# SEISMIC RISK ASSESSMENT:
# WITH AN APPLICATION TO THE SOUTH AFRICAN INSURANCE INDUSTRY

## By N Davies and A Kijko

ABSTRACT

This study provides a seismic risk assessment for various sites in South Africa and discusses the possible impact of seismic activity on the South African insurance industry in the light of this analysis. The work begins with an introduction and an historical perspective on the estimation of seismic damage to buildings. The methodology for the estimation of expected damage from a probabilistic point of view is presented. The work continues with an application of the described methodology to several sites around the country. The result of the investigation is that the seismic risk faced by South Africa is non-negligible.

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## 1.    INTRODUCTION AND PROBLEM FORMULATION

1.1    'Seismic hazard' is the probability of occurrence, within a specified period, of a seismic event that could damage buildings or objects.

1.2    Seismic risk estimation involves the assessment of the adverse consequences that a society may be subjected to as a result of future earthquakes, as well as the estimation of the probability of these consequences. Current earthquake damage or loss studies fall into two main categories: deterministic and probabilistic.

1.3    The typical deterministic approach starts from a hypothetical, user-chosen earthquake, known as the worst-case-scenario earthquake or the maximum credible earthquake. (Alternatively, a what-if scenario, based on a predetermined return period between occurrences, could be used.) Based on this scenario, the expected ground motion is calculated. Finally, the expected damages or losses arising from these ground motions are calculated. This approach is often used in the insurance industry and for the purpose of this paper will be referred to as the probable-maximum-loss (PML) calculation. Clearly, the procedure can be useful when a clear strategy is required to cope with potential catastrophic losses. The strongest point of the scenario earthquake approach and

procedure lies in the fact that it provides a means for the consideration of an extraordinary earthquake and a consequently unusual set of damages or losses.

1.4     It should be noted that a strict division of seismic risk models into deterministic and probabilistic categories might be superficial. Often the deterministic risk models contain random variables or various probabilistic elements. Early techniques used in earthquake risk insurance employed such models, which included a significant number of statistical elements in order to estimate, for example, the 90th percentile of a loss from a maximum credible earthquake. Although these estimates are deterministic (being based on an arbitrary, set-scenario earthquake), they make use of statistical tools in providing a distribution of damage.

1.5     Most of the earthquake risk assessment models currently in use tend to be probabilistic in that they provide assessments of the probability distributions of losses based on a sample of scenarios that is considered most appropriate in the light of current knowledge. (Kunreuther & Roth, 1998)

1.6     If, in addition to the damage distributions, we can associate a certain probability with the scenario earthquake, and all other possible scenario earthquakes, we will have a full probabilistic seismic risk analysis (PSRA). A PSRA evaluates the probabilities for all degrees of damage arising from seismic events, including the event considered in the PML procedure.

1.7     The deterministic and probabilistic seismic risk analysis are complementary and provide a total picture of the earthquake threat that neither of the individual procedures is capable of giving alone.

1.8     The history of efforts to model risk from natural hazards, especially from seismic hazard, and the history, if any, of the application of these models to earthquake insurance business, is sparse. The first comprehensive study of structural damage under induced forces such as that caused by an earthquake, was probably Freeman (1932). Further development in the estimation of losses has often been performed by, or on request of, the insurance industry. In this development an especially important role was played by the Insurance Service Office of the United States (Steinbrugge, 1982).

1.9     Probably the first systematic and comprehensive estimates of the effects of major earthquakes in large urban areas of the United States began with Algermissen *et al* (1972). The study includes estimates of direct economic losses, casualties, functionality of essential facilities and impact on lifelines such as electricity cables, roads and highways, and telephone cables.

1.10    At the same time, after the 1971 San Fernando earthquake, the programme Seismic Design Decision Analysis began at the Massachusetts Institute of Technology

under the directorship of Professor Robert Whitman. One of the most significant outputs of the programme was the development of the new practice of connecting the ground motion parameters with damage and losses, by means of the damage probability matrix (DPM) (Whitman *et al*, 1973). A typical DPM is shown in Table 1. The extent of damage, from none to total, is divided into damage states, each of which is described both in words and by a range of damage factors, where 'damage factor' denotes the ratio of the value of physical damage or rand loss due to the earthquake to the replacement value (ATC-13, 1985). In this study we shall call it simply 'damage' and express it as a percentage.

1.11     The strength of a seismic event at a given site can be measured in terms of the Modified Mercalli (MM) intensity scale, a subjective scale based on resultant structural damage to buildings (see Appendix B). Intensity will always be understood to be the mean value of MM intensity. In the typical DPM shown in Table 1, for each MM intensity of ground shaking, the numbers in the corresponding column give the fractions of buildings experiencing different damage states. Note that the values in each column sum to 100%.

TABLE 1. A typical damage probability matrix
(Source: Panel on Earthquake Loss Estimation Methodology, 1989: 82)

| Damage state | Damage factor range (per cent) | Central damage factor (per cent) | Probability of damage (per cent) by MM intensity and damage state | | | | |
|---|---|---|---|---|---|---|---|
| | | | VI | VII | VIII | IX | X |
| 1 | 0 | 0,0 | 95,0 | 49,0 | 30 | 14 | 3 |
| 2 | 0–1 | 0,5 | 3,0 | 38,0 | 40 | 30 | 10 |
| 3 | 1–10 | 5,0 | 1,5 | 8,0 | 16 | 24 | 30 |
| 4 | 10–30 | 20,0 | 0,4 | 2,0 | 8 | 16 | 26 |
| 5 | 30–60 | 45,0 | 0,1 | 1,5 | 3 | 10 | 18 |
| 6 | 60–100 | 80,0 | – | 1,0 | 2 | 4 | 10 |
| 7 | 100 | 100,0 | – | 0,5 | 1 | 2 | 3 |

1 – none: no damage
2 – slight: limited localised minor damage not requiring repair
3 – light: significant localised damage of some components generally not requiring repair
4 – moderate: significant localised damage of many components warranting repair
5 – heavy: extensive damage requiring major repairs
6 – major: major widespread damage that may result in the facility being razed
7 – destroyed: total destruction of the majority of the facility

1.12     Before the concept of the DPM was developed, the most common procedure for quantifying the ground-motion–damage relationship was to use the so-called loss ratio curve (Steinbrugge *et al*, 1984). Such a curve, known also as percent-loss or mean-

damage-factor curve, describes the cost of damage expressed as a percentage of replacement value. This is a mean value for a large population of buildings of a given class. Such ground-motion–damage relationships are needed for each type of facility. In most cases the ground motion is characterised by MM intensity.

1.13     However, it is often insufficient to know only the mean level of damage. Losses and damages experienced as a result of an event with a particular intensity are widely distributed between insignificant or very little damage, and substantial damage. In particular, serious casualties and injuries are usually related to extreme damage experienced by a minority of buildings. Replacement of the mean-damage-ratio curves by the DPMs provides not only the mean value of damage, but also the damage distribution. Both can be estimated for specified values of MM intensity.

1.14     The seismic risk study that was probably the most important and influential was done by the Applied Technology Council in 1985 (ATC-13, 1985). This report, which used the DPM as its central framework, provided estimates of physical damage per cent versus seven levels of MM intensity ground motion for 78 facility classes, including 36 building structure classes. It also introduced several other new tools, which soon became standard in the assessment of seismic risk in the United States and other countries. For example, the recently published assessments of the potential earthquake damage and losses for Salt Lake City County, Utah, (Rojahn *et al*, 1997), and Portland Oregon, (McCormack & Rad, 1997), are conceptually based on the methodology described in ATC-13 (*op. cit.*). A procedure very similar to the ATC-13 approach is currently used in China (Chen *et al*, 1997; Yong *et al*, 1998), Russia and the former Soviet Union (Shojgu *et al*, 1992), New Zealand (Dowrick and Rhoades, 1990; 1993), Italy (Bramerini *et al*, 1995; Orsini, 1999) and Portugal (D'Ayala *et al*, 1997).

