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# Indirect assessment of the earthquake vulnerability of a city's physical infrastructure

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## ABSTRACT

This paper introduces a new methodology that is being developed to compare the earthquake vulnerability of the physical infrastructure (e.g., buildings, bridges, pipelines) in different cities worldwide. This indirect approach identifies the characteristics of a city's historical development that generally lead to low vulnerability (e.g., early adoption of a seismic building code), and defines scalar indicators to represent them. Comparing the values of the indicators for two cities provides an indication of their relative physical infrastructure vulnerability. The indicators can be aggregated to obtain a scalar measure of a city's relative physical infrastructure vulnerability. This paper introduces this indirect approach, and compares it with the loss estimation modeling approach to infrastructure vulnerability assessment. The paper concludes with remarks about calibrating and validating the new methodology. Sample results for about 70 cities worldwide will be available at the time of the conference.

## INTRODUCTION

The Earthquake Disaster Risk Index (EDRI) is a composite index introduced to systematically and quantitatively compare greater metropolitan areas worldwide according to the magnitude and causes of their risk of earthquake disaster (Davidson 1997). The EDRI can serve as a public education tool to raise stakeholder awareness of earthquake risk, its causes, and strategies to manage it. The ability to make inter-city risk comparisons could help international aid organizations to allocate resources more effectively, and reinsurance companies to develop diversified portfolios, and to establish international consistency in their policies.

The physical infrastructure vulnerability is a critical component of the EDRI, because of its influence in determining the overall risk, and because it is one of the causal factors over which society has a relatively significant amount of control (as opposed to the hazard, for example). The most effective mitigation efforts undertaken to date are those aimed at reducing physical infrastructure vulnerability, e.g., seismic building code adoption and land use zoning. Because the available loss estimation approach to infrastructure vulnerability assessment is too data- and calculation-intensive for inter-city comparison, an indirect approach was developed and used in the EDRI. This paper introduces that method. The paper begins by clarifying the definition of a city's physical infrastructure vulnerability. The conceptual basis and application procedure of the indirect infrastructure vulnerability assessment approach are then discussed. After comparing the new method to the loss estimation modeling approach, the paper concludes with remarks about calibrating and validating the methodology.

## DEFINITION OF A CITY'S PHYSICAL INFRASTRUCTURE VULNERABILITY

A city's physical infrastructure comprises all components of the built physical environment, including, for example, buildings, bridges, and pipelines. A city's *physical infrastructure vulnerability* describes the ability of the infrastructure to withstand applied loads, or expressed differently, the expected damage given different levels of hazard. Note that while expected damage is a function of hazard, vulnerability is not. Vulnerability is an inherent characteristic of the infrastructure. It depends on the quality of design, materials, and construction, but not on the hazard to which the infrastructure is exposed. If the infrastructure were moved to another location, its vulnerability would not change (although the hazard, and therefore the expected damage, would). A city's physical infrastructure vulnerability includes the vulnerability of each building and bridge, and the vulnerability of each lifeline system as a whole.

## AN INDIRECT ASSESSMENT OF A CITY'S INFRASTRUCTURE VULNERABILITY

### Conceptual Basis

The indirect approach is based on the idea that, in a general sense, a city's physical infrastructure vulnerability depends on the circumstances of the city's development—when, where, how, how fast, and why structures have been built to

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serve society's needs, and how they have been maintained since their construction. Although every city is unique, and the process of urban development is complex, some general observations may be made about the relationship between a city's vulnerability and the history of its development. In the absence of good luck (i.e., traditional construction styles that are unintentionally earthquake-resistant), a city must have the motive, means, and opportunity to create an infrastructure with low vulnerability (Figure 1).

Motive refers to (1) an awareness of the earthquake risk at the time the infrastructure is built, and (2) a desire to address the problem, i.e., a perception that the risk is unacceptably severe in the context of the city's other problems. Means refers to adequate human and financial resources to reduce the vulnerability, i.e., the individuals, organizations, and money to develop, adopt, and enforce effective seismic codes. Opportunity refers to (1) good timing (i.e., the motive and means must exist at the time the infrastructure is constructed; and if construction is more recent, the effects of aging will be less significant), (2) ample physical space to accommodate the population growth so that the infrastructure is not too dense, there is room for lifeline redundancy, and the most hazardous areas (e.g., those with steep slopes or artificial fill) do not have to be occupied, and (3) ample time to construct the infrastructure in a quality-controlled way.

