Fluid-Induced Seismicity in the Central Rand Basin Area: Ground Motion Prediction and the Development of an Early Warning System for Risk Reduction

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Executive Summary

Three and a half years after pumping water was stopped in the ERPM mine, the evolution of seismicity has indicated that the Central Rand Basin area is not yet in equilibrium. Because the Central Rand Basin seismicity is located directly beneath the densely populated area of Johannesburg, a full understanding of its mechanism is required. Seismic data clearly shows that the level of seismicity in the rock mass influenced by water ingress tends to be much larger than in the surrounding rock mass.

Presented in this report are probabilistic seismic hazard analysis results for areas surrounding the mining regions of the East Rand, Central Rand and West Rand. Hazard maps were produced for Spectral Acceleration (SA) at $T = 0.1s$ and $T = 1.0s$, both at return periods of 475 years and 979 years. The UHS for three sites, Central Johannesburg, OR Tambo International Airport and Soweto were prepared. The acceleration values are almost the same at OR Tambo and Johannesburg, whilst values at Soweto are much less.

The theoretical review provides the methodology and quantification of the seismic risk associated with seismic activity caused by an increase in the water level in abandoned mines under the Johannesburg CBD. The expected damages for 12 of the most characteristic building classes in the Johannesburg CBD are included. The assessment of the maximum regional seismic event magnitude is provided. From the background study and analysis performed on Council for Geoscience and the International Seismological Centre datasets, it is concluded that there appears to be an increasing trend in the level of seismicity, with the nature of the seismicity changing from induced to tectonic-like origin.

One of the objectives was to determine the subsoil and groundwater conditions at the site in order to delineate the most favourable locality for the first level microzonation map in support of the strong ground motion amplification prediction and the development of an early warning system for risk reduction. The results have indicated that the most favourable topographic situation for thick soil deposits in the study area occupy the Johannesburg graben valley. The underlying geological formation on the site is lava of the Ventersdorp Supergroup. It is weathered to depths greater than 40m to a low density, sandy silt. The decomposed lava is covered by approximately 300 mm of well-developed pebble marker of vein quartz and quartzite gravels and a thick deposit of transported soils consisting of compressible silty sand. The transported soils are, in turn, covered from ground surface by shallow thicknesses of fill.

Another activity within this project was to model the structural trends within the Central Rand Basin using an assumed pre-mining stress model in order to identify zones in the basin that are more “seismicity-prone” than others. The mechanism for triggering instability in the model is an applied pore pressure, representing the flooding that has taken place. A detailed map of the structural geology together with a review of the structural setting formed the basis for this study. The 12 station seismograph network which spans the Central Rand Basin provided locations of seismic events with which to validate the results of our model. Results from the 3D models showed an average shear displacement of approximately 5 cm and a maximum 12 cm. Joint shear stresses up to 60 MPa were induced by the removal of material to form the void. The model produced stress and strain conditions comparable to those observed underground and demonstrated the strong dependence of an intersecting feature’s propensity to slip on its relative orientation with respect to the mine void. There was good agreement between the spatial distribution of seismicity and the positions of potentially unstable features, which suggests two possibilities: (1) Seismicity is being controlled by stresses induced by the shape and orientation of the mined-out reef on intersecting geology rather than tectonic stresses and (2) The shallow crust can be described by a homogenous material and uniform stress model.

The evaluation of the attenuation of ground motion amplitude is an essential problem for the seismological characterization of a region. The attenuation of the P- and S-waves in the Central Basin is estimated by using the coda normalization methods. The frequency dependence of
parameters for the P- and S-wave are calculated for a set geometrical spreading constant, which is fixed at unity for distances less than 45 km.

A catalogue of almost 1000 earthquakes was created and the spectral parameters of the events were estimated. A new relation between $M_L$ and $M_w$ was obtained. An increase in static stress drop with increasing seismic moment is observed. Several comparisons were presented between the seismic source parameters obtained in this study and those of other regions. The dependence between seismic moment and radiated energy in different studies shows a similar pattern to the one observed here. However, there are some significant differences; static stress drop for the Central Rand Basin area is one order of magnitude larger than in the case of observed seismicity induced by a water reservoir in China. The amplitudes of ground motion are controlled by the amount of static stress drop during a seismic event; therefore, areas where large stress drop is observed are areas where strong ground motion is expected.