1.15     Comprehensive reviews and assessments of earthquake loss-estimation methodologies developed and used in the USA up to the eighties have been compiled by Reitherman (1985) and Whitman (1986). Analogous work has been performed in the former Soviet Union and was applied in the assessment of earthquake losses for the largest cities of the world (Keilis-Borok *et al*, 1984). More recently an excellent review of the state of the art of earthquake loss estimation methodologies, including the HAZUS methodology, has been conducted by the National Institute of Building Sciences under the Federal Emergency Management Agency (FEMA, 1994). The review, which covers all aspects of the problem of earthquake loss estimation, is probably the most comprehensive ever written on this subject. One of the purposes of the document is to stimulate the development of a universally applicable, standardised methodology for the estimation of potential earthquake losses.

1.16     It must be noted that alternative approaches to that of the DPMs are also possible. For example, an approach based on formalism of Markov chains is proposed by Thiel and Zsutty (1987). In their approach, Markov chains are used to relate the probability of

occurrence of five discrete damage states for a specific building type during an earthquake. Also, Sánchez-Silva & García (2001) presented a methodology for damage assessment of structures that combines systems theory, fuzzy logic and neural networks. In their methodology, a feed-forward neural network, supported by the systematic collection of relevant damage information, is used to assess the future structural damage for a given earthquake.

1.17    What follows in this paper is a broadening and advancement of the theory discussed above, together with the methodology of quantitatively linking the concepts of seismic hazard and seismic risk. This link provides a new tool for the assessment of seismic risk, which is applied to the South African insurance industry. The paper closes with a discussion of the impact of mining activities in and around Johannesburg on the seismic risk to which the area is exposed.

## 2.    PROBABILISTIC SEISMIC RISK ANALYSIS: THEORETICAL BACKGROUND

### 2.1    GENERAL FORMULA

2.1.1    A PSRA begins with a probabilistic seismic hazard analysis (PSHA). A PSHA evaluates the seismic hazard (i.e. the probability of occurrence, within a specified period of time, of a seismic event that could damage buildings or objects, as defined in ¶1.1). By default, PSHA includes the single seismic event considered in the PML procedure. The results of the PSHA are then used to estimate seismic risk by translating probabilistic estimates of ground motion into damage via ground-motion–damage relationships. Since the induced motion of the ground is vibratory, the acceleration, the ground-motion parameter responsible for damage, will vary with time as the energy radiated by the seismic event arrives at the site. The maximum value of the acceleration recorded at a particular site during the event is termed the peak ground acceleration (PGA). The PGA, $a$, experienced at a particular site can be described by the attenuation equation (Boore & Joyner, 1982; Ambraseys, 1995):

$$\ln(a) = c_1 + c_2 M + c_3 R + c_4 \ln(R) + \varepsilon \; ; \tag{1}$$

where $c_1$, $c_2$, $c_3$ and $c_4$ are empirical constants, $M$ is the earthquake Richter magnitude[1], $R$ is the earthquake distance and $\ln(\bullet)$ the natural logarithm. The term $\varepsilon$ is a random error, which has been observed to have a normal (Gaussian) distribution. Since there is no simple and direct relationship between PGA and seismic risk, the approach that will be adopted is one that links seismic risk (i.e. expected characteristics of damage) with PGA via MM intensity.

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1    Richter magnitude measures of the size of an earthquake related to the total strain energy released at the hypocentre of the seismic event, while MM intensity and PGA measure the effects of the event at a specific site.

2.1.2     In the following we assume that, for a specific site, seismic hazard $H(a;T)$ is provided in the form of the probability that a certain level of ground shaking, characterised by PGA $a$, will be exceeded (i.e. the probability of 'exceedance' of $a$) at least once within the specified time interval $T$. By definition, seismic hazard is:

$$H(a;T) = 1 - F_A^{max}(a;T);$$

where $F_A^{max}(a;T)$ denotes the cumulative distribution function of the largest PGA expected to occur during a specified time interval $T$. Figure 1 shows the annual (i.e. $T = 1$ year) seismic hazard curve for a site in the vicinity of Tulbagh, a village located about 90 km northeast of Cape Town, where the largest observed seismic event in South Africa (Richter magnitude 6.7) was recorded.

FIGURE 1. Annual probability of exceedance of a given PGA for a site
in the vicinity of Tulbagh (Source: Kijko *et al*, forthcoming a)
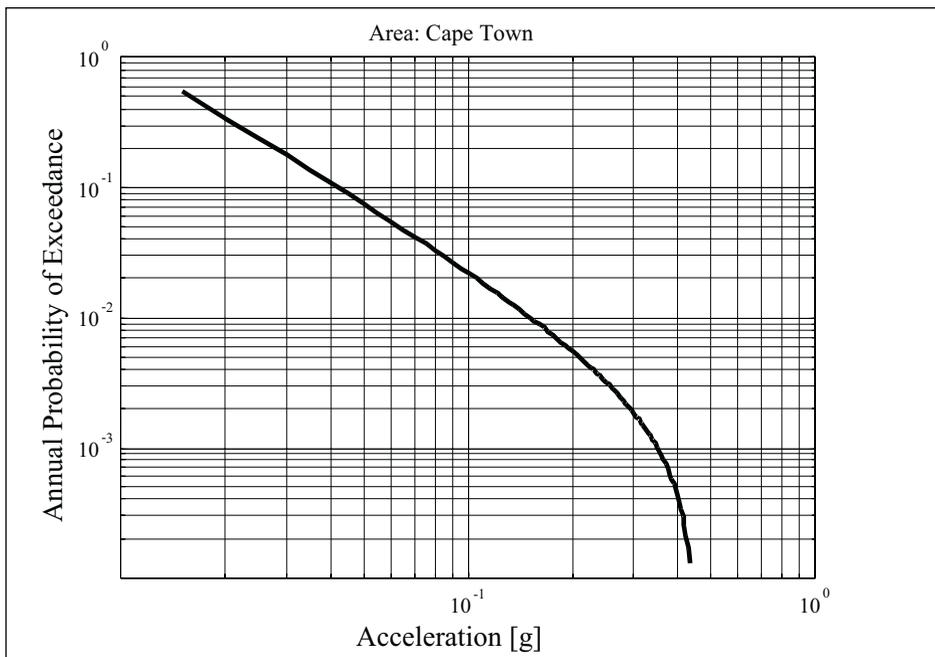


2.1.3     The earthquake damages can be expressed in a variety of ways. To avoid potential confusion about the terminology used in this study, the authors have tried to follow the conventions used in ATC-13 (*op. cit.*) and by the insurance industry as closely as possible.

2.1.4     For a building within a specific region, the main question of interest is: what is the expected damage to the structure resulting from an earthquake during a

specified time interval $T$? For a time interval of one year, such damage is often called the 'normal expected damage' or 'normal expected loss'. In this study we shall call it the 'expected annual damage' (EAD).

2.1.5    From a mathematical point of view, there are strong similarities between the procedures of the PSRA and the PSHA (McGuire, 1993). In both cases, the respective relationships are not deterministic and they must be expressed in terms of conditional probability density functions.

