STRATEGIC ENVIRONMENTAL ASSESSMENT FOR EXPANSION OF ELECTRICITY GRID INFRASTRUCTURE IN SOUTH AFRICA

Seismicity Assessment Report

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Draft v3 Specialist Assessment Report for Stakeholder Review

SEISMICITY SPECIALIST REPORT

Impacts of Earthquakes, Seismicity and Faults

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ABBREVIATIONS AND ACRONYMS

CGS	Council for Geoscience
DEA	Department of Environmental Affairs
DRR	Disaster Risk Reduction
EGI	Electricity Grid Infrastructure
GMPE	Ground motion prediction equation
M	Earthquake Magnitude
M_L	Local Magnitude
M_{max}	Magnitude of the largest credible earthquake
M_w	Moment Magnitude
MMI	Modified Mercalli Intensity
MASW	Multi-channel analysis of surface waves
PGA	Peak Ground Acceleration
PGPN	Phased Gas Pipeline Network
PPV	Peak Particle Velocity
PSA	Peak Spectral Acceleration
PSHA	Probabilistic Seismic Hazard Assessment
SANSN	South African National Seismograph Network
SANS	South African National Standard
SEA	Strategic Environmental Assessment

SUMMARY

South Africa is generally described as a **'stable continental region'** (SCR) as it is remote from the boundaries of tectonic plates and active continental rifts. This does not mean that large earthquakes cannot occur, but that they occur far less frequently than in places such as California, Italy and Japan, and the maximum credible magnitude M_{max} is somewhat lower. Eight damaging earthquakes (5.0<M<6.3) have occurred in South Africa during the last 120 years (Earthquake activity in South Africa is reviewed in Appendix A of this report). Five had an unequivocal tectonic origin, while three were in mining districts. **Mining-related earthquakes (M_{max}5.7) are restricted to the regions where deep and extensive gold mining has taken place**, notably the Welkom and Klerksdorp districts. Thus a potentially damaging earthquake (say 5.0<M<6.5) occurs somewhere in South Africa, on average, every 10-20 years; structural damage is limited to a radius of 100 km from the epicentre. Three of these earthquakes caused deaths: the toll of the 1969 Ceres-Tulbagh earthquake is reported as either nine or 12; two underground workers died as a result of the 2005 Stilfontein earthquake; and one person was killed by a collapsed garden wall during the 2014 Orkney earthquake.

Larger tectonic earthquakes (6.5<M<8.0) are rare in stable regions, but may occur both on faults with a recent (100s-10,000s years) history of earthquake activity, and in areas with no known precursory activity. Such events could therefore take place anywhere. Thus the locations of historical earthquakes cannot be taken as reliable indicators of areas where large earthquakes will occur.

The **key issue** associated with the development of electricity grid infrastructure in relation to seismicity is the **potential damage to EGI due to seismic (related) hazards, and associated social, environmental and economic risks**. Damage to EGI (damage to the structure itself or breakage of cables) can result from (a) ground shaking or displacement across the earthquake fault (Direct impact) or (b) ground displacements triggered by the earthquake shaking, such as landslides, liquefaction and lateral spreading.

Local conditions that might increase the hazard posed by secondary effects of earthquakes should therefore also be taken into account when siting and constructing EGI; i.e. steep slopes that are prone to landslides and thick soils and alluvium that may amplify ground motions and/or liquefy when shaken. These areas should either be avoided, or the EGI reinforced, or ground improvement measures implemented.

EGI such as pylons and sub-stations built according to international standards are generally resilient to moderate levels of ground shaking expected in South Africa. There is abundant local and international literature describing risks that earthquakes pose on EGI and the required mitigation measures.

Given that South Africa is low seismic hazard region and providing that the above design and management actions are effectively implemented in areas prone to landslides and/or characterised by problem soils, risks posed by primary or secondary effects of earthquakes are considered to be low for the development of EGI within the proposed corridors. **Earthquakes do not pose a significant risk to Electricity Grid Infrastructure (EGI) in the expanded Eastern and Western corridors**.

In must be noted that earthquake risk should not be seen in isolation. The risk posed by other natural hazards, such as floods, wind and landslides should also be considered.

Corridor	Overall Suitability	Comment
Expanded Eastern	Suitable	Earthquake shaking may trigger rock falls and landslides in areas of rugged topography that may damage EGI. Thick soils and alluvium may amplify ground motions and/or liquefy when shaken. For example, liquefaction occurred during the 1932 M_L6.3 St Lucia earthquake. Sites prone to landslides and liquefaction should be identified and either avoided or the EGI reinforced appropriately, or ground improvement measures implemented.
Expanded Western	Suitable	Earthquake shaking may trigger rock falls and landslides in areas of rugged topography that may damage EGI. For example, the 1969 M_L6.3 Ceres-Tulbagh earthquake triggered some rock movements. The Expanded Western corridor has regions of rugged topography. Sites prone to landslides should be identified and either avoided or the EGI reinforced appropriately.

1

1 INTRODUCTION

The Department of Environmental Affairs (DEA) commissioned a Strategic Environmental Assessment (SEA) for a phased gas pipeline network (PGPN) and electricity grid infrastructure (EGI) expansion in South Africa. The geographic extent of the "energy corridors" covered by the SEA is shown in Figure 1. The expanded EGI corridors shown in diagonal lines in Figure 1 are part of this assessment. They are extensions to the gazetted Western and Eastern EGI corridors (as identified in the 2016 EGI SEA).