Spatial variation of seismicity in the Central Rand Basin area was analysed. Over the last year of monitoring no major increase of polygons with earthquakes was observed, but the number of events per polygon increased significantly. The distribution of seismicity shows a reduction in the level of seismicity in the western part of the Central Rand Basin during 2012. The strongest events in 2012 year were concentrated in the eastern part the Central Rand Basin area. However, the earthquakes with the largest stress drops are observed in the eastern and central parts of the Central Rand Basin.

The predominant mode of strain rate in the Central Rand Basin was estimated to be $0.57 \times 10^9$ year$^{-1}$. The cumulative seismic moment and radiated seismic energy as functions of time were calculated. The variation these parameters with time indicates that a constant deformation rate model is not suitable for the Central Rand Basin area. However, evolution with time of the cumulative parameters and estimated strain rate could be used as indicators of future seismic activity.
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1. Introduction - Project objectives

The proposed project addresses the problem of the risks of fluid-induced seismicity in the greater Johannesburg area by focusing on accurate quantification of the most important factors that contribute to the estimation of the hazard and risk. The project includes all four key elements of an early warning system: risk knowledge (see Objective 1) monitoring (dense network of 12 seismic stations), an early warning service (see Objective 2) and dissemination of warnings (see: Transfer of Research Outcomes). Investigations conducted under the proposed project will utilize existing procedures and develop a few new ones to quantify the strong ground motion parameters and to quantify the spatial-temporal variation of the rock mass state of the Central Basin.

Objective 1: Strong ground motion prediction for the maximum expected magnitude and the evaluation of damage potential, as it is defined by the South African Building Codes.

It is required to develop and implement a realistic assessment of the seismic hazard and risk rooted in well-established methodology developed for tectonic earthquakes. However, it has to be modified in order to accommodate rapid changes in the stress conditions caused by the flood water. The investigation is concentrate on the understanding of seismic source properties, propagation mechanisms and local site effects as the physical factors controlling strong ground motion.

Activity for 2012/2013

- Attenuation of seismic waves in the Central Basin area
- Subsurface engineering evaluation of the Johannesburg City area
- Probabilistic seismic hazard analysis for hard rock in the Central Basin
• Risk assessment due to seismic activity for different types of building classes in the Johannesburg CBD

Objective 2: Development of an Early Warning System for risk reduction by monitoring the state of dynamic processes in the rock mass of the Central Basin.

Changes in the rock mass of the Central Basin imposed by fluid related seismicity should be re-evaluated periodically. The Central Basin is divided into cells. In each cell, the value of the parameters that characterize the dynamic processes that currently occur in the rock mass is displayed. The list of parameters includes: number of events, cumulative deformation, cumulative radiated seismic energy. The relationship between apparent stresses and seismic moments is updated and analysed periodically as well.

Activity for 2012/2013

• Subsurface stress modelling in mining areas – defining zones of seismic potential

• Temporal and spatial variation of seismicity in the Central Rand Basin 2012

2. Attenuation of seismic waves in the Central Basin area

(by A. Cichowicz and D. Birch)

The evaluation of the attenuation of ground motion amplitude is an essential part of the seismological characterization of a region. The path effect is given by the multiplication of the geometrical spreading and the diminution function represents the attenuation of seismic waves passing through the earth’s crust. In the first year of investigation (2011/2012), the attenuation of seismic waves obtained for the KOSH
district has been used as for estimation of seismic source parameters. This was the initial approximation of the attenuation. Seismic source parameters and ground motion equations have been based on an attenuation model obtained using data from the Central Basin.

An important step towards understanding fluid-induced seismicity involves a detailed analysis of the seismic source parameters in the Central and East Rand districts. Accurate evaluation of attenuation is important to evaluate $M_w$ magnitude, radiated seismic energy, seismic moment, source dimension prediction and static stress drop. Studies of attenuation in seismically active regions are very popular; however the stable parts of continents around the world do not provide many opportunities to investigate this. A study of regional attenuation contributes to the seismological and geological characterization of the region.