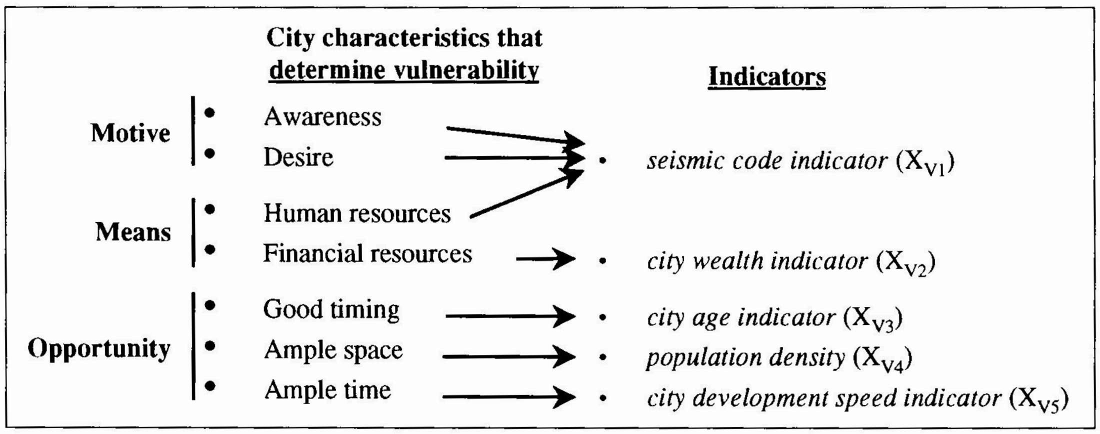


Figure 1. Relationship between city characteristics believed to determine a city's physical infrastructure vulnerability and indicators designed to represent them

In the indirect approach, a city's relative physical infrastructure vulnerability is estimated, therefore, by assessing the extent to which its historical development had the motive, means, and opportunity, relative to other cities. *Note that the following discussion aims only to introduce the concept of the indirect approach, and to suggest how it may be implemented. Future research will finalize the form of the mathematical model and its parameter values.*

Measurement Procedure

To apply the indirect approach, a few simple, scalar, measurable indicators are defined to represent each of the city development characteristics identified in the previous section. The indicators are then scaled to be commensurable, and aggregated to produce an assessment of a city's relative physical infrastructure vulnerability. The model used to aggregate the indicators may be additive, multiplicative, or multilinear. Davidson (1998) explains alternative methods for scaling and weighting indicators in an additive model, and the implications of using one method or another. Keeney and Raiffa (1993) and von Winterfeldt and Edwards (1986) discuss the multiplicative and multilinear models. *Note that these models all produce relative measures of vulnerability only.* The scaling method used will dictate which benchmark(s) the measure is relative to (e.g., a reference city, some minimum and maximum values, or the average of a sample of cities) (Davidson 1998). The current form of the EDRI uses an additive, or linear combination, model to combine the indicators.

While no indicators can be proven to be *the* correct ones, for the EDRI project, indicators were selected so as to meet the following criteria as well as possible: validity, data availability and quality, quantitativeness and objectivity, understandability, and directness (Davidson 1997). Five indicators were defined to represent the characteristics of a city's development that generally influence the infrastructure vulnerability (Figure 1). They are discussed in turn below. Note that although the infrastructure is the real quantity of interest, since population data are more easily available, all five indicators use population data instead of physical infrastructure data, relying on the assumption that infrastructure construction coincides with population growth.

The *seismic code indicator* ($X_{V1}$) assesses the degree to which a city had the awareness, desire, and human resources necessary to develop, adopt, and enforce effective seismic codes at the time the infrastructure was built. The seismic code indicator can be calculated by following a five-step process. First, identify the benchmark years in which significant changes in the quality of the city's seismic code took place. Second, assess the sophistication of the seismic code during each inter-benchmark period using the Sophistication Rating Scale (Table 1). Third, determine the percentage of the current city population that arrived in each inter-benchmark period. Fourth, rate the quality of code enforcement in the city using the Enforcement Rating Scale (Table 2). Fifth, evaluate the seismic code indicator using Eq. 1:

$$X_{V1} = e * \left[ \sum_{k=1}^{nbp} s_k p_k \right], \quad (1)$$

where e is the enforcement rating, nbp is the number of inter-benchmark periods, $s_k$ is the sophistication rating for inter-benchmark period k, and $p_k$ is the percentage of the current population that arrived in inter-benchmark period k (i.e., $p_k = (Pop_{by,i} - Pop_{by,i-1}) / Pop_{current\ yr.}$). The summation is essentially a weighted average of the sophistication of the seismic code during each inter-benchmark period, where the weights are the percentages of the current infrastructure built (or population arrived) during that period.

