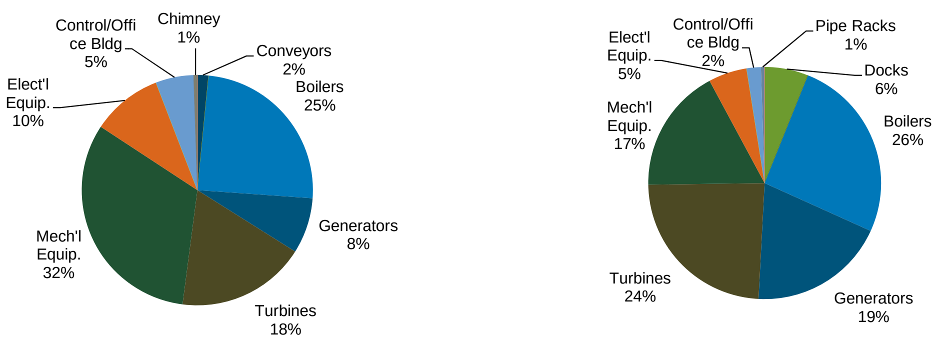

Figure 2. Breakdown of exposure value amongst component classes for two coal-fired power plants.

A component-level evaluation of the seismic vulnerability also has the added advantage of being able to capture the business interruption loss potentials associated with product disruptions on the account of physical damage to the components. The components (or aggregates of the same) can be placed on the facility operational network which additionally comprises of lifelines and interdependencies. The component physical damage loss potentials can then be carried forward to capture the impact on the facility BI loss potential.

Thus, reliable quantification of the seismic loss potentials associated with industrial facilities requires the ability to capture both the difference in relative vulnerability of each component type and the distribution of components within a facility. The methodology presented in this paper utilizes an engineering-based component-level approach to evaluate the seismic risk for industrial facilities.

2. METHODOLOGY OVERVIEW

The methodology presented in this paper employs a component-level approach to develop the seismic vulnerability of the major component classes typically observed at industrial facilities. The vulnerability is defined in terms of damage functions,[1] for evaluating the physical damage (PD) loss to industrial facilities. The advantage of the engineering-based component-level approach is that since it aggregates up the expected performance at the component level to the facility level, it is capable of capturing the differences in valuation and performance of constituent components thereby providing realistic estimates of the PD losses. Furthermore, this approach results in uniformity in the risk evaluation across different types of industrial facilities. The component-based approach to estimating PD losses also provides a reliable means for assessment of the business interruption (BI) losses. The capability of modelling the damage states of components, coupled with industrial process network modelling, allows for a robust determination of the facility BI losses, which are heavily dependent on the numerous interactions between the various components and lifelines (e.g., electricity generation and supply, steam, nitrogen, transportation networks, among others). The PD portion of the methodology essentially comprises of the following three primary steps:

- **Step 1:** Different assets within an industrial facility are categorized into component classes (e.g., tanks, flares, cooling towers, process towers, equipment, and contents) and sub-components (e.g., in the case of flares: freestanding, guyed, and derrick flares) and their vulnerability is derived based on on-site investigations, engineering analysis, literature review, and historical data. The grouping of assets into component classes is done based on similarity of structural characteristics, functionality, and importance, while the sub-grouping is intended to capture any significant differences in vulnerability that may exist within a component class.
- **Step 2:** The replacement cost for the entire industrial facility is partitioned into the replacement costs for the previously defined component classes.
- **Step 3:** The PD damage function for the entire industrial facility is derived by appropriately weighting the PD damage functions of the component classes and sub-components at the facility.