One important element of seismic hazard assessment is the selection of the seismic wave attenuation equation. Seismic hazard assessment projects in South Africa are mostly utilizing the attenuation equations from central and eastern US. This is done on the assumption that both areas are intra-plate regions. The quantification of similarities and differences between the South African and other crustal models is vital for assessing the sensitivity of the hazard assessment. Earthquakes of very large magnitude that could be of relevance to hazard assessment are not often produced in mining districts. Therefore, the ground motion caused by earthquakes of magnitude ranging from 1 to 3.5 will be used to estimate attenuation parameters. Those parameters will next be used to predict ground motion caused by seismic events with magnitudes as large as 5 or 5.5.

The observed ground motion generated by earthquakes is complicated because it is affected by the source, travel path, and local site conditions. Geometrical spreading and attenuation control travel path effects.
The objective of this evaluation is to determine the relevant attenuation parameters that control ground motion in the mining districts. This evaluation provides useful insight into the attenuation of seismic waves in South Africa.

2.1 Estimation of attenuation in the Central and East Rand path effect

The attenuation of the P- and S-waves in the Central Basin is estimated by using the coda normalization methods. The purpose of the coda normalization technique is to remove the effects of the seismic source, site effect and instrument response by dividing the amplitudes of direct body waves by coda amplitude. The coda normalization technique was introduced by Aki (1980), and used by Frankel et al. (1990), Yoshimoto et al. (1993) and many others. The coda normalization technique was applied to single station data and groups of stations (Aki, 1980; Frankel et al., 1990, Chung and Sato, 2001; Kim et al. 2004; Dutta et al.2004; Padhy (2009 ). The similar algorithm was already used to estimate attenuation parameters in the KOSH mining district (Cichowicz and Birch 2010 and Cichowicz and Birch 2011).

The data analyses are based on seismicity recorded by 12 seismic stations deployed in the Central and East Rand. These stations recorded data in continuous mode at 100 or 200 samples per second and with 24-bit resolution. The epicentral distances of the earthquakes range from 2 km to 50 km.

Coda normalized amplitudes at 16 different central frequencies were calculated for three components of P- and S-waves for all suitable waveforms from all seismic stations.

Coda amplitude was obtained from the root-mean-squared amplitude for a 5 sec time window at a time greater than the lapse time, in this case it was 22 sec for
events located closer than 45 km. The lapse time is measured from the source origin
time. The coda normalization method was used to obtain the quality factors for \( Q_p^{-1} \)
and \( Q_s^{-1} \) for three component data. Normalized amplitude is calculated for all
acceleration stations in the Central and East Rand from one joint attenuation
relationship. The unknown values of \( Q^{-1} \) for the P- and S-wave are determined by
assuming that \( \gamma_1 = 1 \) for distances less than 45 km. Figures 1 shows example of
coda normalized amplitude of the S-wave N component versus distance for all the
seismograph stations from the Central Basin for the central frequencies 14Hz, 12Hz
and 10Hz. The best-fit line from the least-squares estimate is indicated by the solid
line. Figure 1 shows a smooth decay of normalized amplitude with distance for all
analysed frequencies.

The coda normalized amplitude versus distance was obtained for E, N, and Z
components for the P-wave and S-waves. The obtained values of \( Q_s^{-1} \) vary from
0.0098 to 0.00150 (\( Q_s \) from 102 to 665) and of \( Q_p^{-1} \) from 0.01338 to 0.00378 (\( Q_p \) from
75 to 266) in the frequencies ranging from 3 to 32Hz.

A power law \( Q^{-1}(f) = Q_o^{-1} f^{-n} \) for the frequency relationships with the body wave
quality factors is assumed. The example of frequency-dependent relationships for
the region are presented in Figure 2. The frequency dependent relationships for the
three components of the P- and S-wave are expressed as:

\[
\begin{align*}
Q_{p-z}^{-1} &= 0.0492 f^{-0.79}, \quad Q_{p-N}^{-1} = 0.0737 f^{-0.91}, \quad Q_{p-E}^{-1} = 0.0274 f^{-0.626}, \\
Q_{s-z}^{-1} &= 0.0197 f^{-0.69}, \quad Q_{s-N}^{-1} = 0.0074 f^{-0.41} \text{ and } Q_{s-E}^{-1} = 0.011 f^{-0.49}.
\end{align*}
\]
Figure 1. Coda normalized amplitude versus distance between source and seismic station for the S-wave N component at 14 Hz, 12 Hz and 10 Hz central frequencies.
where $Q^{-1}$ index P-Z means the P-wave Z component, P-N means the P-wave N-S component, P-E means the E-W component and, in the same way, names are given to the inverse of the quality factors for the S-wave.