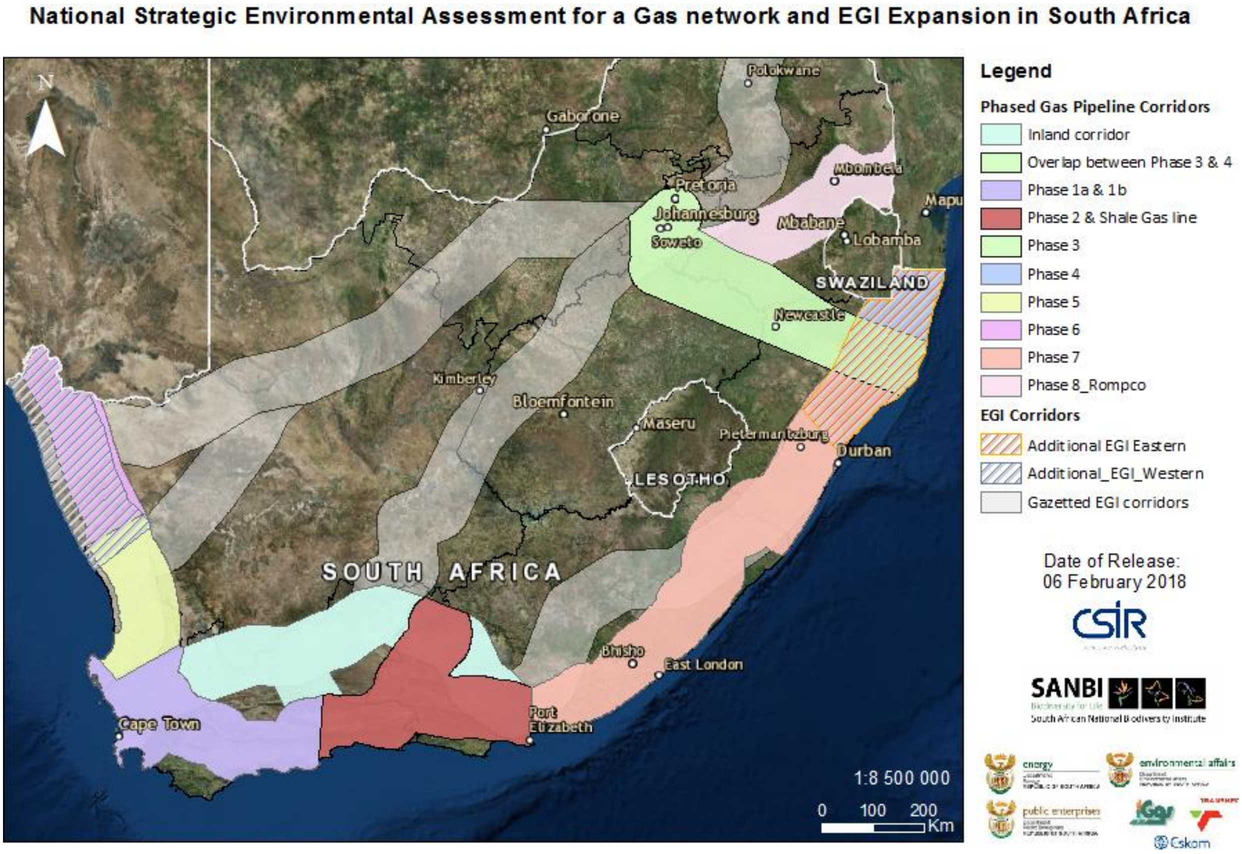

Figure 1: The PGPN and additional EGI Corridors for Specialist Assessment

This Specialist Assessment Report addresses the risks posed by earthquakes and associated phenomena such as landslides, liquefaction and tsunamis on the expanded EGI corridors.

The high level conclusions and recommendations are contained in the body of the report. The evidence on which these conclusions are based is contained in three appendices:

A. Earthquake monitoring, hazard and risk assessment in South Africa;
B. OpenQuake PSHA computation for South Africa and the energy corridors; and
C. Vulnerability of EGI.

2 SCOPE OF WORK

2.1 Terms of Reference

EGI are "lifelines", a term used by the Disaster Risk Reduction (DRR) community to describe *"man-made structures [that are] important or critical for a community to function, such as roadways, pipelines, power lines, sewers, communications, and port facilities"* (Aki & Lee 2003: 1821). Lifelines are vulnerable to damage caused by the shaking of the ground during an earthquake, as well as associated phenomena such as the displacement of the ground across a fault, landslides, liquefaction of soils and tsunamis. Not only will damage to EGI and pipelines disrupt the supply of electricity and gas, but it could also trigger a cascade of other hazardous situations, such as fires, explosions, asphyxiation and electrocution.

Earthquakes are driven either by geological forces (e.g. motion of tectonic plates, isostatic response to erosion, volcanism) or certain human activities (e.g. mining, impoundment of reservoirs, fluid injection or extraction). EGI do not affect seismicity in any known way. The following issues are assessed in this study:

- What damage could earthquake-related phenomena (e.g. strong ground motion, surface displacement as the result of fault rupture, landslides triggered by strong ground motion, liquefaction of soils induced by ground shaking, tsunami) cause to EGI?
- What impact would the damage to EGI have on the environment and people?

This assessment focuses primarily on the interpretation of existing data and is based on defensible and standardised and recognised methodologies. It discusses direct, indirect and cumulative impacts, and identifies any gaps in information linked to earthquakes and seismicity with respect to EGI.

2.2 Methodology

The following methodology was used to assess the impact of earthquakes on EGI, and the consequent impact of any damage on the environment or people, as well as measures to mitigate the impact:

1. Review of available seismic and geological data, previous hazard and risk assessments and relevant research work (Appendix A).
2. Computation of the Probabilistic Seismic Hazard Assessment (PSHA) for the energy corridors considering recurrence periods, Peak Ground Acceleration (PGA) and spectral accelerations (Appendix B).
3. Assessment of the vulnerability of the proposed energy infrastructure (e.g. pylons, transformers, substations, etc.) to ground vibrations (Appendix C).
4. Assessment of the impact of earthquakes on the proposed energy infrastructure and the consequent impact of any damage on the environment or people.
5. Recommendations for site specific seismic hazard assessment studies or any supplementary monitoring that may need to be done for the proposed and actual EGI infrastructure routes within the corridor.

2.3 Data Sources

The primary sources of information used in this study are listed in Table 1 below.

Table 1: Data Sources

Data title	Source and date of publication	Data Description
Landslide geohazard for South Africa	Singh et al. 2011	Detailed study on landslides in South Africa
CGS Geohazard Atlas	http://197.96.144.125/jsviewer/Geohazards/index.html#	Collapsing and swelling soils
Earthquake seismology	Durrheim 2015	Comprehensive review of earthquake monitoring, hazard and risk assessment in South Africa.
The history of mining seismology	Durrheim & Riemer 2015	Comprehensive review of mining-induced earthquake monitoring, hazard and risk assessment in South Africa.
Compiling a homogeneous earthquake catalogue for Southern Africa	Mulabisana 2016 (MSc dissertation)	Earthquake catalogue for South Africa
Seismic sources, seismotectonics and earthquake recurrence for the KZN coastal regions.	Singh 2016 (PhD thesis)	Active faults in the KZN coastal region
Seismotectonics of South Africa	Manzunzu et al. 2019	Seismotectonic model for South Africa, which includes active faults and earthquake source mechanisms.
The Probabilistic Seismic Hazard Assessment (PSHA) of South Africa.	Midzi et al. 2018 (in review)	PSHA for South Africa
Development of a South African Minimum Standard on ground vibration, noise, air-blast and flyrock near surface structures to be protected	Milev et al. 2016	Blasting-induced ground vibrations
Global catalogues of earthquakes in stable continental regions	Johnston et al. 1994	Global catalogues of earthquakes in stable continental regions

Relevant information from the primary sources listed in Table 1 above and many secondary sources are reviewed in the appendices.

2.4 Assumptions and Limitations

The limitations and assumptions applicable in this study are listed in Table 2 below.

Table 2: Assumptions and Limitations

Limitation	Included in the scope of this study	Excluded from the scope of this study	Assumption
Completeness of the earthquake catalogue	Earthquake catalogue published by the SANSN.	Data recorded by local mine and research networks.	Catalogue sufficiently complete to provide a reasonable estimate of recurrence times and M_{max}; values from similar tectonic domains elsewhere in the world provide reasonable constraints (see Johnston et al. 1994; Vanneste et al. 2016).
Ground motion prediction equations (GMPEs)	GMPEs from similar tectonic domains elsewhere in the world.	Measurement of local GMPEs.	GMPEs from similar tectonic domains elsewhere in the world are adequate.
Site effects	Descriptions of site effects in published papers and reports.	Measurement of site effects.	Reasonable estimates of local site amplification can be made from geological knowledge.
Site Specific PSHA	Review of published regional PSHA studies.	PSHA calculations that include local site effects.	PSHA for regional studies is for bedrock.
Analysis of liquefaction potential	Reports on occurrence of liquefaction in KwaZulu-Natal.	Measurement of liquefaction susceptibility.	Knowledge of liquefaction potential is poor.
Active faults	Traces of active faults described in published papers and reports.	Mapping and monitoring of active and capable faults.	Knowledge of active and capable faults is poor.
Vulnerability of EGI structures	Published papers and reports.	Measurement or calculation of seismic response.	Local EGI structures meet international standards.

2.5 Relevant Regulatory Instruments

Table 3 below provides feedback on the relevant regulatory instruments.