2.1 Component and Facility Damage Functions Development

The derivation of the seismic vulnerability, in terms of damage functions, for the various component classes and specific sub-components is based on a combination of information obtained from literature reviews, on-site investigations and information from facility personnel, engineering analyses, and historical data. These primary building blocks of the methodology are discussed below:

- **On-site investigations:** On-site investigations conducted by the authors both in the pre-catastrophe situation (for risk assessment and mitigation purposes) and in the post-catastrophe situation (for damage assessment and repair) have resulted in a wealth of information such as condition of key components, observed failure modes, unique characteristics of components, clarifications on the valuation breakdowns for various facilities, among other information, which is invaluable in developing the component-level vulnerability.
- **Literature review:** A thorough review of the technical literature provides information on the documented performance of various components during laboratory testing and/or detailed analytical evaluations.
- **Historical observations:** Review of documentation of observed damage to various facilities

[1] Damage functions for physical damage (PD) are relationships between a measure of the physical hazard (e.g., ground shaking, wind speed, and flood depth) and a "damage ratio," which is a ratio of the cost for repair of the component to the total replacement value of the component.

during past catastrophe events provides information for assessing the expected perormance of similar components in future catastrophe events. Data available from facility owners or insurers regarding losses experienced by facilities during past events is critical and is used for validation of the component vulnerability.

- **Engineering analyses:** the authors have conducted detailed analytical evaluations using computer models of representative and unique components to determine the expected performance of such components. The analyses include sensitivity analyses (to capture variability in material properties, design characteristics, among others) that assist in improving the confidence in the expected performance of the components.

Implementing the process described above, the authors have developed component-level damage functions for over four-hundred components and sub-components. Figure 3 (left) presents the *mean* damage functions for some components. Some of the components are further categorized into sub-components, for example flares (guyed, derrick, or free standing), tanks, among others. Tanks will exhibit different vulnerability based on height-to-diameter ratios, roof type, construction, maintenance, actual level of fill during the time of the event, among other factors. Where these conditions result in significant differences in vulnerability, sub-component-level damage functions are developed. The primary observations from Figure 3 (left) are that different components exhibit different vulnerability; 1) the hazard intensity for onset of physical damage varies amongst components; 2) the rate at which damage increases with increasing hazard intensity varies amongst components; and 3) the maximum damage ratio attained by the different component also varies.

Additionally, there is intrinsic variability in the actual damage sustained by a component for a given hazard intensity. As conceptually shown in Figure 3 (right), there is a distribution of possible damage (or loss) ratios for every hazard intensity value; it is the mean (or the expected value) of that distribution that is shown in Figure 3 (left). The quantification of this uncertainty, which also varies from component to component, has been carried out based on engineering analyses, onsite observations, historical performance reports, and claims data. During evaluation of the catastrophe risk the uncertainty in the damage ratios is explicitly considered.

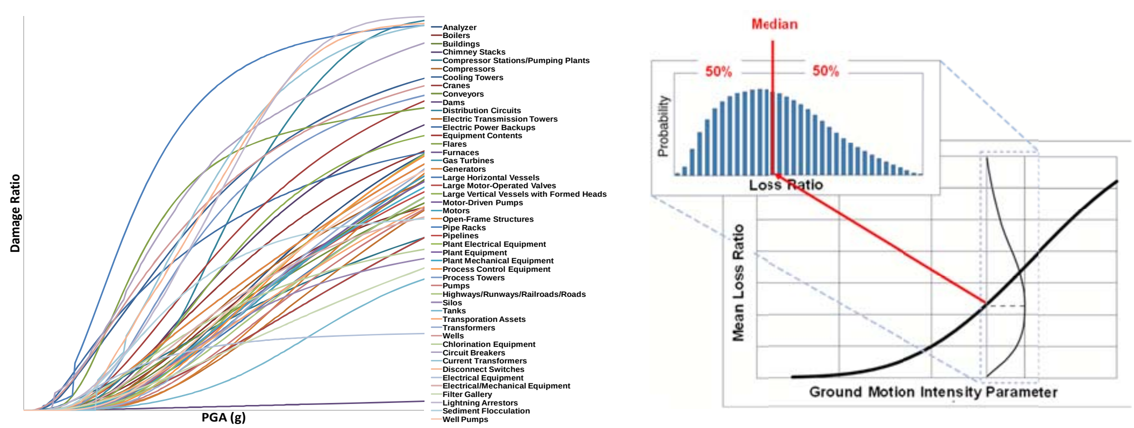

Figure 3. [Left] Example of damage functions for select components commonly found in industrial facilities (y-axis not shown to preserve proprietary nature of this information). [Right] Conceptual figure of uncertainty quantification of damage functions.