Figure 2. $Q_s^{-1}(f)$ frequency dependence for horizontal components. Bold line refers to the best-fit regression by the least-squares method and the error bars indicate the standard deviation.

2.2 Discussion - Models comparison

The obtained models have two parameters ($Qo^{-1}$, $n$). with average values and standards deviations ($\delta Qo^{-1}$, $\delta n$). It is assumed that the acceptable attenuation can follow all combinations of average values and standard deviations ($Qo^{-1}$, $n$), ($Qo^{-1}$,
\( \exp(-\pi f R (Q_0^{-1} + \delta Q_0^{-1}) \sqrt{(n+\delta n)/V_{direct}}) \)

where \( R = 10\text{km} \). Figure 3 shows results of attenuation as the function of frequency for a fixed distance. For each component seven models of attenuation are plotted. Figure 3 shows a strong overlap between the two horizontal components (blue and red lines) of the S-waves. Therefore, in the future applications of attenuation the average model obtained from the two horizontal components will be used (see black line).
of quality factors parameters (Qo⁻¹, n), (Qo⁻¹ +δQo⁻¹, n), (Qo⁻¹ –δQo⁻¹, n), (Qo⁻¹ +δQo⁻¹, n+δn), (Qo⁻¹ +δQo⁻¹, n–δn), (Qo⁻¹ –δQo⁻¹, n+δn), (Qo⁻¹ –δQo⁻¹, n–δn).

The ratio of Q_p⁻¹/Q_s⁻¹ versus frequency was obtained by using two methods. In the first method the P-wave quality factor was estimated using only the Z-component and the quality factor of the S-wave is an average value of Q_s⁻¹ for the two-horizontal components. In the second method the ratio Q_p⁻¹/Q_s⁻¹ is calculated from the average of the three components in Q_p⁻¹ and the average of the three components in Q_s⁻¹. The ratios are greater than 1.5 and the ratio values reported from different regions are generally larger than 1.

2.3 Conclusion

The coda normalization technique was applied to evaluate the attenuation of the Central and East Rand Basin. The technique assumes a power law relation of Q⁻¹(f) = Q_o⁻¹ f⁻ⁿ for frequency with respect to the body wave quality factors. The coda normalization method is used to obtain a quality factor as a function of frequency with an assumed model for geometrical spreading.

The coda normalization method provided the Q⁻¹ models of the P- and S-waves propagating through the crust for a given geometrical spreading model. Quality factors for P- and S waves were calculated as functions of frequency for a distance interval of 2 - 45 km. Strong frequency dependency of Q_p⁻¹(f) and Q_s⁻¹(f) suggests heterogeneity of the medium. S- and P-wave frequency dependencies are similar and the ratio Q_p⁻¹/Q_s⁻¹ varies from 1.5 to 4.
3. Probabilistic seismic hazard analysis for hard rock in the Central Basin
(by B. Manzunzu, B. Zulu and V. Midzi)

The scope of work in calculating the seismic hazard within the region bounded by the coordinates (27.6° to 28.4° Longitude and -26.4° to -26.0° Latitude), included the following:

- Review of local seismological information within the East Rand, Central Rand and West Rand.
- Preparation of a local seismotectonic model on the basis of the earthquake catalogue defined above including recurrence parameters of identified seismic source zones.
- Selection of a ground motion prediction equation (GMPE) that is appropriate for mining induced seismicity.
- Calculation of seismic hazard and preparation of hazard maps at periods T = 0.1s and T = 1.0s, for the region mentioned above. The hazard maps will be prepared for 10% probability of exceedance in 50 years (return period of 475 years) and also in 100 years (return period of 979 years).
- Uniform Hazard Spectra for three selected sites in Gauteng (i.e. Johannesburg, Soweto and OR Tambo International Airport)

3.1 Seismic source characterisation

In a typical seismic hazard assessment, seismic sources are considered to be those sources that are capable of contributing to the ground-motion hazard at the region of study. In this study, the identification and demarcation of sources was restricted by the scope of the SWMP project. Thus the sources are located in the Central Rand,
East Rand and West Rand (Figure 4). These were selected as the seismic sources and modeled as area source zones.