Table 3: Relevant Regulatory Instruments

Instrument	Key objective
International Instruments	
Eurocode 8	In the Eurocode series of European standards (EN) related to construction, Eurocode 8: Design of structures for earthquake resistance (abbreviated EN 1998 or, informally, EC 8) describes how to design structures in a seismic zone, using the limit state design philosophy. http://eurocodes.jrc.ec.europa.eu/
ISO4866	ISO4866 provide guidelines for the measurement of vibrations and evaluation of their effects on fixed structures, not safe limits of vibration for structures. Section 12.4 of the ISO4866 guideline refers users to safe limits published by authorities in France, Germany and Norway, noting that these limit values take building category, vibration category, and frequency range into account.
National Instruments	
South African Constitution	Section 24 states: "Everyone has the right – a) To an environment that is not harmful to their health and well-being, and b) To have the environment protected, for the benefit of the present and future generations, through reasonable legislative and other measures that – i. Prevent pollution and environmental degradation; ii. Promote conservation; and iii. Secure ecologically sustainable development and use of natural resource while promoting justifiable economic and social development."
Disaster Management Act (Act 57 of 2002; amended in Act 16 of 2015)	Each metropolitan and district municipality is required to develop such a disaster management strategy.
Geoscience Act (Act 100 of 1993; amended in Act 16 of 2010)	The Act mandates the Council for Geoscience to be the custodians of geotechnical information, to be a national advisory authority in respect of geohazards related to infrastructure and development, and to undertake reconnaissance operations, prospecting research and other related activities in the mineral sector; and to provide for matters connected therewith.
South African National Standard (SANS) SANS4866	The South African Bureau of Standards adopted standard ISO4866 of the International Organization for Standardization (ISO). The first ISO edition was published in 1990 and a second edition in 2010. SANS4866:1990 = ISO4866:1990 SANS4866:2011 = ISO4866:2010
SANS 10160-4-2017	South African National Standard (2017). Basis of Structural Design and Actions for Buildings and Industrial Structures. Part 4: Seismic Actions and General Requirements for Buildings. Pretoria: South African Bureau of Standards. ISBN 978-0-626-30384-6.
Provincial Instruments	
Local Government Municipal Systems Act (No. 32 of 2000)	In terms of the Local Government Municipal Systems Act (No. 32 of 2000) all municipalities are required to complete Spatial Development Frameworks (SDFs) as a core component of Integrated development Plans (IDPs). The Department of Rural Development and Land Reform has developed guidelines to assist with the process. http://www.ruraldevelopment.gov.za/phocadownload/spatial_Planning_Information/SDF-Guidelines/A5.pdf

3 KEY SEISMIC-RELATED ATTRIBUTES AND SENSITIVITIES OF THE STUDY AREAS

3.1 Terminology

Magnitude (M) is a measure of the energy released by the earthquake and the amount of slip on the fault. Seismograms recorded by many widely-spread seismograph stations are used to assign a single magnitude to an event. The SANSN uses either the local magnitude scale (M_L) or the moment magnitude scale (M_w), which are essentially equivalent for M<6.5. The M_L scale uses the maximum amplitude of ground motion recorded at the various local stations, is quick and easy to measure, but saturates above M6.5. The M_w scale takes the entire seismogram into account and is derived from an assessment of the mass of rock moved (or work done, hence the subscript 'w') by the earthquake. M_w does not saturate and can be estimated from local, regional or global stations. It has been calibrated to match M_L for M<6.5. Earthquakes are generally divided into the following categories: micro M<3, small 3<M<5, moderate 5<M<7 and major M>7. Natural earthquakes are generally only felt when M>3 and only cause significant damage when M>6. However, people unaccustomed to earthquakes may be frightened by the shaking that is produced by a M5 event, even though the amplitude of ground motion is only 1/10 that of a M6 event. It should be noted that earthquakes induced by mining or fluid injection may cause damage if 5<M<6 because they generally occur at much shallower depths than natural events.

Intensity (I) describes the shaking experienced on the surface of the earth. Intensity generally decreases with distance from the epicentre (the point on the earth's surface above the earthquake source), but is also affected by near-surface geology. Shaking is generally amplified where there is a thick layer of alluvium. Reports by many widespread observers are collated to derive Intensity Data Points (IDPs) and compile an isoseismal map. The SANSN uses the **Modified Mercalli Intensity (MMI) scale**.

The levels of the intensity scale can be roughly related to the **Peak Ground Acceleration (PGA)**, a quantity that is used by engineers to design structures. It is expressed either in terms of gals (cm/s^2) or the acceleration of gravity (g, 9.8 m/s^2). To give some examples: an MMI of III (0.001 – 0.002 g) indicates ground motion that is perceptible to people, especially on the upper floors of buildings; VI (0.02 – 0.05 g) is felt by all, many people are frightened and run out of doors, and a few buildings may be slightly damaged; VIII (0.1 – 0.2 g) causes slight damage to earthquake-resistant structures, considerable damage to solid buildings, and great damage to poorly-built buildings; while XII (> 2 g) indicates total destruction, with objects thrown into the air. The resonant frequency of structures depends on their height and footprint. Thus engineers make use of estimates of the **Peak Spectral Acceleration (PSA)**, a measure of ground motion at particular frequencies, to determine if structures will respond to an earthquake.

3.2 Background

Southern Africa is, by global standards, a seismically quiet region as it is far from the boundaries of tectonic plates and active continental rifts (Johnson & Kanter 1990). Seismicity in South Africa arises from both natural sources (e.g. plate tectonic forces, buoyant uplift of the continent after erosion) and human-induced sources (e.g. rock failure caused by mining-induced stresses, slip on faults causes by changes in load and pore fluid pressure during the filling of reservoirs, and vibrations produced by blasting for open pit mining, civil excavation and the disposal of expired munitions). Most earthquakes are induced by deep-level mining for gold and platinum, and thus restricted to the mining districts (Figure 2). However, natural earthquakes do take place from time to time. They are driven by various tectonic forces, such as the spreading of the sea floor along the mid-Atlantic and mid-Indian ocean ridges, the propagation of the East African Rift System, and the response of the crust to erosion and uplift (Calais et al. 2016).