Table 1. Seismic code sophistication rating scale

| **Sophistication rating $s_k$** | **Category description** |
|---|---|
| 0.1 | No regulations. |
| 0.3 | Only requirement is to limit the base shear to an arbitrary constant percentage of building weight. Not based on theory. |
| 0.5 | Includes a base shear equation with coefficients to account for some, but not all of the following: soil type, building period, seismic zone, importance of the structure, and ductility of the structural type. |
| 0.8 | Includes some, but not all of the basic components* of a seismic code. |
| 0.9 | Includes all of the basic components of a seismic code. |
| 1.0 | Refined version of a seismic code with all the basic components. |

* Basic components include: (1) provisions for static and dynamic design methods; (2) an equation to calculate the base shear; (3) coefficients in the base shear equation to account for soil type, building period, seismic zone, structure's importance, ductility of the structural type; (4) a method to distribute forces along the structure's height; (5) provisions to address torsion; (6) provisions to address irregularities in plan or elevation; (7) method to address inter-story and total drift; (8) special provisions for essential facilities; and (9) provisions for detailing.

Table 2. Building code enforcement rating scale

| **Enforcement rating e** | **Category description** |
|---|---|
| 0.2 | Poor. Less than 50% of structures built at least to the standards of the code. |
| 0.4 | Below average. About 50%-60% of structures built at least to the standards of the code. |
| 0.6 | Average. About 60%-80% of structures built at least to the standards of the code. |
| 0.8 | Above average. About 80%-90% of structures built at least to the standards of the code. |
| 1.0 | Excellent. At least 90% of structures are built at least to the standards of the code. |

*Structures may not be built to code because of incompetence, lack of resources, or corruption in design or construction. Specifically, inadequate inspection and construction of squatter settlements may indicate poor enforcement.

The *city wealth indicator* ($X_{V2}$) conveys whether adequate financial resources were available to fund high quality design and construction during the city's development. The city wealth indicator equals the average gross domestic investment (GDI) per capita per year in constant 1987 US dollars. Since there is no exact year in which a city begins, and data would not be available for so long ago anyway, a historical time period had to be established over which the average could be taken. Using the time period from the present back to the year in which the city had 50% of its current population ($t_{50}$) makes the number of years averaged different for each city, but the percentage of the total existing infrastructure built with that GDI consistent among cities.

The *city age indicator* ($X_{V3}$) represents the extent to which the effects of aging have increased the vulnerability of the physical infrastructure. It is defined as a weighted average of the age of the population (Eq. 2), where $p_t$ is the percentage of the current population that arrived in year t (i.e., $p_t = (Pop_t - Pop_{(t-1)}) / Pop_{current\ yr.}$), $a_t$ is the age of the population that arrived in year t (i.e., $a_t$ = current year - t), and the summation is over all the years from the year in which the population was 50% of its current level ($t_{50}$) to the current year:

$$X_{V3} = \sum_{t=(t_{50}+1)}^{\text{current year}} p_t a_t \,, \tag{2}$$

The *population density indicator* ($X_{V4}$) represents the extent to which a city had adequate space to develop. Population density is defined as the weighted average of the densities of the counties (or smaller cities, neighborhoods, or other administrative units) that make up the greater metropolitan area, where the weights are the populations of those counties (Eq. 3). In Eq. 3, the variables $d_i$ and $p_i$ are the density and population of county i, respectively, and the summation is over all counties i that comprise the greater metropolitan area. The weighted average provides a more accurate representation of the city's density than a simple ratio of total population divided by total land area, because some greater metropolitan areas are defined to include large, sparsely populated surrounding areas that would make the densities of those cities appear misleadingly low.

$$X_{V4} = \sum_{i=1}^{n}(d_i p_i) \Big/ \sum_{i=1}^{n} p_i \,, \tag{3}$$

In many rapidly expanding cities, the population growth is occurring so quickly that a quality, low vulnerability infrastructure cannot be developed fast enough to support the new residents. The *city development speed indicator* ($X_{V5}$) conveys whether or not the city has been developed with ample time to construct the infrastructure in a quality-controlled way. It is defined as the number of years that have passed since the city population was 50% of its current level (i.e., $X_{V5}$ = current year - $t_{50}$).