The following demonstrates the application of the above described methodology. A representative steel pipe rack was evaluated to illustrate how a component damage function can be formulated from engineering-based analysis. The example pipe rack consists of typical multi-tier steel frame bents. Typical bents include 7 beams supporting pipes, and are 28.5 feet (8.7m) high by 15 feet (4.6m) wide. The beams are bolted to the columns and the lateral load resistance is provided by diagonal bracing in the transverse direction at the bottom bay of each bent and periodic bracing of consecutive bents in the longitudinal direction.

A finite-element model of a typical bent was developed. The dead load and seismic mass were computed from the self-weight of the structural elements and by assuming a range of pipe loads corresponding to 20, 40 and 80 percent of the plastic moment capacity for each beam. An eigen-value analysis was carried out to evaluate the modal properties of the bent structure in the transverse direction; the fundamental periods were computed to be 1.78, 2.47 and 3.46 seconds, respectively, for the 20, 40 and 80 percent beam load cases. A nonlinear static (pushover) analysis was carried out to identify key inelastic response limit states and quantify the corresponding ground motion intensity in accordance with the provisions of ASCE/SEI 41-06. The lateral load was distributed in an inverted triangular pattern. The pushover analysis accounted for the formation of axial plastic hinges (compression buckling and tension yielding) in the bracing elements and columns, and flexural plastic hinges in the columns and at the mid-span of the beams where the braces connect.

Figure 4 presents the pushover curves for lateral loads in the transverse direction, as well as key limit states and corresponding equivalent ground motion PGA. The spectral acceleration (S_a) was predominately utilized to quantify ground shaking intensity, although the corresponding peak ground acceleration (PGA) was also quantified. The hinges are color coded to signify the extent of plastic deformation, which can range from minimal yielding (B-purple) to significant loss of strength associated with member collapse (C-yellow). To quantify the effects of seismic mass (beam gravity loading) on the ground motion intensity associated with each limit state, three PGA values are presented corresponding to the 20, 40 and 80 percent beam load cases discussed previously.

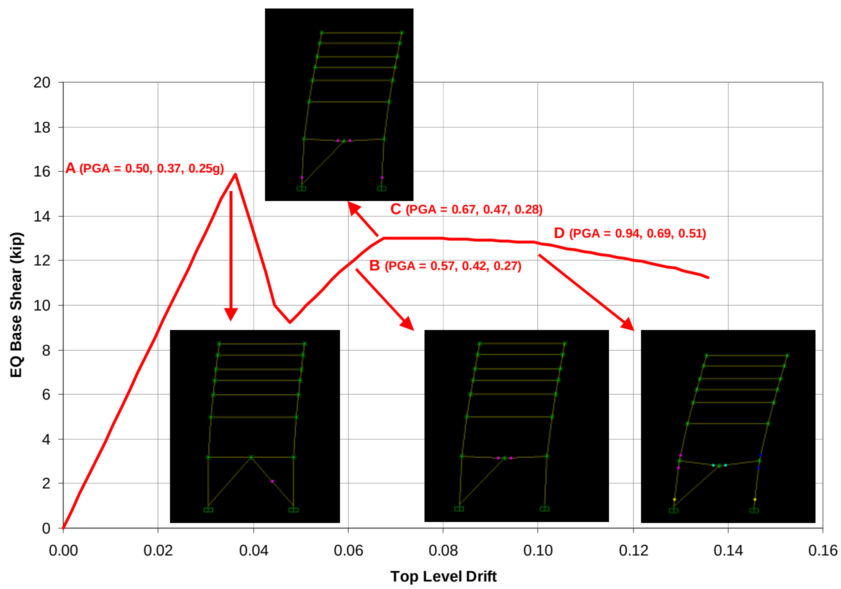

Figure 4. Pushover curve and limit states for representative steel pipe rack.