Figure 4. Events located in the Witwatersrand basin by the CGS and source zones used in this study (Mining source zones – ZONE1, ZONE 2, ZONE 3 and ZONE4 marked with black boundaries). The thin light lines represent boundaries of mine regions.

Mining-related seismic source

Zone 1: About 99 earthquakes were recorded during a period from March 1981 to July 2012. The earthquakes varied from small events of magnitude $M_L$ 1.1 to a maximum of $M_L$ 3.6.

Zone 2: The ZONE2 seismic source zone has 215 earthquakes recorded between January 1971 and March 2012. Most of the events were recorded after 2005 when
monitoring was improved in the mining regions. The largest recorded earthquake had magnitude $M_L 4.1$. Many of the events had small magnitudes with the smallest of magnitude $M_L 0.7$.

**Zone 3:** Only 163 earthquakes were recorded and located in the ZONE3 seismic source zone between May 1971 and September 2012. The magnitudes of the events varied from $M_L 0.6$ to a maximum of $M_L 3.9$. The period between 1989 and 2004 was very quiet with only one event recorded and located in the zone.

**Zone 4:** The seismic source zone, ZONE4, is the most active zone with a total of 1589 earthquakes recorded since 1971. The events were recorded throughout the period, with several peak periods observed. Most of the events had magnitude greater than $M_L 2.0$, with largest earthquake having a magnitude of $M_L 4.8$.

**Earthquake recurrence parameters**

Recurrence parameters used to characterize the four zones were determined and are presented in Table 1. These include $b$ values and the associated activity rates. Also determined were the $M_{max}$ values for each source.

Table 1. The calculated recurrence parameters for the seismic zones used in the hazard assessment. The $b$ values and activity rates were determined using the two computer programs, BVALUE and ZMAP. $M_{obs}$ refers to the maximum observed magnitude of events for each zone.

<table>
<thead>
<tr>
<th>Seismic Zones</th>
<th>Catalogue length</th>
<th>Seisan b-value</th>
<th>Activity rate ($M\geq 3.0$) Seisan</th>
<th>Zmap b-value</th>
<th>Activity rate ($M\geq 3.0$) Zmap</th>
<th>$M_{obs}$</th>
<th>$M_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE1</td>
<td>1981-2012</td>
<td>1.33398</td>
<td>0.054954</td>
<td>1.3198</td>
<td>0.054954</td>
<td>3.6</td>
<td>5.13</td>
</tr>
</tbody>
</table>
3.2 Ground-motion model

The ground-motion model predicts the distribution of expected ground-motions conditional on the occurrence of a given earthquake scenario, which is usually characterised in terms of magnitude, source-to-site distance and site conditions. The equation by Pankow & Pechmann (2004) was found to be appropriate for small to moderate magnitude events and thus was used in the hazard assessment. It is important that equations used in seismic hazard calculations are consistent in terms of the variables considered. Therefore, where there are differences in terms of the definitions employed for the explanatory variables used in the parameterisation of the equation, or in the horizontal component definition used for the predicted variable, adjustment factors need to be applied (Bommer et al., 2005). However, for the equation used, only the style of faulting required an adjustment given that the region under study is dominated by normal faulting (Table 2).

Table 2. Style-of-faulting adjustment.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Style-of-Faulting</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pankow &amp; Pechmann (2004)</td>
<td>Not included explicitly. Dataset is assumed to be 55% Strike-slip, 45% Normal</td>
<td>FN:EQ = 0.9722 at all periods</td>
</tr>
</tbody>
</table>
3.3 Probabilistic seismic hazard analysis

The probabilistic seismic hazard calculations were carried out using the FRISK88M software by Dr Robin McGuire and colleagues at Risk Engineering Inc. (REI).

The following assumptions were made:

- Calculations were made for Spectral Acceleration with 10% probability of being exceeded at least once in 50 years and 100 years (i.e. return periods of 475 and 979 years respectively). The return period (RP) is the reciprocal of the annual frequency of exceedance (AFE).
- The minimum magnitude adopted was $M_{\text{min}} = 3.5$ which is appropriate to capture ground motions induced by mining related seismicity.
- Mining-related seismicity was assumed to be located in the top 2 km and 3 km of the crust.
- Epistemic uncertainty in the recurrence parameters as well as in the focal depth were implemented in the assessment using the logic tree method.