2.1.6    The problem of estimating structural damage arising from a seismic event can be formulated as follows (Cornell, 1989; Panel on Earthquake Loss Estimation Methodology, 1989; Cao *et al*, 1999). Let $p_D(d;T)$ denote the probability of exceedance of a certain level of damage $d$, at least once within the specified time interval $T$. Following the total probability theorem (e.g. Walpole and Myers, 1985), the probability $p_D(d|T)$ can be expressed as (Kijko *et al*, forthcoming b):

$$p_D(d;T) = \int_{d}^{d_{max}} \int_{i_{min}}^{i_{max}} \int_{a_{min}}^{a_{max}} f_D(\tilde{d}\,|\,i) f_I(i\,|\,a) f_A^{max}(a;T)\,\mathrm{d}a\,\mathrm{d}i\,\mathrm{d}\tilde{d}\,; \qquad (2)$$

where $f_I(i|a)$ and $f_D(d|i)$ denote the conditional probability density functions (PDFs) respectively for the MM intensity $I$, given PGA, $a$, and damage $D$, given the intensity $I$. By its definition,

$$f_A^{max}(a;T) = \frac{d}{da}\left[F_A^{max}(a;T)\right]\,;$$

and can thus be obtained from the seismic hazard function; i.e.:

$$f_A^{max}(a;T) = -\frac{d}{da}\left[H(a;T)\right].$$

The innermost integration is over the PGA, $a$, for the chosen time period $T$ where $a_{min}$ is the minimum value of PGA of engineering interest[2] (e.g. 0,05 g), and $a_{max}$ is the maximum possible PGA at the site. Associated with each value of ground acceleration is the distribution of MM intensity, $f_I(i|a)$, and therefore the second innermost integration from $i_{min}$ to $i_{max}$ is over the MM intensity, where $i_{min}$ is the minimum value of intensity which is capable of generating damage (say $i$ = IV) and $i_{max}$ is the maximum possible intensity, ($i$ = XII). Since relations between PGA and damage are not as commonly known or used as the relations between MM intensity and damage, use is made of conditional PDFs $f_I(i|a)$ and $f_D(d|i)$. The outermost integration from $d$ to $d_{max}$ is over the damage where the maximum value of damage, $d_{max}$, is 100%, and corresponds to complete destruction.

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2   The value of PGA of engineering interest is the value of PGA above which damage to infrastructure is likely to result, and is generally around 0,05g, where g represents the acceleration due to gravity. When designing and building structures, engineers are interested in the probability that their structures will be damaged by seismic activity and at what value of PGA damage will occur.

2.1.7    From equation (2), the 'general formula' describing the expected damage to the structure under forces such as those induced by seismic activity, within a specified time interval $T$, can be expressed as:

$$E[D(T)] = \int_0^{d_{max}} \int_{i_{min}}^{i_{max}} \int_{a_{min}}^{a_{max}} d\, f_D(d\,|\,i) f_I(i\,|\,a) f_A^{max}(a;T)\,\mathrm{d}a\,\mathrm{d}i\,\mathrm{d}d \; ; \tag{3}$$

where $E[\bullet]$ denotes the operator of expectancy. The value of expected damage for $T = 1$ year, the EAD (as mentioned earlier), is of special interest to the insurance industry.

2.1.8    From equations (2) and (3) it is clear that, in order to estimate the distribution and the expected value of damage to the structure under seismically induced forces, the conditional distributions $f_I(i|a)$, $f_D(d|i)$ and the PDF of seismic hazard, $f_A^{max}(a;T)$, must be specified.

## 2.2    APPLICATION OF DAMAGE PROBABILITY MATRICES AND SPECIFICATION OF THE PROBABILITY DENSITY DISTRIBUTIONS $F_D(D|I)$, $F_I(I|A)$, AND $f_A^{max}(a;T)$.

2.2.1    First let us show how the DPM can be used in the assessment of the probability of exceedance of a specified value of damage (equation 2), and in the assessment of the value of the expected damage (equation 3).

2.2.2    By definition of the operator of expectancy $E[\cdot]$, equation (3) can be rewritten in the form:

$$E[D(T)] = \int_{i_{min}}^{i_{max}} \int_{a_{min}}^{a_{max}} E[D\,|\,i] f_I(i\,|\,a) f_A^{max}(a;T)\,\mathrm{d}a\,\mathrm{d}i \; ; \tag{4}$$

where the function $E[D|i]$ is:

$$E[D\,|\,i] = \int_0^{d_{max}} d\, f_D(d\,|\,i)\,\mathrm{d}d. \tag{5}$$

2.2.3    The function $E[D|i]$ denotes the 'mean damage factor' for a given MM intensity $i$. When the function $E[D|i]$ is plotted against the intensity $i$, the plot is called the 'vulnerability curve'. In this study use is made of the vulnerability curves provided by ATC-13 (*op. cit.*), in which the conditional PDFs $f_D(d|i)$ are given in the form of the DPM, $DPM_{ij}$ (Table 1), for seven damage states $j$ ($j = 1,\ldots,7$) and seven MM intensity levels $i$ ($i = VI,\ldots,XII$). In ATC-13 (*op. cit.*), for each damage state there are associated what are called the 'central damage factors' (CDF), defined as: 'no damage', ($CDF_1 = 0\%$); 'slight damage', ($CDF_2 = 0{,}5\%$); 'light damage', ($CDF_3 = 5\%$); 'moderate damage', ($CDF_4 = 20\%$); 'heavy damage', ($CDF_5 = 45\%$); 'major damage', ($CDF_6 = 80\%$) and 'total destruction', ($CDF_7 = 100\%$).

2.2.4    The vulnerability curve for a specified kind of structure can thus be calculated from equation (5), where integration is replaced by simple summation:

$$E[D\,|\,i] = \sum_{j=1}^{7} CDF_j\, DPM_{ij}. \tag{6}$$

FIGURE 2. Vulnerability curve for low-rise (1-3 storeys) facilities with load-bearing walls of unreinforced masonry
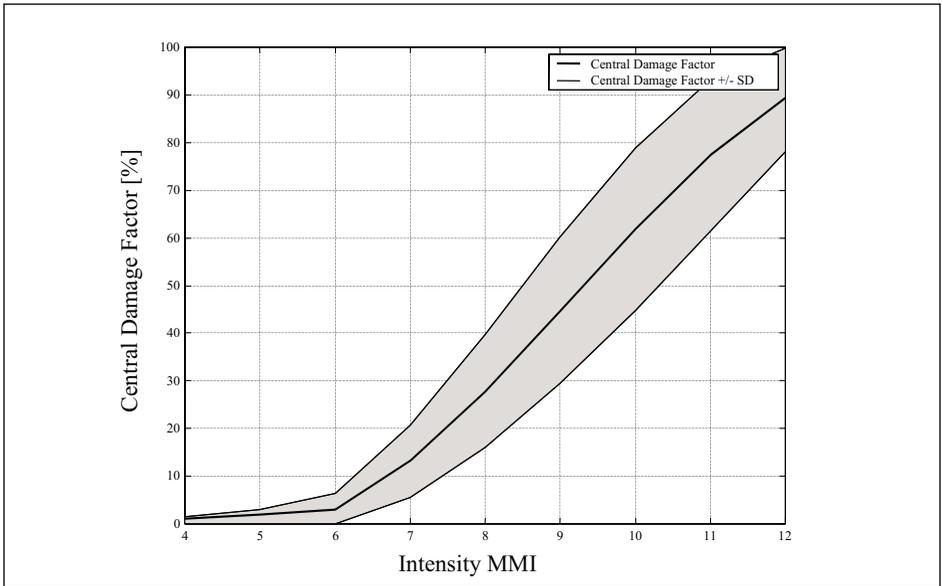