As Figure 4 indicates, with increasing lateral loads in the transverse direction, the first plastic hinge formed at the compression brace (buckling), followed by a sharp drop in strength and subsequent strength gain at a reduced stiffness. Next, flexural hinging of the bottom beam occurred at the brace connection due to the large force unbalance associated with the buckled compression brace. Hinging at the column bases followed near the ultimate strength of the structure. The structure continued to deform with decreasing strength until hinges develop in the columns above the bottom bay. At this point of the analysis, a mechanism formed above the bottom bay, as the beams are not welded to the columns, and the analytical model collapses.

The limit states on the pushover curve in Figure 4, having already been related to ground motion intensity, can be related to levels of damage and corresponding repair costs to establish damage ratios. This exercise was carried out in discussions with facility personnel to determine the actions that would be undertaken at different levels of physical damage; for instance, they may decide to replace the entire rack beyond a certain number of plastic hinge formations, in which case the damage ratio associated with occurrence of that physical state would need to be set to 1. Information from contractors and literature was also obtained to determine cost of repairs at different states of physical damage. Thus, the resulting pair of ground motion and damage data metrics is used to define an engineering-based damage function for the pipe rack component. This damage function is then validated against any historical observations that may be available in the literature.

The vulnerability of the rest of the suite of industrial type components and sub-components has been developed in a similar fashion, with an example of the same as shown in Figure 3. This database of vulnerability relationships can be leveraged for the analysis of a variety of different facility types.

2.2 Derivation of Facility PD Damage Functions from Component PD Damage Functions

The nature of the industrial facility (e.g., manufacturing, petrochemical, heavy/light industrial, power generation) usually defines the types and quantity of components (in terms of value as a fraction of the total replacement cost) at the facility. Given the variations observed in the component vulnerability, it is critical that a reliable distribution of the facility value be obtained in terms of the constituent components. To generalize the procedure, a component class replacement cost is characterized as a fraction of the total replacement cost of the entire facility rather than in absolute terms. This task has been carried out for different types of industrial facilities based on the experience gained from site-specific studies, review of literature, and expert elicitation. The damage functions for an entire facility can then be represented as a weighted average of the damage function for each component class present in that facility. The weighted average is a legitimate operation because the PD loss of the entire facility is desired as opposed to the average damage state of the facility itself.

A schematic description of this process is summarized in Figure 5. Note that to capture the uncertainty in the damage functions for the entire facility, the uncertainty in the component level damage functions (i.e., in the damage ratio for a given level of ground shaking or flood depth) is incorporated via Monte Carlo simulation. Using this process, facility-level damage functions (that are now based on engineering-based component-level damage functions) have been developed for a variety of industrial facility types, but are not shown here for brevity.