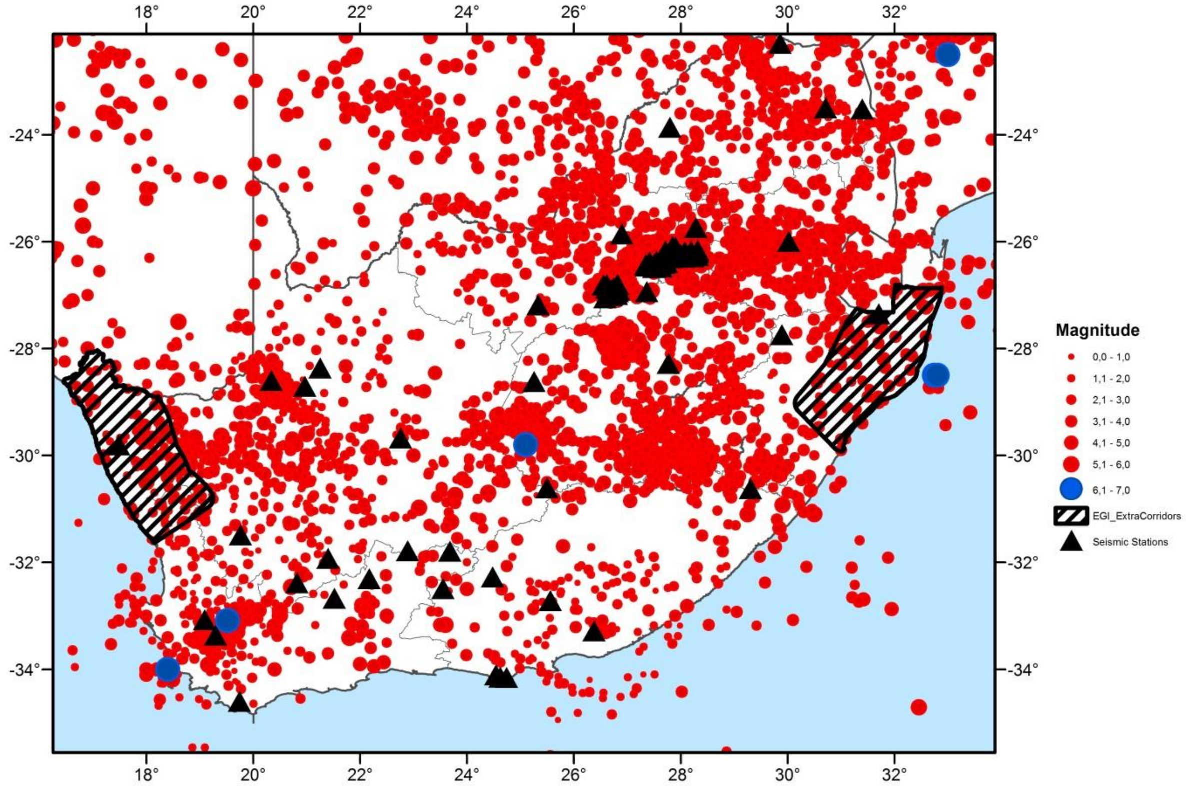

Figure 2: Location of recorded earthquakes in Southern Africa from 1811-2014 in relation to the Expanded EGI corridors which are shown by diagonal lines.

Note: Triangles mark the position of the stations that comprise the South African National Seismograph Network (SANSN).

South Africa has the infrastructure and capability to monitor seismicity and assess seismic hazard and risk. Mulabisana (2016) indicates that the homogenized earthquake catalogue is complete above M2.5 since 1965, but this is thought to be somewhat optimistic as all M>3 earthquakes were only reliably recorded after the establishment of the South African National Seismograph Network in 1971. The bedrock geology has been mapped in fair detail, while geotechnical mapping is largely confined to built-up areas. Studies of earthquake hazard and risk have recently been published by Durrheim (2015), Durrheim & Riemer (2015), Singh (2016), Goedhart (2017), Midzi et al. (2018), and Manzunzu et al. (2019). An assessment of the risk posed by open pit blasting has been published by Milev et al. (2016), while ground vibrations produced by the disposal of expired munitions has been investigated by Grobbelaar (2017).

Ground vibrations may also be produced by blasting in open pit mines and for civil excavations (e.g. road cuttings), and the disposal of expired military explosives. The effect of these blasts is local. Guidelines are available to design rock blasts so that the ground vibration levels are controlled (Milev et al., 2016). Intensities strong enough to cause damage to sensitive structures are usually limited to distances of tens to hundreds of meters, or at most a kilometre or two from the source. Expired munitions are usually detonated on the surface, so relatively little energy is transmitted into the earth and little damage done. However, the shock wave travelling through the air may cause alarm, discomfort, and in some cases damage.

The Council for Geoscience has made measurements of the ground motion produced by military explosives detonated on surface and their effects on buildings (B Manzunzu, pers. Comm., 2018). The measured peak particle velocity (PPV) and dominant frequency of the ground motion was compared with the US Code of Federal Regulations (CFR) that deals with the control of adverse effects caused by explosives. Ground motions were recorded at distances ranging from 5.25 to 29.07 km in a sandy terrain. The biggest charge detonated had a mass of 25000 kg and the highest PPV recorded was 0.0095 cm/s, which is only 0.5% of the CFR limit. The highest PPV was recorded at another range where the geology is hard rock and the equipment was installed within 100 m of the explosion caused by a missile fired from an aircraft. The reading obtained was equivalent to 15% of the CFR limit.

It is important to note that a low rate of seismicity does not mean that there cannot be large earthquakes; just that earthquakes are less frequent. The history of earthquake occurrences and seismological observations and research in South Africa is reviewed in **Appendix A.** Three M>6 tectonic earthquakes have occurred in the last 120 years within the borders of South Africa: in the Western Cape (M6.3, 1969), northern KwaZulu-Natal (M6.3, 1932), and the southern Free State (M6.2, 1912). The 1932 M6.3 St Lucia event is the only M>5 event recorded in either of the EGI corridors considered in this study. A moderately-sized earthquake could prove disastrous should it occur close to vulnerable buildings and lifelines, especially if the structures are not designed to be earthquake-resistant, the terrain is steep and prone to landslides, or the soil is thick and prone to local site amplification or liquefaction.

A recent example of a serious damage produced by a ‘moderate’ earthquake is the M6.0 event that struck Christchurch, New Zealand, on 13 June 2011, claiming nearly 200 lives and causing substantial damage due to soil liquefaction.

Manzunzu et al. (2019) compiled a map of faults that were potentially active during the Quaternary (2.588 ± 0.005 million years ago to the present). See Figure 1 in Appendix B. It should be noted that the time period is considerably longer than that commonly used in the definition of an “active fault”. For example, the glossary in the International Handbook of Earthquake and Engineering Seismology (Aki and Lee, 2003) define an active fault as “a fault that has moved in historic (e.g., past 10,000 years) or recent geological time (e.g., past 500,000 years)”.Only two of these faults (Kango and Bosbokpoort) have palaeoseismological evidence of large earthquakes of magnitude exceeding M7 that caused surface ruptures. It is not clear whether the fissure created by the 1809 Cape Town earthquake (ML6.1) is a surface expression of the fault rupture or the result of near-surface mass movement caused by the shaking.

In summary, a lot is known about the risk that earthquakes pose to EGI from work done both locally and internationally, although further work (e.g. sensitive seismic monitoring, detailed geological and geotechnical mapping) would be beneficial to improve understanding of site specific hazards.

3.3 Key sensitivities within the proposed corridors

Earthquake-related hazards are divided into two categories: (i) primary hazards viz. ground shaking and displacement, and (ii) secondary hazards viz. landslides, soil liquefaction. Parts of the Expanded EGI corridors that are sensitive to earthquake hazards lie within the following regions.

- Regions with **elevated seismic hazard**. An earthquake may cause the ground and EGI to shake to such an extent that damage occurs; or the earthquake rupture causes a displacement between opposite sides of the fault that is large enough to damage structures or break cables that straddle it. Aftershocks may exacerbate the damage caused by the main shock. [Generally the largest aftershock is about 1.2 magnitude units smaller than the main shock (Båth, 1965).] There are numerous examples of damage to EGI as a result of earthquakes in tectonically-active regions (e.g. Fujisaki et al. 2014). Moderate dynamic loading may occur throughout South Africa however while large dynamic loading is possible; the probability of it occurring is estimated to be very low within decadal timescales. EGI built according to international standards should be resilient to this (see **Appendix C**).
- Regions **prone to landslides** and/or characterised by **problem soils** (i.e. soils that are prone to collapse, swelling or liquefaction). Earthquake shaking may trigger landslides and rockfalls and cause soils to liquefy. All these phenomena may lead to damage and loss.

These earthquake-related phenomena could cause damage to EGI that might disrupt the supply of electricity. In worst cases, the damage could trigger a cascade of secondary impacts, e.g. damage to nearby infrastructure and associated impacts/releases.

Of course, there are other many other natural and anthropogenic hazards that may have an impact on these structures, such as storms, floods, wildfires, aircraft crashes and terrorist attacks, and thus the mitigation of the risk posed by earthquakes should not be considered in isolation, but as part of an integrated DRR strategy. The Disaster Management Act (Act 57 of 2002; amended in Act 16 of 2015) makes it obligatory for each metropolitan and district municipality to develop such a strategy.