FIGURE 3. Vulnerability curve for medium rise facilities with reinforced concrete shear walls and moment-resisting frames
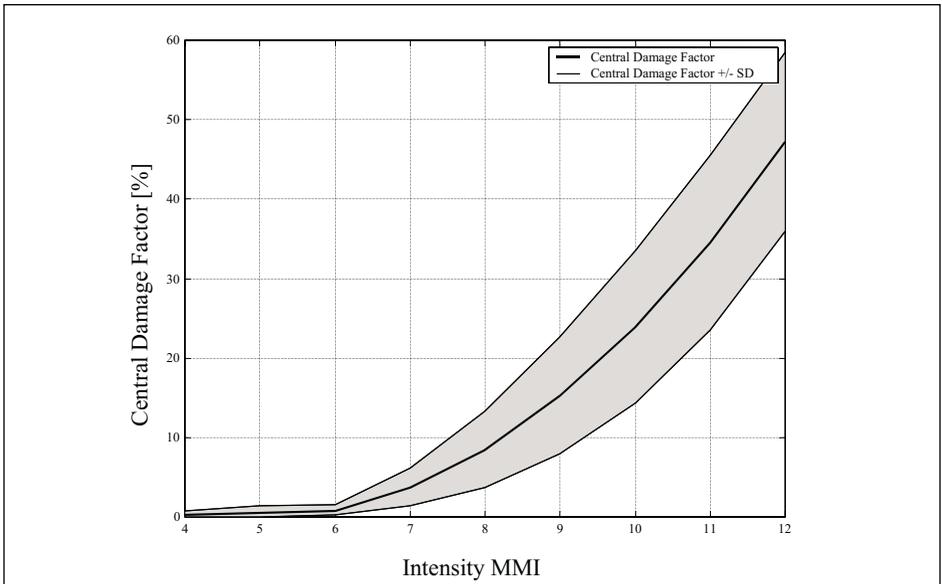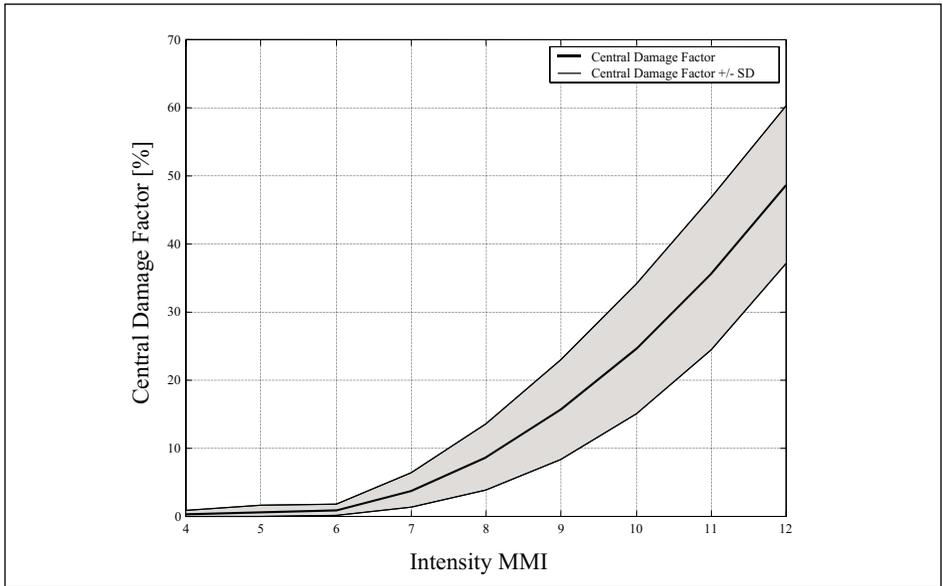
FIGURE 4. Vulnerability curve for low rise facilities with reinforced concrete shear
walls, without moment-resisting frames



As an example, this paper considers three vulnerability curves for three classes of
buildings typical to the Tulbagh area. The DPMs of these buildings are taken from
ATC-13 (*op. cit.*). All vulnerability curves, and the corresponding standard deviations of
the damage factor for a given MM intensity, are shown in Figures 2 to 4. The values of
damage for MM intensity values in the range IV to VI were obtained by linear
extrapolation, as empirically derived central damage factors were not available for
intensity values less than VI. By definition, there is no damage (CDF = 0) for intensity
level IV. Finally, all curves were smoothed. The curves in the following figures are all
taken from ATC-13 (*op. cit.*).

2.2.5    In order to specify the conditional PDF $f_I(i|a)$, use was made of the
classical relationship between the PGA, $a$, and MM intensity, $I$, found by Trifunac &
Brady (1975):

$$E[I \mid a] = 10{,}5 + 1{,}48 \ln a \; ; \tag{7}$$

where $E[I|a]$ denotes the mean value of intensity. On the assumption that the observed
values of intensity for a given peak ground acceleration follow a normal distribution, the
required PDF $f_I(i|a)$ is of the form:

$$f_I(i \mid a) = \frac{1}{\sigma_I \sqrt{2\pi}} \exp\left\{-\frac{(i - E[I \mid a])^2}{2\sigma_I^2}\right\} \tag{8}$$

where the standard deviation of MM intensity, $\sigma_I$, is 0,75 (McGuire, 1993). The same
value of $\sigma_I$ was used by Cao *et al*, (1999).

2.2.6    Finally, the PDF of seismic hazard, $f_A^{\max}(a;T)$, must be specified. This distribution was discussed by Kijko *et al* (forthcoming a). Here, we shall derive an explicit form of the distribution. This paper follows the common assumption made in engineering seismology that the occurrence, at the site, of events with PGA $a$ (where $a \geq a_{\min}$) follows a Poisson distribution, with mean activity rate $v$. The cumulative distribution function of the largest acceleration recorded at the site, within a period of time $T$, is given by the formula

$$F_A^{\max}(a;T) = \begin{cases} 0 & \text{for } a < a_{\min}, \\ \dfrac{\exp\{-vT[1 - F_A(a)]\} - \exp(-vT)}{1 - \exp(-vT)} & \text{for } a_{\min} \leq a \leq a_{\max}, \\ 1 & \text{for } a > a_{\max}. \end{cases} \qquad (9)$$

where $F_A(a)$ is the cumulative distribution of the PGA at the site and is given by the truncated Pareto distribution

$$F_A(a) = \begin{cases} 0, & \text{for } a < a_{\min}, \\ \dfrac{a_{\min}^{-\gamma} - a^{-\gamma}}{a_{\min}^{-\gamma} - a_{\max}^{-\gamma}}, & \text{for } a_{\min} \leq a \leq a_{\max}, \\ 1, & \text{for } a > a_{\max}, \end{cases} \qquad (10)$$

where $\gamma$ is a parameter to be estimated.

2.2.7    Both cumulative distribution functions, (9) and (10), are doubly truncated. The lower truncation, $a_{\min}$, represents the chosen threshold for PGA of engineering interest. The upper truncation, $a_{\max}$, is the maximum possible PGA at the site. From the definition of the PDF, and from formulas (9) and (10), the sought PDF of seismic hazard, $f_A^{\max}(a;T)$, is given by:

$$f_A^{\max}(a;T) = vT \, f_A(a) \, F_A^{\max}(a;T) \frac{\exp\{-vT[1 - F_A(a)]\}}{\exp\{-vT[1 - F_A(a)]\} - \exp(-vT)} \; ; \qquad (11)$$

where $f_A(a)$ denotes the PDF of the PGA at the site. Therefore, for given values of $a_{\min}$ and $a_{\max}$, the seismic hazard at the site is described by the two parameters $v$ and $\gamma$, which are estimated by the maximum-likelihood procedure (Kijko & Graham, 1999).

2.2.8    Knowledge of the DPMs, and of the PDFs $f_D(d|i)$, $f_I(i|a)$ and $f_A^{\max}(a;T)$, makes it possible to calculate the distribution of damage (equation 1) and expected damage during the specified time interval $T$ (equation 3), both of which are obtained by numerical integration.

2.2.9    It is important to note that the above developed formalism of the PSRA makes it possible to assess almost all types of earthquake-associated losses for any type of facility, structure or equipment. In addition, after a simple modification, the general formula (2) can be used to assess risk parameters vital for the insurance industry, such as expected losses over deductibles, and expected losses when the property is underinsured, or when the property value has decreased or increased. It can also be used in assessment of the secondary losses, societal impact, injury or loss of life.