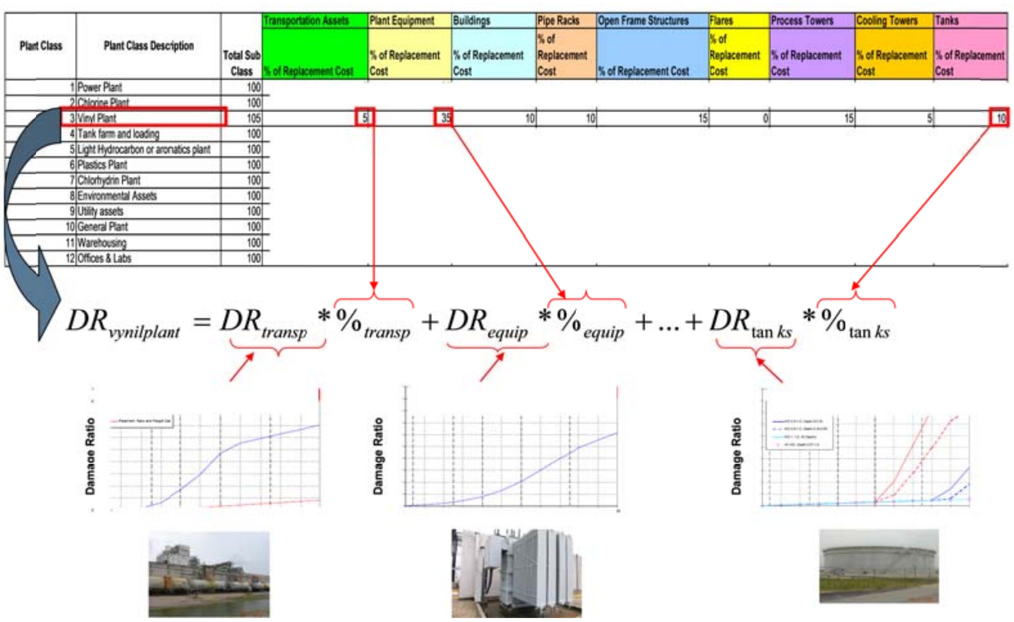

Figure 5. Approach for developing an industrial facility-level damage function using the engineering-based component-level damage functions and replacement values (as fraction of industrial facility replacement value).

2.4 Assessment of BI Loss Potentials for Components and Facilities

The procedure discussed previously results in damage functions for assessing the PD losses. Assessment of BI losses is significantly more complex, especially for highly integrated facilities with multiple process chains, bottlenecks, and redundancies. The major contribution to BI loss is the loss of revenues incurred when product chains are not functioning either partially or completely. Disruption of product chains can occur for a variety of reasons:

- Partial or complete damage to one or more components on the product chain (for example, damage to a particular flare can result in the entire product chain being non-operational);
- An internally consumed by-product from a different product chain is unavailable because that chain has been adversely affected;
- One or more lifelines (e.g., steam, power, gas, nitrogen, transportation networks, electricity generation and supply, among others) feeding the product chain have been adversely affected (this can also include external lifelines, if pertinent data is available), or
- Transfer of finished products has been impeded by damage to storage, loading and/or transportation systems.

A reliable assessment of the BI loss requires that a detailed network model be built that accounts for the functional dependencies between all the components and lifelines comprising a product chain. Key input to this process is a relationship between the physical damage to a component or lifeline and the downtime[2] associated with the same. The authors have assembled information on various components and developed a database that provides estimates of the downtime of a component given the physical damage expectation for the same. Development of this database has relied on information gathered from facility operators at various industrial facilities and information in the public literature. This step also considers whether the damage to a component has occurred in "peace time" (i.e., at a general low level of damage to the facility and surrounding areas) or in "catastrophe time," wherein the facility and other facilities in the area have sustained severe damage and there may be a shortage of parts and labor for getting the component back into service thereby resulting in increased downtime. As with the physical damage relationships, there is variability associated with the downtime for a component given the physical damage, which needs to be explicitly incorporated in a probabilistic loss evaluation.

The process for developing facility-level downtime functions is as follows:

- The expected physical damage to the constituent components of the facility is generated for numerous simulations of the earthquake events. Note that, as shown in Figure 3 (right), different levels of damage are computed for the same component in the various simulations.
- Based on the physical damage estimated for each component for each of the simulations, the distribution of the downtime for each component is calculated.
- The network model is executed and the BI damage functions for the facility are derived under the assumption that a facility is not producing until all components in it have resumed normal operations. Hence, in each simulation used to derive the facility downtime function, the downtime value retained for the facility is equal to the largest downtime value of all the constituent components. Different variations of this process can be implemented depending on particular facility and product chain characteristics.

The process described above, in itself, does not capture the entire risk potential as additionally lifelines including third-party vendors may need to be considered. It is important to recognize that, especially in large industrial facilities, if the interaction between product chain components and lifelines is neglected, then the prediction of the downtime of the product chain and therefore of the BI losses may be systematically underestimated. This can only be addressed through a facility specific evaluation.

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[2] Business interruption is typically quantified in terms of downtime, or the time in days it would take for a component or network to return to full operability. A downtime function relates the intensity of physical damage sustained by a component or facility to the number of days it would take to return the component or plant or facility to pre-event conditions or full operability.