3.3.1 Probabilistic Seismic Hazard Assessment

The latest and most complete assessment of seismic hazard (PSHA) in South Africa was performed by the Council of Geoscience (Midzi et al. 2018) using an up-to-date homogenised earthquake catalogue. Here we extend the CGS assessment to focus on the energy corridors (Appendix B). The main results for the PGA calculations are shown in Figure 3.

It is important to realise that these are probabilistic estimates made on a relatively coarse grid (0.5° x 0.5°) and at a few key localities. There is no quick and easy way to increase spatial resolution or reduce uncertainty in the PSHA calculations. This can only be done through decades or centuries of monitoring. Identification and mapping of palaeoseismic faults will require extensive field work.

The PGA (10% probability of exceedance in 50 years) in the Eastern and Western extension corridors reach values of about 0.04 g and 0.07 g, respectively. These values are typical of MMI VI, where the shaking is strong enough to cause alarm but only cause minor damage to buildings and well below the damage thresholds of modern EGI (Appendix C). Larger events are possible, but have recurrence times of centuries.

Regions where the risk is relatively high (but still low) are the Klerksdorp and Welkom mining districts in the North West and Free State Provinces, where gold mining at depths approaching 4 km had induced three shallow earthquakes with M>5 that caused damage to surface structures (M5.2, Welkom,1976; M5.3, Stilfontein, 2005; M5.5, Orkney, 2014). Here the PGA (10% probability of exceedance in 50 years) reaches values of about 0.2 g, which is typical of MMI values of about VIII where the shaking is strong enough to cause slight damage to earthquake-resistant structures, considerable damage to solid buildings, and great damage to poorly-built buildings. These regions are far removed from the EGI corridors considered here.

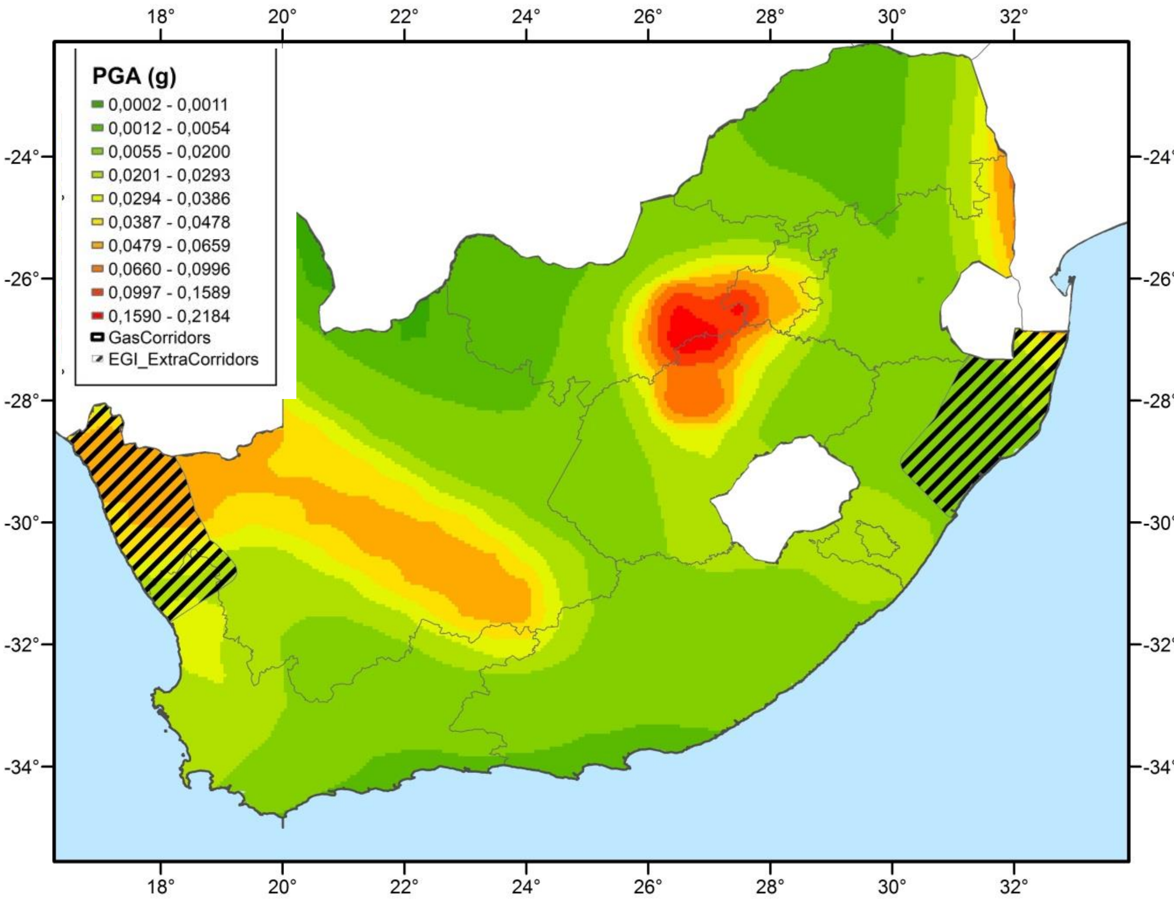

Figure 3: PGA (g) with 10% probability of exceedance in 50 years

The South African National Standard seismic hazard map and hazard zones (SANS, 2017) is shown in Figure 4 and is computed for 10% probability of exceedance in 50 years (return period of 475 years) with the nominal peak ground acceleration expressed in g (9,98 m/s^2). The parametric-historic procedure (Kijko & Graham 1998; 1999) used to produce the seismic hazard map is described in the Council for Geoscience report, *Probabilistic Seismic-Hazard Maps for South Africa*, Version 1, 2003, Pretoria (Kijko et al. 2003). The parametric-historic procedure was developed to combine the best features of the "deductive" and "historic" procedures. Two zones are identified, namely: Zone I Natural seismic activity only, and Zone II Regions of mining-induced and natural seismic activity. Buildings were classified into four "importance classes": I Buildings of minor importance for public safety, e.g. agricultural buildings, etc.; II Ordinary buildings, not belonging to the other categories; III Buildings for which seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions, etc.; and IV Buildings for which integrity during earthquakes is of vital importance for protection, e.g. hospitals, fire stations, power plants, etc. Depending on the seismic zone and importance classes, building were required to comply with certain construction standards.

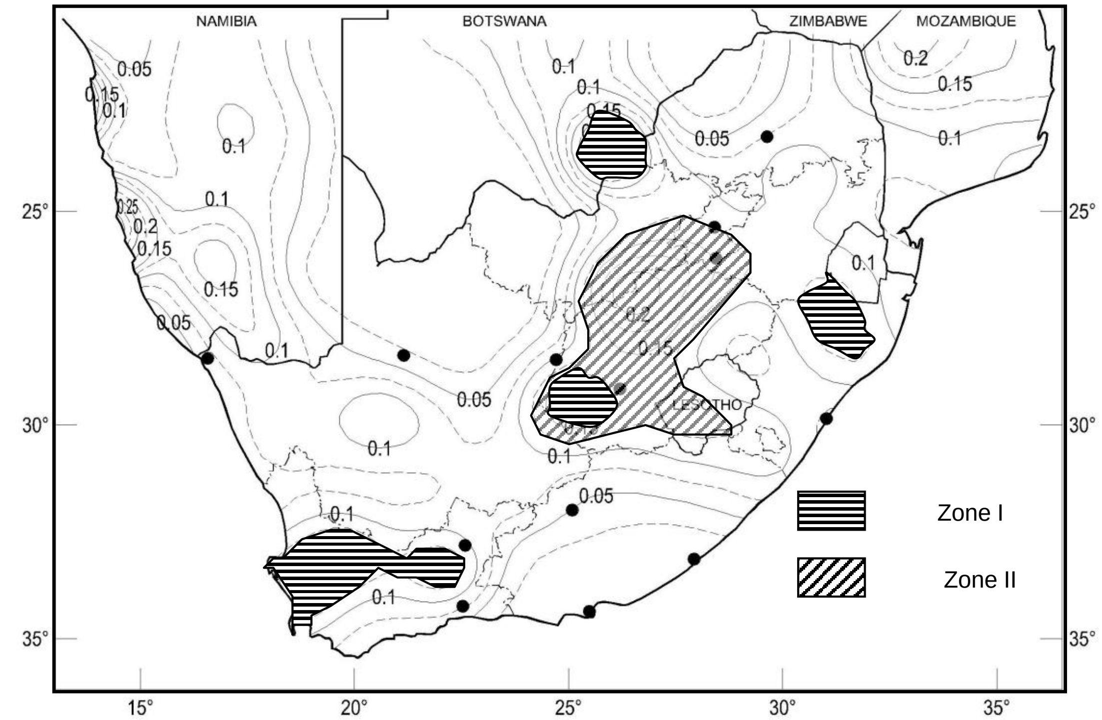

Figure 4: South African National Standard Seismic Hazard Map and Hazard Zones (SANS, 2017)