## 3.        SEISMIC RISK AND THE SOUTH AFRICAN INSURANCE INDUSTRY

3.1     In South Africa, 'catastrophe' is most often associated with floods, hail storms and drought. Earthquakes and tremors, being relatively infrequent in the vast majority of the country, are seldom accorded the depth of attention given to other catastrophe risks. In particular, the risk posed by mining-induced seismicity has enjoyed little public acknowledgement or debate, despite the fact that recent years have seen at least four[3] seismic events that caused significant damage. The 1976 Welkom event cost the insurance industry R4,5 million, which was just under half the total damage (AXCO, unpublished). The 1998 earthquake that affected Anglovaal caused insured losses settled at US$2,3 million (approximately R23 million at today's exchange rates). As noted in AXCO (*op. cit.*), it is difficult to establish, legally, the degree to which mining activity was responsible for such events and others like them.

3.2     The last century was characterised by several earthquakes of note in South Africa. The most widely known is probably the Richter magnitude 6,7 earthquake that struck the Ceres–Tulbagh region in 1969. According to AXCO (*op. cit.*), this event had an insured loss, at that time, of US$7,4 million (approximately R75 million at today's exchange rates). The total uninsured loss was 3,5 times as high.

3.3     In South Africa, separate earthquake policies are rarely issued. Cover for seismic risk is generally combined under standard multimark III policies or asset all-risk policies. As a result there is potentially very high exposure. Some 95% of commercial and industrial risks are insured against earthquakes with sums insured being the same as for basic fire cover (AXCO, *op. cit.*). There are no specific market rates for earthquakes but one estimate quoted in the AXCO report was that the portion of property rate attached to the earthquake risk, at least theoretically, was 15%.

3.4     Any comfort sought by insurers and reinsurers in the implementation of exclusion clauses precluding payment in the event of mining-induced seismic events is seemingly misplaced. Legal opinion suggests that it would be close to impossible to produce conclusive evidence that an event supposedly related to mining is in fact so related. Insurers and reinsurers would thus do well to factor in the risk of mining-induced seismicity (as well as natural seismicity) in their catastrophe calculations. Landslip and subsidence will currently be covered only as a separate policy extension, subject to stringent terms, and at a rate of around 0,25 per mille (AXCO, *op. cit.*).

3.5     Before further consideration of the methodology and the presentation of the numerical results, some qualitative discussion is necessary.

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3   Welkom, 1976; Klerksdorp 1977; Welkom 1989 and Carletonville 1992), (Seismological Series 10, 24, 27)

3.6    Many countries affected by seismic activity have drawn up building codes of minimum standards to be met by various types of construction. It is strongly believed that the implementation of such codes in countries prone to earthquake activity, for example China, the former Soviet Union, Japan and the United States have proved helpful in reducing loss of life and limiting damage as a result of seismic activity (e.g., Collins, 1997; Alexander Howden, 1995).

FIGURE 5. SABS areas requiring adherence to specific seismic building requirements
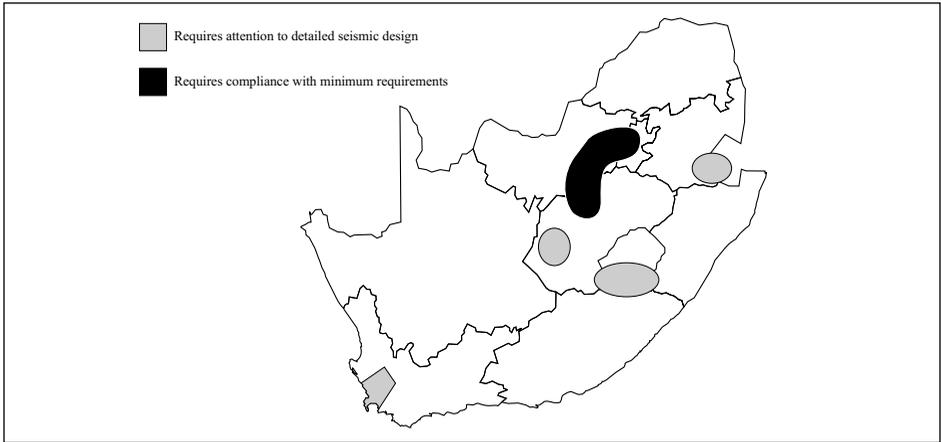


3.7    The South African Bureau of Standards (SABS) has issued minimum building requirements[4] to be implemented in areas it has identified as having inherent seismic risk. These areas are predominantly in mining areas as well as the Tulbagh–Ceres region (see Figure 5). No requirements exist outside of such areas. The extent to which adherence to these requirements is carried through is unknown, and the extent to which these particular requirements will limit damage in the event of seismic activity is untested.

3.8    ATC-13 (*op. cit.*) made mention of 36 different classes of building structures for which estimates of damage as a function of MM intensity were given. In the case of insured property in South Africa, discussions with civil engineers, building-science academics and other practitioners[5] suggest that of these 36 classes, 12 can be identified as being relevant to the local insurance industry. Kijko & Retief (2001) list these 12 classes as well as their assumed distribution.

3.9    For the purposes of this part of the paper, assumptions about the distributions of these building classes in South African metropolises, cities and towns have been made.

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4   SABS 0160–1989 (as amended 1990, 1991 and 1993)

5   KAYE Building Construction, Rand Afrikaans University Department of Building Science, CP DeLeeuw Quantity Surveyors

These assumptions were arrived at through verbal discussions with the civil engineers, building-science academics and quantity surveyors consulted. Insurance companies would need to make more accurate and specific assessments quantifying the extent of their seismic risk with reference to the particular portfolios of buildings they insure.

3.10    While building class is the basic determining factor of the amount of damage likely to be sustained in a seismic event of given magnitude, other factors also play a role. Already mentioned is the adherence to prescribed minimum seismic design requirements. In addition, both empirical and theoretical evidence has shown that foundation symmetry is also an important factor in seismic damage. Building design that emphasises almost absolute regularity of shape is undoubtedly the safest in terms of seismic risk. Asymmetry includes split-level buildings, differing flexibility of building material and L-shaped designs.

3.11    For the purpose of this study, assessment of the seismic risk in South Africa is made via representative proxy sites selected in each of the 12 CRESTA (catastrophe risk evaluating and standardising target accumulations) zones containing areas of like risk for a given hazard. In the larger zones, more than one site was selected. The seismic risk at each of these sites was assumed to be representative of the seismic risk in the CRESTA zone, or in the event that a CRESTA zone has more than one proxy site, representative of those points in the CRESTA zone for which the proxy site in question is the closest proxy site.

3.12    The procedure described in Section 2 was used to estimate the seismic risk for the different types of building structures found in the urban areas of South Africa. As an example, the results for the region surrounding the greater Johannesburg proxy site (Central Johannesburg city centre) are shown in Table 2 below, together with the assumed distribution of building types for this site.

3.13    For a given proxy site, combining the information on seismic hazard with the information on the attenuation of the PGA with distance (equation 1), yields the estimated distribution of PGA at that particular site. Combining this in turn with the relationships between PGA and MM intensity (equation 8) leads to the basic seismic hazard curve: the annual probability of exceeding a given MM intensity for each of the proxy sites (similar to Figure 1).

3.14    Following equation (2), combination of the seismic hazard curve with the vulnerability curves (Figures 2 to 4) leads to the annual probabilities of exceedance of given values of damage, or equivalently the seismic risk curves. For illustrative purposes, the seismic risk curves, together with the standard deviations of the damage, are shown in Figures 6 to 8 for three classes of structures considered for Johannesburg.