3. CASE STUDY APPLICATION

The methodology presented in this paper was applied to a large industrial facility, which similar to many other industrial facilities, is comprised of a variety of components. Figure 6 (left), shows the distribution of the replacement value for the facility's primary components. Although the value is distributed into many different types of components, the facility's mechanical equipment, at the dock and on-shore, represent the largest share, about 47%, of the total facility replacement value.

The on-site investigation of the plant, which was carried out alongside various members of the client's key engineering staff allowed detailed data acquisition of the physical characteristics of the components, their role in the facility processes, and a quantitative understanding of the actions which would be undertaken by the client in the event of damage to such components. The vulnerability of the primary components comprising the facility was determined from the database of component damage functions described in the preceding sections. The individual component damage functions were integrated into a custom facility-level damage function utilizing the particular plant value distribution which is illustrated in Figure 6 (right). Note that Figure 6 (right) shows the damage functions for six such facilities; the damage functions are quite different and evidence the ability of the methodology to discern differences in vulnerability amongst similar facilities.

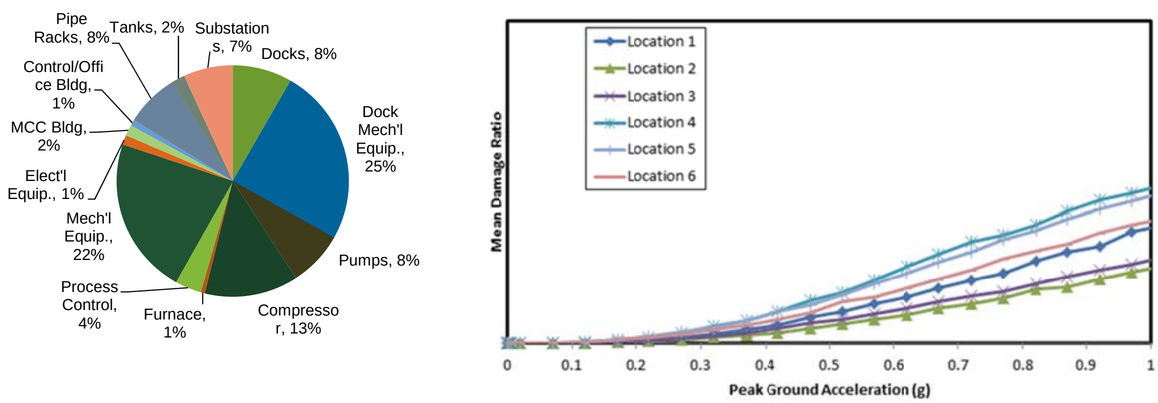

Figure 6. Facility value distribution (left); facility-level damage functions for six similar facilities (right).

The facility-level damage relationship was combined with a probabilistic site-specific hazard analysis to obtain a loss exceedance probability curve for the industrial facility (Figure 7, left). According to the figure, the 500-year loss (or equivalently, a loss with an exceedance probability of 0.2% which is approximately the design-level earthquake) corresponds to a mean damage ratio of 2.7%. Other risk metrics such as the Average Annual Loss (AAL) can also be determined. The AAL is shown disaggregated amongst the various component classes and indicates that the pipe racks, which constitute only 8% of the facility value, dominate the loss potential (at the AAL level) comprising about 42% of the AAL. This component-level loss potential allows for determining the appropriate components to focus on for physical risk mitigation.

Further, the determined component level physical damage is then related to the downtime for each component and plant, which is then convolved with the explicit network model generated for the facility (not presented in this paper for brevity) to determine the facility downtime for each of the seismic event simulations. For example the resulting downtime at the mean return period of 500-years was estimated to be 20 days.