There are significant differences between the seismic hazard maps produced using Probabilistic Seismic Hazard Assessment (PSHA) method (Figure 3) by Midzi et al (2018) and the parametric-historic method (Figure 4) by Kijko & Graham (1998, 1999), most significantly in the distribution of areas with relatively high PGAs. Both methods agree that PGAs >0.1g have a 10% or greater chance of exceedance in 50 years in the gold mining districts. However, there are large differences with regard to the assessment of the hazard posed by tectonic seismicity. The parametric-historic method gives greater weight to the regions where the large earthquakes have been recorded in the last century, (e.g. southern Free State, Western Cape, northern KwaZulu-Natal), while the PSHA method places greater weight on regions with generally elevated seismicity (e.g. Northern Cape). It is beyond the scope of this study to evaluate the methods, apart from noting that the PSHA method places great emphasis on the definition of seismic source zones using both seismic and non-seismic data, while the parametric-historic method relies on seismic data alone. Of course, the ultimate test lies in the accuracy of their predictions. Unfortunately this will take decades or even centuries as large events are rare and the predictions are long term. They may be considered to provide an example of the challenges of earthquake hazard assessment

3.3.2 Landslide Hazards

Comprehensive surveys of the **landslide hazards** in KwaZulu-Natal and South Africa have been conducted by Singh et al. (2008, 2011). The landslide susceptibility map is shown in Figure 5. [Note that the predominant trigger of landslides is intense rainfall, not earthquakes.] Landslide susceptibility is low for the western EGI corridor, but is significant in parts of the eastern corridor.

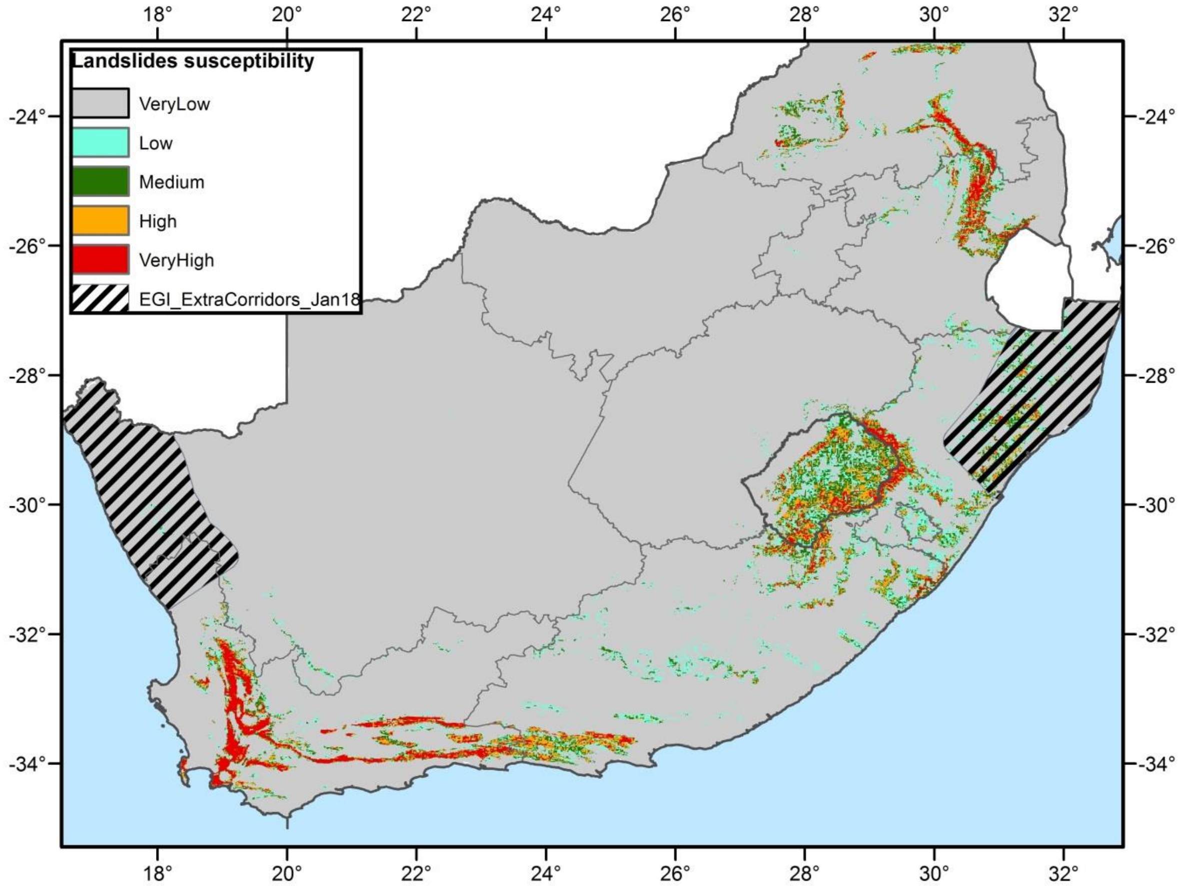

Figure 5: Landslide susceptibility map. This page of the CGS Geohazard Atlas can be viewed online at http://197.96.144.125/jsviewer/Geohazards/index.html. (Singh et al. 2011)

3.3.3 "Problem-Soil" Hazards

The EGI will require excavation for the power line pylons. Thus the upper few meters of the earth should be mapped at the proposed pylon locations to establish the optimum trenching method (e.g. what type of mechanical excavator is required, or if blasting is necessary). Some soils may liquefy during an earthquake. These zones should be identified so that they can be taken into account when choosing EGI routes or deciding on remedial measures. However, it is important to note that some soils can create problems even in the absence of earthquakes. The severity of the problem along proposed EGI routes should be assessed by geotechnical engineers as it is affected by a host of factors (e.g. soil properties and thickness, weight and 'footprint' of structures) that affect the cost of remedial measures (e.g. re-routing of EGI, re-siting of infrastructure, re-design of foundations). Problem soils are divided into two main categories.

i. **Collapsible soils** (Figure 6), also known as metastable soils, are unsaturated soils that undergo a large volume change upon saturation. The sudden and usually large volume change could cause considerable structural damage. The most common types are aeolian soils, typically wind-deposited sands and or silts, such as loess, aeolic beaches, and volcanic dust deposits characterized by showing in-situ high void ratios and low unit weights; and residual soils, which are a product of the in-situ weathering of local parent rocks that leaches out soluble and colloidal materials producing soils with a large range of particle size distribution and large void ratios. Collapsible residual granite sand is found in parts of the Expanded Eastern EGI Corridor; and collapsible transported sands are found in parts of both the Expanded Eastern and Western EGI Corridors.

ii. **Swelling soils** (Figure 7), also known as expansive clay soils, are prone to large volume changes (swelling and shrinking) that are directly related to changes in water content. Soils with a high content of expansive minerals can form deep cracks in drier seasons or years, e.g. the ‘black turf’, a product of the weathering of the mafic rocks of the Bushveld Complex (not located within the Expanded EGI corridors). The occurrence of swelling soils in the Expanded Eastern EGI Corridor ranges from “very low” to “moderate to high” (in some small sections). The occurrence of swelling soils in the Expanded Western EGI Corridor is “very low”.