TABLE 2: Building class description and distribution

| Class | Central damage factor (%) | Class description | Class distribution for Johannesburg (% of total replacement costs) |
|---|---|---|---|
| 1 | 0,54 | wood frame, low rise | 0,09% |
| 2 | 0,28 | light metal, low rise | 0,10% |
| 3 | 1,06 | unreinforced masonry, with load-bearing wall, low rise | 9,17% |
| 4 | 0,64 | unreinforced masonry without load-bearing wall, low rise | 0,09% |
| 5 | 1,4 | unreinforced masonry, with load-bearing wall, medium rise | 5,06% |
| 6 | 2,8 | reinforced concrete shear wall with moment resisting frame, medium rise | 5,14% |
| 7 | 0,3 | reinforced concrete shear wall with moment resisting frame, high rise | 13,80% |
| 8 | 0,49 | reinforced concrete shear wall without moment resisting frame, medium rise | 17,48% |
| 9 | 0,67 | reinforced concrete shear wall without moment resisting frame, high rise | 46,01% |
| 10 | 0,53 | braced steel frame, low rise | 0,79% |
| 11 | 0,11 | precast concrete, low rise | 0,51% |
| 12 | 0,26 | long span, low rise | 0,99% |

3.15    As an example of the interpretation of the risk curves, it can be stated that the seismic risk curve for low-rise, unreinforced masonry buildings having load-bearing walls (Figure 6) indicates a $10^{-2}$ probability that, during one year, such a class of structure located in Johannesburg or its vicinity will experience a mean value of damage of 20%. Interpretation of the seismic risk curves for the remaining classes of structures is done in a similar fashion. It should always be borne in mind that the central damage factor curve should be considered as being applicable to a portfolio of buildings of the same class and not a single structure.

3.16    The expected annual damage ratio for a given proxy site can be calculated from the formula

$$\sum_{i=1}^{12} DR_i \times \frac{TRV_i}{TRV};$$
(12)

where $DR_i$ is damage ratio of building class $i$, $TRV_i$ is the total replacement value of building class $i$ and $TRV$ is the total replacement value of buildings of all classes.

FIGURE 6. Risk curve for low-rise facilities with load-bearing walls
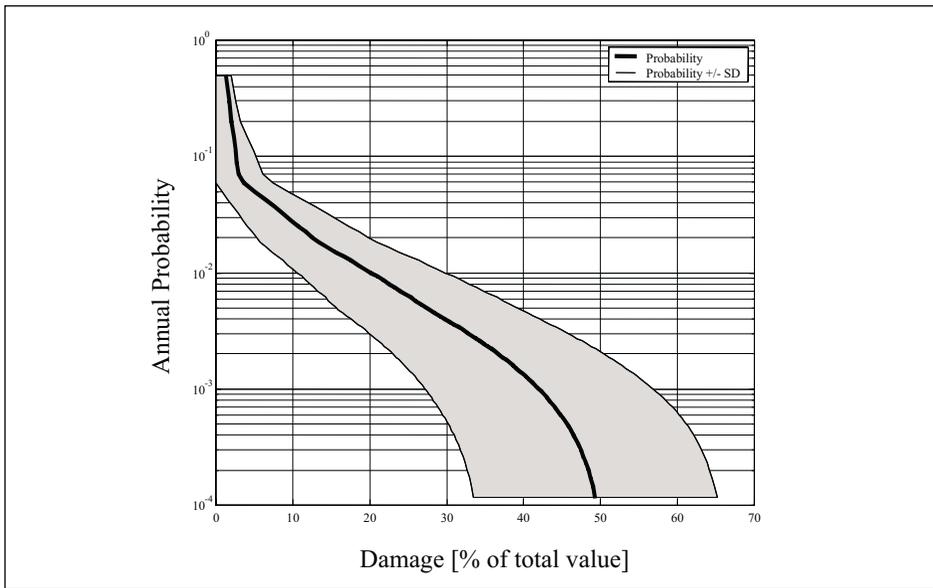of unreinforced masonry



FIGURE 7. Risk curve for medium-rise facilities with reinforced concrete shear walls
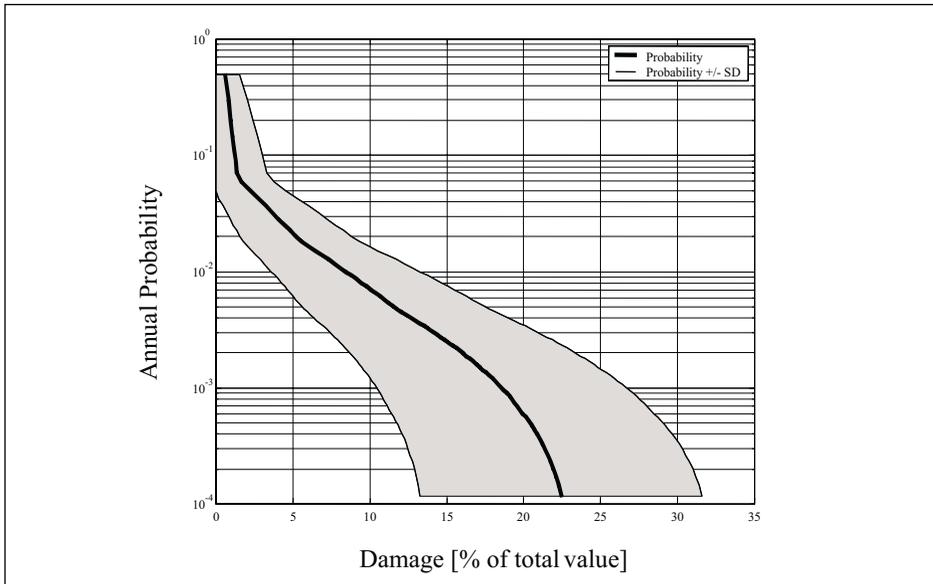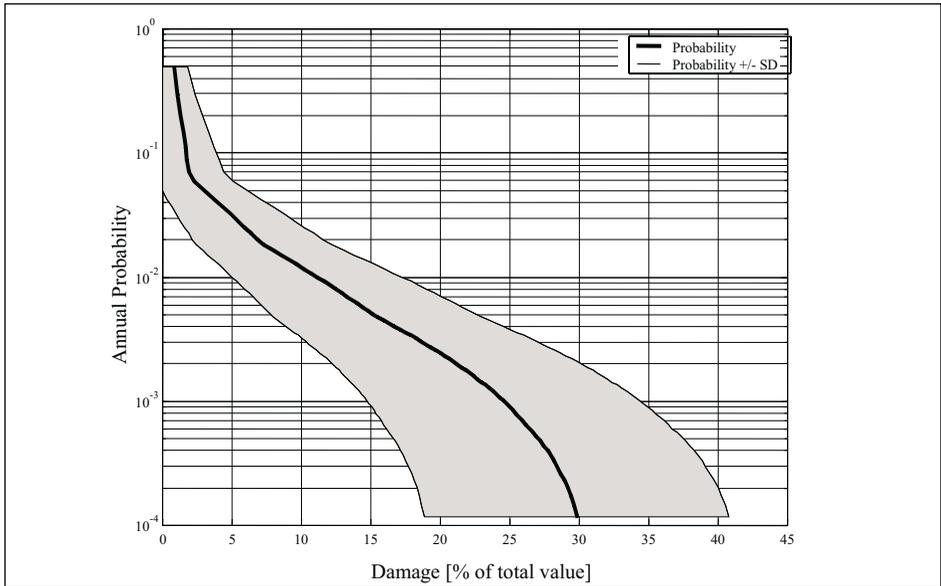without moment-resisting frames

FIGURE 8. Risk curve for high-rise facilities with reinforced concrete shear walls
without moment-resisting frames



3.17     Table 3 shows the mean expected annual damage ratio for three metropolises and
two smaller towns with different building-class distributions. The mean EAD is
calculated as the weighted average, over all building classes, of the central damage factor.
For Johannesburg, the value is obtained from columns 2 and 4 of Table 2.

TABLE 3. Mean EAD for Selected Areas

| City/area | CRESTA Zone | Mean EAD* |
|-----------|-------------|-----------|
| Johannesburg | 6 | 0,63% |
| Cape Town | 8 | 1,08% |
| Durban | 9 | 0,5% |
| Piketberg – NE Cape | 10 | 1,10% |
| King William's Town | 14 | 1,37% |

*Damage is from the first rand and assumes no excesses. The mean EAD is expressed per cent of
replacement value.