Comparing the values of the five indicators ($X_{V1}$ to $X_{V5}$) for one city with the values for another provides an indication of the cities' relative physical infrastructure vulnerability. As discussed earlier, the indicator values can be combined using an additive, multiplicative, or multilinear model to get a scalar measure of a city's relative physical infrastructure vulnerability.

Limitations

The indirect approach has a few key limitations. First, the approach is difficult to calibrate and validate (see Calibration section). More work is needed to confirm the best form of the model, and the best parameter (e.g., weight) values. Second, because it makes a scalar assessment of vulnerability, the indirect approach implicitly assumes that the *relative* vulnerability of two cities' infrastructure is the same for all hazard levels. It does not allow for the possibility that, given a low hazard level, City A would experience more damage than City B, but given a high hazard level, the reverse might be true. The indirect approach simply asks, given a specified level of hazard, which city will experience more damage? Third, the indirect approach cannot be used to assess the vulnerability of a single structure. Fourth, like most indirect measures, it holds only in the general case. Surely there will be instances in which other urban development processes interfere to create outcomes entirely different from those predicted by this method. Finally, maintenance, previous damage, and retrofitting can affect the vulnerability of the physical infrastructure, but they are not included because there are no acceptable indicators available to represent them, and at a city level, they are probably insignificant relative to the other determinants. Vulnerability to nonstructural and content damage are not represented, because there is little data or theory to suggest how these ideas could be included, or if they would vary significantly from city to city.

## COMPARISON OF INDIRECT AND LOSS ESTIMATION MODELING APPROACHES

Since most readers will be familiar with the loss estimation modeling approach to physical infrastructure vulnerability assessment, this section compares the two methods directly to show that they use fundamentally different approaches to satisfy their distinct objectives. While the indirect method only needs to be detailed enough to compare, for example, the physical vulnerability of San Francisco to that of Jakarta, loss estimation's intended uses demand higher resolution and greater precision. After the loss estimation approach is reviewed briefly, the principal differences are highlighted. Table 3 summarizes the comparison.

In assessing structural vulnerability, loss estimation modeling divides the entire stock of infrastructure into components that exhibit similar levels of earthquake resistance (e.g., braced steel frame buildings, low-rise unreinforced masonry buildings), and assesses the vulnerability of a model example of each component. It is assumed that every structure of a given component type would exhibit the same vulnerability as the model. Vulnerability is expressed as the set of probabilities $P(D_i \mid H_j)$, for all possible damage levels, $D_i$, and hazard levels, $H_j$. Damage levels may be defined in terms of a damage ratio or a qualitatively defined damage state; hazard levels in terms of ground shaking intensity, peak values (e.g., PGA, PGD), or spectral parameters. Specifically, vulnerability is portrayed using a set of fragility curves, a damage curve, or a damage probability matrix. For a particular structural type, the curve(s) or matrix is determined using empirical damage data and an understanding of structural engineering principles.

Table 3. Comparison of two approaches to physical infrastructure vulnerability assessment

| Loss estimation approach | Indirect approach |
|---|---|
| Assess each structure individually | Assess entire city at once |
| Direct | Indirect |
| Based on empirical data, engineering judgment | Based on urban development process |
| Absolute measure | Relative measure |
| Expresses vulnerability as expected damage<br>Given different hazard levels (curve(s), matrix) | Expresses vulnerability as infrastructure's qualitative ability to resist applied loads (scalar) |
| Combine with hazard before aggregation | Aggregate before combining with hazard |
| Data- and labor-intensive | Modest data and calculation requirements |

The loss estimation approach examines each structure individually as it exists, without regard for how it came to exhibit or not exhibit earthquake resistant properties. It is a direct, micro technique that produces a vulnerability assessment on an absolute scale. The indirect approach addresses the city as a whole, and bases its assessment on the characteristics of the urban development process that generally lead to lower vulnerability. It is an indirect, macro technique that offers a relative measure of vulnerability only. Using the loss estimation approach to assess a city's risk requires (1) assessing the vulnerability of each structure in the city, (2) combining that with the hazard at the site to assess the risk of each structure, and (3) aggregating the risk of each structure located in the city to determine the city's overall risk. The indirect approach uses a different aggregation process (Figure 2). It (1) assesses the vulnerability of the entire city, then (2) combines that with a hazard assessment for the entire city to produce a final assessment of the city's risk.