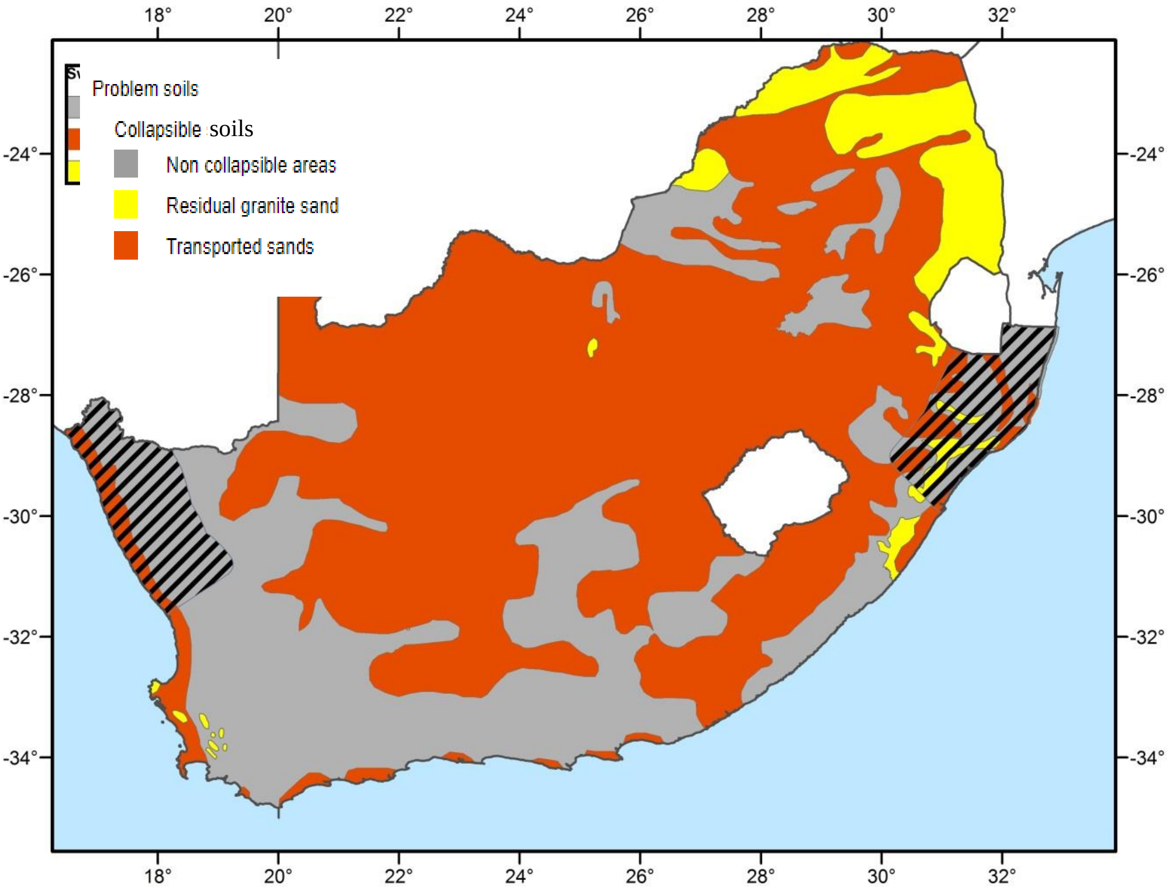

Figure 6: Collapsible soils. This page of the CGS Geohazard Atlas can be viewed online viewed at http://197.96.144.125/jsviewer/Geohazards/index.html

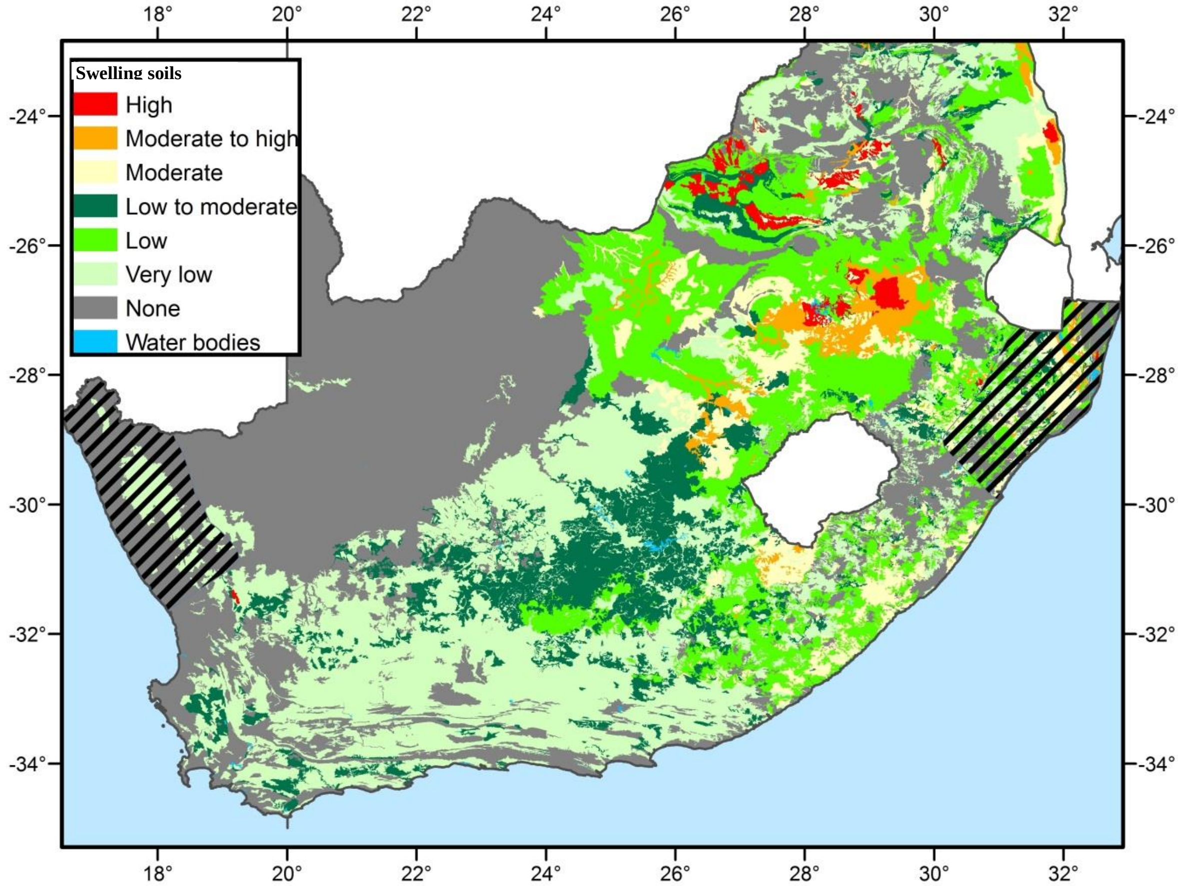

Figure 7: Swelling soils. This page of the CGS Geohazard Atlas can be viewed online viewed at http://197.96.144.125/jsviewer/Geohazards/index.html

3.4 Key sensitivities criteria

The following criteria are proposed to identify regions where EGI may be sensitive to the effects of earthquakes:

1. Elevated seismic hazard, *viz.* regions that have:
    a. Historical or instrumental records of M>5 earthquakes,
    b. Paleoseismic evidence of M>6 earthquakes (age <100,000 years, indicated by mapped and dated fault scarps),
    c. PGA>0.05 g (475 years recurrence, equivalent to 10% probability of exceedance in 50 years), or
    d. Active faults (indicated by present-day seismic activity).
2. Elevated vulnerability, *viz.* sub-regions that have:
    a. Steep topography prone to seismically-triggered landslides,
    b. Thick near-surface low-seismic-velocity layers prone to site amplification, or
    c. Saturated soils and sands prone to liquefaction when shaken.