## 4.     ULTRA-DEEP MINING

4.1     The mining industry has known for some time that gold-bearing reefs continue far
below current mining depths. At present the deepest gold mines in South Africa are the

Great Noligwa—formerly Vaal Reefs no. 8 shaft—and what was formerly known as Western Deep Level East, both mining as deep as the 3,5km mark. It is estimated that the extent of the gold resources at depths of 3km to 5km is equal to those recovered from the reefs of the Witwatersrand basin during the past century[6]. The problem up to now has been how to extract the gold at these levels. Indeed, unlike conventional mining, deep mining has its own unique problems, in particular, high rock pressure and the associated seismicity.

4.2     While these conditions have meant that some reserves have had to be left untouched for more than a century, a research project[7] is currently under way to explore means of going deeper than current depths in search of gold.

4.3     Research shows that, depending, amongst other factors, on the inherent seismicity of the area and the type of rock in the area, as the mining goes deeper and deeper, both the number and Richter magnitude of seismic events increase more and more rapidly. (Neyman, 1972; Kijko, 1978)

4.4     The Carletonville area (where the current depth of gold mining is about 3,5 km) has been highlighted as one area for the implementation of the Deepmine programme. There is consequently a very real possibility of a seismic event of unprecedented regional magnitude in this area. The area has, to date, experienced two strong seismic events (Richter magnitudes 4,7 and 4,8) and the potential for seismic events of even higher magnitude once ultra-deep mining gets under way is high. Following simple physical considerations and simple extrapolation of existing data (Neyman, 1972), seismic experts are of the opinion that an event of magnitude 5,5 could well be induced in the area, with significant damage to both the immediate area and areas further afield.

4.5     Using the modified Atkinson-Boore attenuation equation (Kijko *et al*, forthcoming a), it is projected that the PGA likely to be experienced in the Johannesburg area as a result of a 5,5 magnitude event in the Carletonville area, would be around 0,06g. Taking into account the statistical spread of data relative to the empirically obtained equation used to estimate this value, the PGA plus standard deviation is close to 0,1g. Both of these aforementioned PGA values are above the PGA value deemed to be of engineering interest, namely 0,05g.

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6     http//deepmine.csir.co.za

7     The Deepmine programme was launched in July 1998. It aims to create a technological and human resources platform that will make it possible to mine gold at ultra-depth, up to 5km below surface. Mining houses collaborating on the project include Anglogold, Gold Fields and Durban Roodepoort Deep, the CSIR, government, organised labour, universities and other research institutions.

4.6     The extent of the damage resulting from such an event can be calculated from the Trifunac-Brady equation (7), linking PGA and intensity, together with the DPMs. The PGA values of 0,06g and 0,1g translate to expected MM intensities of VI and VII respectively. For such MM intensities the damaged caused to a portfolio of, for example, medium-rise buildings consisting of unreinforced masonry with load-bearing walls is projected to be in the range of 1–9% of replacement value for intensity VI and in the range 4–16% for intensity VII. To explain these values, the maximum value of 9% for intensity VI events is the product of the second column of the table in Appendix A (probability of damage) with the maximum values of the appropriate band for which the central damage factor (column 1 of Table A1 of Appendix A) is representative. (These bands are given in Table 1.) In matrix algebra:

$$0.09 = \begin{pmatrix} 0.5 & 15.3 & 81.2 & 3 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 10 \\ 30 \\ 60 \\ 100 \\ 100 \end{pmatrix}$$

4.7     Expanding on this and applying the various DPMs to all the assumed building types present in a large South African city (see Table 2), it is possible to ascertain the proportion of each class of building that is likely to experience a particular degree of damage. Taking into account the distribution of these different building types (as a percentage of total replacement cost—Table 2) it is then possible to calculate overall expected damage states for such a city via the formulae:

$$P_x = \sum_{i=1}^{12} \alpha_i \delta_i^x \; ;$$

where:

$P_x$ is the proportion of the total city portfolio with a CDF of x%;

$\delta_i^x$ is the proportion of class $i$ buildings experiencing x% damage (the value of which is determined from the DPM); and

$\alpha_i$ is the contribution of class $i$ buildings to the total replacement cost for Johannesburg (the value of which is determined from Table 2).

For Johannesburg, these formulae indicate that, on average, light damage (with a mean damage factor of 5%) could be experienced by as many as 45% of all buildings for an MM intensity VI event. An MM intensity VII event in the city could result in 80% of all structures experiencing light damage and another 10% experiencing moderate damage (with a mean damage factor of 20%).

4.8     For the sake of completeness, mention needs to be made in this section of a further mining project that has recently been launched, Project Argonaut. Following, amongst

other things, the technological developments arising from the Deepmine programme and the consolidation to one owner of various mines, one of the mining companies is now planning to reinvigorate mining activities in a belt through the southern suburbs of Johannesburg. This belt, which will see mining to depths of 3 000m, stretches from Durban Roodepoort Deep in the west to East Rand Proprietary Mines in the East. This project's attaching seismic risk has yet to be quantified. Suffice it to say that any mining in such close proximity to residential, commercial and industrial locations will only aggravate the existing seismic risk in that area[8].

## 5.     CONCLUSION

5.1     It can be seen that, from the combination of the information contained in Figures 1 to 4, i.e. the seismic hazard curve and vulnerability curves for different classes of buildings, the seismic risk curves as well as the EAD for each building type can be obtained. Although the same vulnerability curve can be used for each type of building at different locations, the risk curves and EAD values are site-dependent, since the seismic hazard is site-dependent. However, for a city or settlement in which the buildings are all concentrated within the same, relatively small area, the seismic hazard curves associated with the locations of each building can be approximated by the hazard curve calculated for a site with co-ordinates representing the centre of the settlement. If the distribution of building types within the settlement is known, the calculated site hazard information can then be combined with the vulnerability information on the different buildings and a weighted average risk curve as well as EAD value can be obtained, representing the total seismic risk posed to the settlement. Furthermore, if the replacement value of each building is known, the damage (in Figures 6 to 8) can be expressed in terms of monetary value, since, by definition, damage is the ratio of the rand loss to the replacement value.

5.2     Using the above methodology, the mean EAD values for the three most densely populated cities in South Africa were calculated. The values of 1,08%, 0,63% and 0,5% for Cape Town, Johannesburg and Durban respectively, suggest that seismic risk is not a negligible component of property rating. In fact it has been shown earlier in this paper that as a result of an MM intensity VII event (Cape Town, return period of 40 years), up to 80% of all structures could experience light damage (mean damage ratio 5%) and another 10% could experience moderate damage (mean damage ratio of 20%).

5.3     The research findings reflected in this paper arise from the most detailed investigation of its kind done to date. It should be noted, though, that this paper is but the first step in an endeavour to fully understand and accurately assess the seismic risk in South Africa. This research and these findings have led to some new ideas to pursue in further research. Indeed, future undertakings in this field should investigate the effects, if

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8     www.durbans.com; *The Star* newspaper, 3 Feb 2003.

any, of matters such as local soil structure. In addition, increased accuracy of expected and maximum values of damage may be reached with a finer grid of proxy points.