3.4 Results and discussion

Seismic hazard maps were prepared at $T = 0.1\text{s}$ and $T = 1.0\text{s}$ for return periods of 475 years and 979 years. An example of the results is presented in Figure 5. The highest accelerations were observed to coincide with areas of high seismicity.
Figure 5. SA at $T=0.1\text{s}$ map for the 475 years return period (units in g). Also shown are three sites for which site specific hazard assessment was carried.

Also determined were uniform hazard spectra (UHS) for both return periods of 475 and 979 years for sites in Central Johannesburg, Soweto and OR Tambo International Airport. The results are shown in Table 3 and illustrated in Figure 6. All the UHS are based on an inherent structural damping of 5% and also at a $V_{s30}$ of 750 m/s.

Figure 6. Uniform Hazard Spectra at 5% damping for the return periods of 475 years (solid lines) and 979 years (broken lines) at the 3 sites.
Table 3. Spectral accelerations (g) for the return periods of 475 and 979 years expected at the 3 sites.

<table>
<thead>
<tr>
<th>Periods (s)</th>
<th>Johannesburg 475</th>
<th>Johannesburg 979</th>
<th>Soweto 475</th>
<th>Soweto 979</th>
<th>OR Tambo 475</th>
<th>OR Tambo 979</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.1265</td>
<td>0.1557</td>
<td>0.1290</td>
<td>0.1580</td>
<td>0.0840</td>
<td>0.1050</td>
</tr>
<tr>
<td>0.10</td>
<td>0.1450</td>
<td>0.1820</td>
<td>0.1470</td>
<td>0.1825</td>
<td>0.0960</td>
<td>0.1220</td>
</tr>
<tr>
<td>0.15</td>
<td>0.1605</td>
<td>0.1965</td>
<td>0.1620</td>
<td>0.1970</td>
<td>0.1090</td>
<td>0.1360</td>
</tr>
<tr>
<td>0.20</td>
<td>0.1540</td>
<td>0.1880</td>
<td>0.1550</td>
<td>0.1890</td>
<td>0.1050</td>
<td>0.1310</td>
</tr>
<tr>
<td>0.30</td>
<td>0.1410</td>
<td>0.1720</td>
<td>0.1405</td>
<td>0.1720</td>
<td>0.1405</td>
<td>0.1720</td>
</tr>
<tr>
<td>0.50</td>
<td>0.0835</td>
<td>0.1032</td>
<td>0.0850</td>
<td>0.1055</td>
<td>0.0555</td>
<td>0.0674</td>
</tr>
<tr>
<td>1.00</td>
<td>0.0400</td>
<td>0.0497</td>
<td>0.0414</td>
<td>0.0510</td>
<td>0.0260</td>
<td>0.0320</td>
</tr>
<tr>
<td>2.00</td>
<td>0.0170</td>
<td>0.0223</td>
<td>0.0173</td>
<td>0.0226</td>
<td>0.0112</td>
<td>0.0141</td>
</tr>
<tr>
<td>3.00</td>
<td>0.0091</td>
<td>0.0113</td>
<td>0.0093</td>
<td>0.0113</td>
<td>0.0058</td>
<td>0.0070</td>
</tr>
</tbody>
</table>

As expected the acceleration of the 979 year return period UHS was higher than that observed for the 475 year period at all sites. The hazard at Central Johannesburg and OR Tambo International airport is very similar with that at the airport slightly less. The UHS observed at Soweto has a shape that is very different to that at the other sites at short periods, with two peaks observed at 0.15s and 0.3s. However, the main peak is observed at 0.3s compared to 0.15 sec for the other two spectra.
4. Risk assessment due to seismic activity for different types of building classes in the Johannesburg CBD

(A. Kijko and A. Smit)

Problem Statement

The aim of the study was to provide a methodology and quantification of the seismic risk associated with seismic activity caused by an increase in the water level in abandoned mines under the Johannesburg (JHB) CBD. The expected damages for 12 of the most characteristic building classes in the Johannesburg CBD were estimated and described in theoretical overview in the main report.