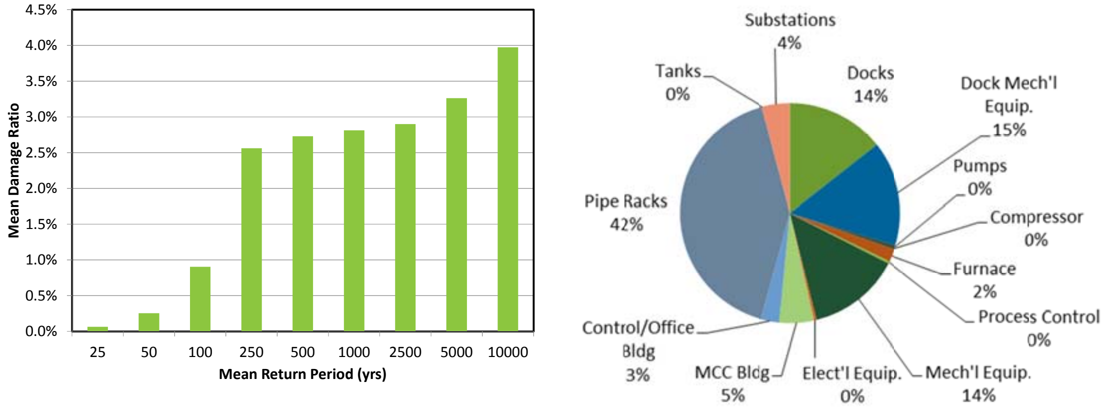

Figure 7. Probabilistic loss curve (left); disaggregation of AAL amongst primary component classes (right).

4. MITIGATION MEASURES

Identification of the primary risk drivers, in terms of the components, allows for development of physical risk mitigation options, which can be hypothetically integrated into the analysis to obtain a "mitigated" loss potential. As an example, Figure 8 presents the results for an industrial facility highlighting the reduction in the loss potentials upon implementation of two different risk mitigation options. Evaluation of the area under the mitigated versus non-mitigated curves provides a quantitative benefit, which can be evaluated against the cost of the mitigation option, thereby providing cost-benefit evaluations for all physical options being considered. This approach allows for informed decision making based on quantitative information.

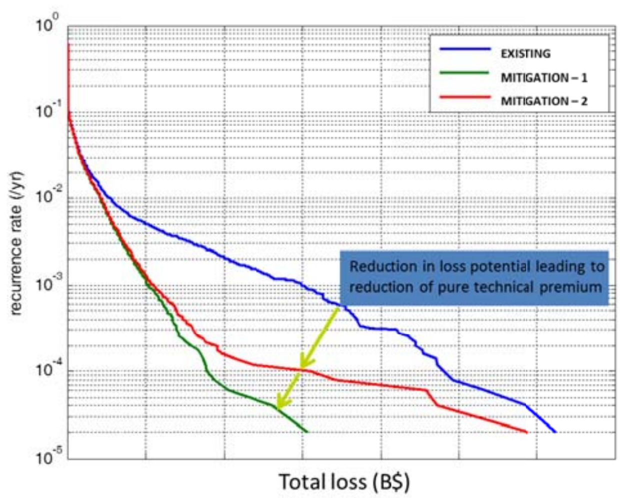

Figure 8. Probabilistic loss curves for a facility with and without implementation of mitigation options.

4. CONCLUSIONS

This paper describes a methodology that has been developed and successfully implemented to result in reliable quantification of the seismic risk for industrial facilities. The methodology computes the catastrophe risk to the individual components (such as process towers, tanks, flares, electrical and mechanical equipment, silos, chimneys, etc.) that comprise typical industrial facilities using detailed engineering analysis of representative components resulting in the development of vulnerability functions for the same. The relative value of the major component classes is then used to weigh the individual components' vulnerability to arrive at the overall industrial facility vulnerability. This approach results in a transparent and more reliable quantification of the catastrophe risk as it quantifies the risk at the component level, which is not only based on sound engineering, but can also be validated against the limited historical data more effectively. Furthermore, assessment of the risk at the component level allows for developing risk hierarchies that allow for development of focused mitigation options and cost-benefit evaluations amongst various mitigation options. Combining component level risk assessments with network modelling further allows for quantification of the business interruption risk associated with the process network.

The methodology not only yields itself to computing mean loss potentials, but can also be used to propagate the variability associated with the individual component vulnerability (in terms of physical damage and downtime) to obtain the uncertainty of the loss potential at the facility level. In summary, the methodology presented allows for reliable quantification of the catastrophe risk that can then be used for informed decision making for risk management purposes.

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