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# APPENDIX A
# WHITMAN DAMAGE PROBABILITY MATRIX FOR BUILDING CLASS 6:
# UNREINFORCED MASONRY, LOAD BEARING FRAME, MEDIUM RISE

TABLE A1. Probability of damage (percent) by MMI and damage state

| Central damage factor % | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|
| 0 | 0,5 | – | – | – | – | – | – |
| 0,5 | 15,3 | 2,9 | – | – | – | – | – |
| 5 | 81,2 | 66,6 | 13,5 | 1,9 | 0,3 | – | – |
| 20 | 3,0 | 30,1 | 69,3 | 40,6 | 14,1 | 2,0 | 0,2 |
| 45 | – | 0,4 | 17,2 | 54,4 | 63,4 | 28,4 | 8,5 |
| 80 | – | – | – | 3,1 | 22,2 | 67,5 | 78,8 |
| 100 | – | – | – | – | – | 2,1 | 12,5 |

# APPENDIX B
# MODIFIED MERCALLI (MM) INTENSITY SCALE OF 1931[9]

**MM I:** not felt, except rarely under especially favourable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
– sometimes birds or animals are reported to be uneasy or disturbed;
– sometimes dizziness or nausea is experienced;
– sometimes trees, structures, liquids, bodies of water, may sway, or doors may swing, very slowly.

**MM II:** felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in MM I, but often more noticeable:
– sometimes hanging objects may swing, especially when delicately suspended;
– sometimes trees, structures, liquids or bodies of water, may sway, or doors may swing, very slowly;
– sometimes birds or animals are reported to be uneasy or disturbed;
– sometimes dizziness or nausea is experienced.

**MM III:** felt indoors by several, motion usually rapid vibration.
– The event is sometimes not recognised to be an earthquake at first.
– The duration is estimated in some cases.
– Vibration is experienced like that due to the passing of light or lightly loaded trucks, or heavy trucks some distance away.
– Hanging objects may swing slightly.
– Movement may be appreciable on upper levels of tall structures.
– Standing motor cars are slightly rocked.

**MM IV:** felt indoors by many, outdoors by few.
– The event awakens a few, especially light sleepers.
– It frightens no one, unless apprehensive from previous experience. Vibration is experienced like that due to the passing of heavy or heavily loaded trucks. Sensations like a heavy body striking the building, or the falling of heavy objects inside, may be experienced.
– Dishes, windows and doors may rattle; glassware and crockery may clink and clash.
– The creaking of walls or the frame may be heard especially in the upper range of this grade. Hanging objects swing in numerous instances.
– Liquids in open vessels are slightly disturbed.
– Standing motor cars slightly are slightly rocked.

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9   Source: Adapted from Sieberg's Mercalli-Cancani scale (Sieberg A, 1923). Slight grammatical changes were introduced to the description in the quoted source in order to improve readability.

**MM V:** felt indoors by practically all, outdoors by many or most; outdoors, the direction of the event may be estimated.
– The event awakens many, or most.
– It frightens few, but slight excitement may be reported; a few may run outdoors.
– Buildings tremble throughout.
– Dishes and glassware are broken to some extent.
– Some windows may be cracked.
– Small or unstable objects are overturned occasionally falling.
– Hanging objects, doors, swing generally or considerably.
– Pictures are knocked against walls, or swung out of place.
– Doors and shutters are abruptly opened or closed.
– Pendulum clocks stop, start, or run fast, or slow.
– Small objects and furnishings are moved, the latter to a slight extent.
– Liquids are spilt in small amounts from well-filled open containers.
– Trees and bushes are shaken slightly.

**MM VI:** felt by all, indoors and outdoors.
– The event frightens many, excitement is general, there is some alarm, and many run outdoors. It awakens all.
– Persons are made to move unsteadily.
– Trees and bushes are shaken slightly to moderately.
– Liquid is set in strong motion.
– Small bells are rung at churches, chapels, schools etc.
– Damage is slight in poorly built buildings.
– Plaster falls in small amount.
– Plaster is somewhat cracked, especially fine cracks in chimneys in some instances.
– Dishes and glassware are broken in considerable quantity, also some windows.
– Ornaments, books and pictures fall.
– Furniture is overturned in many instances.
– Moderately heavy furnishings are moved.

**MM VII:** frightens all, raising general alarm, and all run outdoors.
– Some or many find it difficult to stand.
– The event is noticed by persons driving motor cars.
– Trees and bushes are shaken moderately to strongly.
– Waves form on ponds, lakes, and running water.
– Water is turbid from stirred-up mud.
– Sand or gravel stream banks cave in to some extent.
– Large church bells etc. are rung.
– Suspended objects are made to quiver.
– Damage is negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, abode houses, old walls (especially where laid up without mortar), spires, etc.

– Chimneys are cracked to a considerable extent, walls to some extent.
– Plaster falls in considerable to large amount, also some stucco.
– Numerous windows, and to some extent furniture, are broken.
– Loosened brickwork and tiles are shaken down.
– Weak chimneys are broken at the roof-line, sometimes damaging roofs.
– Cornices fall from towers and high buildings.
– Bricks and stones are dislodged.
– Heavy furniture is overturned, with damage from breaking.
– Damage to concrete irrigation ditches is considerable.

**MM VIII:** general fright; alarm approaches panic.
– Disturbs persons driving motor cars.
– Trees shaken strongly – branches, trunks, broken, especially palm trees.
– Ejected sand and mud in small amounts.
– Changes occur in the flow of springs and wells; flow is renewed in dry wells; the temperature of spring and well waters changes.
– Damage is slight in brick structures, especially those built to withstand earthquakes.
– Damage is considerable, to the extent of partial collapse, in ordinary substantial buildings; in some cases, wooden houses tumble down; panel walls are thrown out of frame structures, decayed piling is broken off. Walls topple.
– Solid stone walls are seriously cracked and broken.
– Ground is wet to some extent.
– Chimneys, columns, monuments, factory stacks and towers twist and fall.
– Very heavy furniture is conspicuously moved and overturned.

**MM IX:** general panic.
– Ground cracks conspicuously.
– Damage is considerable in masonry structures built especially to withstand earthquakes.
– Some wood-frame houses built especially to withstand earthquakes are thrown out of plumb.
– Substantial masonry buildings are badly damaged, some collapsing in large parts.
– Frame buildings may be wholly shifted off their foundations.
– Reservoirs are seriously damaged.
– Underground pipes are sometimes broken.

**MM X:** cracked ground, especially when loose and wet, up to a width of several inches; fissures up to a metre in width running parallel to canal and stream banks.
– Considerable landslides occur from river banks and steep coasts.
– Sand and mud shifts horizontally on beaches and flat land.
– The level of water in wells is changed.
– Water is thrown out on the banks of canals, lakes, rivers, etc.
– Serious damage occurs to dams, dykes and embankments.
– Well-built wooden structures and bridges are severely damaged; some are destroyed.

– Dangerous cracks develop in excellent brick walls.
– Most masonry and frame structures are destroyed, including their foundations.
– Railway lines are slightly bent.
– Underground pipe-lines are torn apart or crushed.
– Open cracks and broad wavy folds appear in cement pavements and asphalt road surfaces.

**MM XI:** disturbances in ground many and widespread, varying with ground material.
– Broad fissures, earth slumps, and land slips occur in soft, wet ground.
– Water is ejected in large amounts, charged with sand and mud.
– Sea-waves of significant magnitude occur.
– Wood-frame structures are severely damaged, especially near shock centres.
– Dams, dykes and embankments are severely damaged, often for long distances.
– Few, if any, masonry structures remain standing.
– Large, well-built bridges are destroyed by the wrecking of supporting piers or pillars.
– Yielding wooden bridges are less affected.
– Railway lines are severely bent.
– Underground pipe-lines are forced completely out of service.

**MM XII:** damage total; practically all works of construction greatly damaged or destroyed.
– Disturbances in the ground are great and varied, numerous shearing cracks appearing.
– Landslides and falls of rock are significant, and the slumping of river banks etc. is extensive.
– Large rock masses are wrenched loose and torn off.
– Fault slips develop in firm rock, with notable horizontal and vertical offset displacements.
– Water channels, both surface and underground, are disturbed and modified greatly.
– Waterfalls are produced and rivers are deflected.
– Waves are seen on ground surfaces.
– Lines of sight and level are distorted.
– Objects are thrown upward into the air.