The deliverable in this investigation contains an assessment of the seismic risk associated with the JHB CBD infrastructure caused by the maximum possible seismic event magnitude. The investigation also includes an assessment of the expected damage to 12 classes of buildings as a function of distance to seismic event location with the maximum possible magnitude.

The main report provides a methodology for a) the assessment of the maximum possible seismic event magnitude, caused by an increase in the water level in abandoned mines under the JHB CBD and b) the assessment of the seismic risk associated with a scenario seismic event derived in a). Deterministic seismic risk analysis (DSRA), also known as probable maximum loss (PML) in insurance industry, is the methodology applied in this project to calculate the required parameters. The methodology was implemented by utilizing the following two ground motion prediction equations (GMPE):

i. GMPE that are based on records of seismicity of the so called Central South African Low Zone (Du Plessis, 1996). The applied GMPE is
expressed in terms of Modified Mercalli (MM) intensity (Singh and Hattingh, 2008).

ii. GMPE expressed in terms of peak ground acceleration (PGA) (Atkinson and Boore, 2006) which was then converted into MM intensity by use of the relation derived by Ambraseys (1974).

Each of these GMPEs was applied for the maximum estimated seismic event magnitude $M_{\text{max}}$ as well as four assumed local magnitudes ($M_L$): 5.0, 5.6, 6.0 and 6.8. All calculations were repeated at distances of 5, 10, 15 and 25 km in the JHB CBD area.

The assessment of the seismic risk caused by an increase in the water level in abandoned mines under the JHB CBD resulted in an investigation into the seismic activity of the area. This effect was graphically portrayed in the quantification of the seismicity before and after the discharge of the water for the provided time period.

The methodology and detailed results for this project are available in “Risk Assessment due to Seismic Activity for Different Types of Building Classes in the Johannesburg CBD”, Part 1 and 2.

4.1 Results and Discussion

Two different seismic event catalogues (International Seismological Centre (ISC) and Council for Geoscience (CGS)), were used in this report. This was due to concerns being raised regarding the level of completeness of the data contained in the supplied seismic event catalogue and the consistency of seismic event magnitude determination. It must be strongly emphasized, that the estimated maximum seismic event magnitude and therefore, by definition, the results of the
DSRA are heavily dependent on the underlying seismic event catalogue. To provide a point of comparison, seismic event data was extracted from the ISC for approximately the same area and for the period January 2000 to May 2011.

From the study, it is concluded that there appears to be an increasing trend in the level of seismicity and the amount of energy released, with the nature of the seismicity changing from induced to tectonic-like origin.

The increase in the water level as well as the above results, gave rise to the strong suspicion that the nature of the seismicity in the area could have changed from pure induced to tectonic-like in origin. For this reason four additional, tectonic-like scenarios, (events with magnitude 5.0, 5.6, 6.0 and 6.8) were also included and analysed in the risk assessment process.

The results of the calculation of the maximum seismic event magnitude, as summarized in Table 4 (Table 3 in the main report), also indicate the change of the pattern of seismicity with time.

The very significant decrease in the $b$-value of the Gutenberg-Richter frequency magnitude relation, from 1.5 (before 2005) to close to 1.0 (after 2005), was observed in the analysis of both catalogues and is extremely worrying. Such a significant decrease of the $b$-value is indicative of an overall change in the generating mechanisms of the seismic events after 2005 and coincides with the time when the flooding in the area commenced. High $b$-values are characteristic of induced seismicity and $b$-values close to 1.0 are typical for tectonic origin seismicity.

It can be concluded that the seismicity under the JHB CBD has changed its pattern from induced to tectonic-like origin. A hypothetical explanation of such a phenomenon can be derived from the underlying physical problem. Acid water that is under great pressure penetrates the deep rock masses, thus lubricating the faults, and realising tectonic origin stresses. In another words, the acid water is triggering
tectonic origin earthquakes. With tectonic origin seismicity there exists the possibility to observe a very strong seismic event e.g. magnitude 6.0 and larger. Whether this hypothesis true, the authors can only speculate.

Table 4. Estimated area-characteristic seismic hazard parameters for the CGS and the ISC sub-catalogues. The maximum possible seismic event magnitude was calculated according to the Kijko-Sellevoll-Bayes procedure (Kijko, 2004).