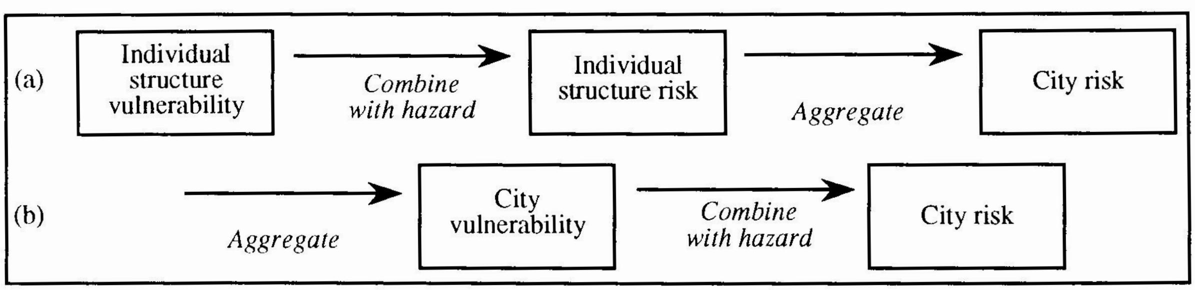


Figure 2. Aggregation process comparison for (a) loss estimation and (b) indirect approaches

## CALIBRATION AND VALIDATION

Calibrating and validating the indirect vulnerability assessment model requires comparing the results of the indirect vulnerability assessment to similar results calculated using another vulnerability assessment technique, e.g., the loss estimation modeling approach or an empirically-based method. Comparison with the loss estimation modeling approach poses two main challenges. First, since loss estimation assesses vulnerability in terms of a curve or set of curves, a scalar quantity must be derived from that curve(s) so that it can be compared with the indirect method's scalar value. Alternatively, the indirect method must be modified so that it is assesses vulnerability as a curve of the form (EDRI | Hazard). Second, an adjustment must be made to deal with the difference in aggregation processes. One possibility is to combine the loss estimation modeling damage curves into a composite damage curve for each city. Each curve would be a weighted average of the damage curves for the individual infrastructure components, with the weights equal to the proportion of the total infrastructure in the region that is composed of the corresponding type of infrastructure component. The composite damage curve would represent an assessment of city-level vulnerability that could be compared to the indirect approach's assessment of city-level vulnerability. Another option is to compare the final city risk instead of the city vulnerability. In that case, all other elements of the analysis (e.g., the hazard and exposure assessments) would have to be consistent between methods so that any difference in final risk assessments could be attributed to the difference in vulnerability assessment.

A strictly empirically-based approach would compile for each city the level of hazard and degree of damage it experienced in past earthquakes. The probability of a damage state given each hazard level would be computed and compiled directly into city-level, composite damage curves. The major difficulty with this approach is that there are not enough data to calculate the probabilities precisely. The problem of inadequate empirical data is especially acute when assessing the vulnerability of *cities* instead of *infrastructure components*. Furthermore, while this approach would circumvent the aggregation process issue, it would still result in a vulnerability assessment that is a curve, from which a scalar would have to be derived.

## CONCLUSION AND FUTURE WORK

This paper presents a new, indirect approach for systematically and quantitatively comparing the vulnerability of the physical infrastructure of cities. While more research is required to calibrate the model, the approach potentially could offer a way to assess infrastructure vulnerability that is more appropriate for inter-city comparison than the available loss estimation approach. As part of the United Nations IDNDR Secretariat's "Understanding Urban Seismic Risk Around the World" (UUSRAW) project, currently underway to evaluate the EDRI of more than 70 cities worldwide, local city representatives are gathering the information necessary to calculate the five indicators described herein ($X_{V1}$ to $X_{V5}$). The UUSRAW data set will be useful in the future work that is planned to improve calibration and validation of this method. Example results of the indirect vulnerability assessment approach for the 70 cities in the UUSRAW project will be available at the conference.

## REFERENCES


Davidson, R. A. 1997. "An Urban Earthquake Disaster Risk Index." The John A. Blume Earthquake Engineering Center Report No: 121, Blume Center, Stanford, CA.

Davidson, R. A. 1998. "Comparative measurement with an additive composite index: Mathematical theory and construction issues." In preparation.

Keeney, R., and Raiffa, H. 1993. *Decisions with multiple objectives: Preferences and value tradeoffs*, Cambridge University Press, Cambridge, UK.

Von Winterfeldt, D., and Edwards, W. 1986. *Decision analysis and behavioral research*, Cambridge University Press, Cambridge, UK.