<table>
<thead>
<tr>
<th>Period</th>
<th>Catalogue Name</th>
<th>CGS</th>
<th>ISC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(CGS Cat1)</td>
<td>2000-2005</td>
<td>2005-2012</td>
</tr>
<tr>
<td></td>
<td>(CGS Cat2)</td>
<td>2000-2005</td>
<td>2005-2011</td>
</tr>
<tr>
<td>$b$</td>
<td>1.50 ± 0.00</td>
<td>0.87 ± 0.38</td>
<td>1.50 ± 0.00</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>95.46 ± 29.73</td>
<td>23.65 ± 16.67</td>
<td>62.08 ± 19.01</td>
</tr>
<tr>
<td>$m_{max}$</td>
<td>4.42 ± 0.34</td>
<td>3.99 ± 0.13</td>
<td>4.09 ± 0.25</td>
</tr>
</tbody>
</table>

Table 5 (Table 4 in the main report) represents the expected damage for the three most typical building structures in South Africa, for a magnitude 6.0 at an epicentral distance of 10 km for GMPE calculated via MM intensity and for GMPE calculated via PGA translated to MM intensity respectively. The equivalent results for the four
assumed local magnitudes ($M_L$): 5.0, 5.6, 6.0 and 6.8, derived for the two types of ground motion prediction equations, at distances of 5, 10, 15 and 25 km in the JHB CBD area are provided in Appendix 5 and 6 of the main report.

Table 5: Central damage factors for the three most typical building structures in South Africa, for a magnitude 6.0 at an epicentral distance of 10 km for GMPE calculated via MM intensity and for GMPE calculated via PGA translated to MM intensity respectively.

<table>
<thead>
<tr>
<th>Building Class Description</th>
<th>Central Damage Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MM Intensity</td>
</tr>
<tr>
<td>#3: Unreinforced Masonry, Bearing Wall, Low Rise.</td>
<td>18.35</td>
</tr>
<tr>
<td>#8: Reinforced Concrete Shear Wall without Moment Resisting Frame, Medium Rise.</td>
<td>7.63</td>
</tr>
<tr>
<td>#9: Reinforced Concrete Shear Wall without Moment Resisting Frame, High Rise.</td>
<td>10.07</td>
</tr>
</tbody>
</table>

From Table 5 it is evident that there is a discrepancy when utilizing GMPE with MM Intensity compared to the GMPE which utilize PGA transformed into MM Intensity. However, at this stage it is very difficult to judge, which set of results provide a more accurate overview of the seismic hazard and risk of the Johannesburg CBD due to the rising acid water level. Based on all the information as described in Part 1 of the main report, the authors recommend the DSRA results based on the GMPE which are expressed in terms of MM intensity (Appendix 5 in the main report).

The conclusions and statements, made in the main report as well as in this summary, are very preliminary since it is based on a very short, incomplete and
inconsistent catalogues. It is essential that it should be verified with additional analysis and a follow-up study in the years to come when more information are available, in terms of additional observed seismic events from more seismic stations and information on the depth and mechanism of the observed events.

5. Subsurface engineering evaluation of the Johannesburg City area

(by S. Diop)

A significant part of the damage related to destructive earthquakes around the world is associated with seismic wave amplification due to local site effects. The local site conditions could be very different due to variations in thickness and properties of soil layers. In the first year of investigation (2011/2012), three case studies have been considered to generate useful depth-to-bedrock profiles for preliminary planning purposes in identifying areas, where strong ground motion could be amplified. The results have also indicated that the most favourable topographic situation for thick soil deposits in the Johannesburg city area occupies a graben valley striking east-west through the centre of Johannesburg city.

This research topic was initially proposed with the following main objectives: (i) to collect, analyse and evaluate all available data in the published literature and confirm the geological formations, nature and depth of the underlying materials on site, (ii) to establish the engineering properties of the relevant soil layers encountered, and (iii) to analyse and interpret the factual data obtained from the study, and provide recommendations regarding the spatial distribution of soil depth in a depositional landscape of the study area in order to delineate the most favourable locality for the first level microzonation map in support of the strong ground motion amplification prediction and the development of an early warning system for risk reduction. This report briefly reviews these objectives focussing on identifying near-surface geological and geotechnical conditions in Johannesburg city area and surrounds.