The pertinent results of the PSHA (Midzi et al. 2018, Appendix B), landslide susceptibility and problem soil cover for the EGI corridors are summarised in Table 4 below. A value of 7.5 has been used for M_{max}. In their global study of M_{max} in stable continental regions, Vanneste et al. (2016) found that M_{max}7.9, and suggested that the recurrence rate for an event this size in an area of 106 km^2, roughly the size of South Africa, was about 70,000 years.

Table 4: Corridor Sensitivities

<table>
<tr><th>Site</th><th>Brief description
PGA (peak ground acceleration) and PSA (peak spectral acceleration) for a return period of 475 years (10% probability of exceedance in 50 years); M_{max} is the size of the largest credible earthquake.</th></tr>
<tr><td>Expanded Eastern EGI Corridor</td><td>East coast from Mozambique border to beyond eThekwini Metropolitan.

The Tugela Fault has been mapped as “potentially active” by Manzunzu et al. (2019).
Areas of rugged topography are prone to landslides. These generally triggered by high rainfall, which may occur from time to time.
Collapsible residual granite soils and collapsible transported sands are found in limited areas.
Swelling soils occur in some areas
$M_w > 6$ tectonic earthquake occurred near St Lucia (1932, with liquefaction).
$M_w > 6$ events could recur one or twice per century
$M_{max} < 7.5$
PGA < 0.03 g except for extreme northern KZN.

Estimates of PGA and PSA on bed rock for Richards Bay
<table>
<tr><th>PGA</th><th>PSA= 0.1s</th><th>PSA = 0.5s</th><th>PSA = 1.0s</th></tr>
<tr><td>2.74E-02</td><td>6.14E-03</td><td>3.24E-04</td><td>8.46E-05</td></tr>
</table></td></tr>
<tr><td>Expanded Western EGI Corridor</td><td>Namibian border towards Abrahamvilliersbaai

Several faults have been mapped as “potentially active” by Manzunzu et al. (2019).
Areas of rugged topography are prone to landslides. These are generally triggered by high rainfall, which is rare.
Collapsible transported sands are found along the coast line
Swelling soils do not occur
No recorded $M > 6$ earthquakes
$M_w > 6$ events could recur one or twice per century
$M_{max} < 7.5$

Estimates of PGA and PSA on bed rock for the Namaqua National Park (NNP) and Loeriesfontein (LF)
<table>
<tr><th></th><th>PGA</th><th>PSA= 0.1s</th><th>PSA = 0.5s</th><th>PSA = 1.0s</th></tr>
<tr><td>NNP</td><td>4.41E-02</td><td>2.91E-02</td><td>9.12E-04</td><td>6.90E-05</td></tr>
<tr><td>LF</td><td>3.38E-02</td><td>9.25E-03</td><td>2.17E-04</td><td>2.30E-05</td></tr>
</table></td></tr>
</table>

Sensitivity maps have not been produced because of the poor resolution of probabilistic seismic hazard assessments, large uncertainties, and the lack of detailed information regarding currently active faults and near-surface geology. Note also that no active faults have been mapped because the accuracy of earthquake locations is too poor to definitively associate them with a particular fault plane, and no historical earthquakes have caused surface ruptures. The fissure created by the 1809 Cape Town earthquake is considered more likely to be due to near-surface slip or spreading caused by the shaking than to be the surface expression of the fault rupture itself.

4 ASSESSMENT OF THE IMPACT OF EARTHQUAKES AND MANAGEMENT ACTIONS

In this desktop study we review what is known about earthquake hazard and risk in South Africa along the EGI corridors, as well as international standards and best practice for the mitigation of the risk posed by earthquakes to EGI.

As noted above, shaking may directly damage EGI; and also cause damage indirectly by triggering landslides and rockfalls, causing soils to liquefy, or even dams to fail. All these phenomena may lead to damage and loss. Consequently, a cascade of effects needs to be considered involving large uncertainties. Earthquake-related phenomena could cause damage to EGI that might disrupt the supply of electricity. In worst cases, the damage to EGI could trigger a cascade of other hazardous phenomena (secondary impacts) such as fires, explosions, asphyxiation, electrocution, release of toxic and radioactive substances, etc.

Two hazard scenarios are considered:

1. **Direct impact** i.e. ground displacement across the earthquake fault that is large enough and/or ground motion that that is strong enough to damage EGI. A significant surface rupture would likely require an earthquake with M>7, producing a surface rupture with a length of 20-80 km and a displacement exceeding 0.5 m. The likelihood of such an earthquake occurring in South Africa is considered to be of the order of 1/1000 per annum. The likelihood of a randomly located active fault being close enough to an EGI element (substation or pylon) to damage it is perhaps 1/10, and thus the combined probability of an M>7 occurring and damaging EGI is perhaps 1/10,000 per annum. Shaking strong enough to cause damage to nearby EGI would likely require a tectonic earthquake with M>6 or a shallow mining-related earthquake with M>5.
2. **Indirect impact** i.e. ground displacement such as landslides, liquefaction and lateral spreading triggered by the earthquake shaking causes damage to EGI.

While considered unlikely, such events are certainly possible. In the last 120 years, three M>6 earthquakes have occurred, giving an average recurrence time of, say, 40 years. However, none of these events caused a surface rupture. A M7.4 event that occurred about 10,000 years ago in the Cape Fold Belt had a rupture length of about 80 km and a throw of up to 2 m. The M7.0 earthquake that occurred in the Machaze district of Mozambique in 2006 had a rupture length of the order of 40 km and a maximum displacement 1.0-1.5 m. The Hebron fault in Namibia is another example of a southern African fault with clear surface offsets, although the number and magnitude of the events that formed this scarp remain debatable (White et al. 2009). Tectonic earthquakes could occur anywhere in South Africa. Three M>5 mining-related earthquake have occurred in the last 50 years, and caused strong shaking due to their shallow origin. None of these events caused a surface rupture, although the tectonic earthquakes triggered some sort of ground displacement, notably a few landslides or areas of liquefaction. The mining-related earthquakes did not cause any landslides or liquefaction, probably because there were no susceptible conditions nearby. However, the risk of a tailings dam liquefying cannot be overlooked. On the night of 22 February 1994 a tailings dam failed due to operational shortcomings and flooded the suburb of Merriespruit in Virginia in the Free State. Eighty houses were destroyed, 200 houses were severely damaged, and 17 people were killed. The frequency of earthquakes capable of triggering indirect impacts is considered to be of the order of 1/20 per annum. The maximum distance from the epicentre in which significant mass movements (e.g. landslides) could be triggered is about 50 km for 5<M<6.5 earthquakes.

Table 5 below indicates the potential impacts, effects and mitigation.

Table 5: Potential Impacts, effects and mitigations

Corridor	Key Impacts	Site Specific Descriptions	Possible Effect	Mitigations
Expanded Eastern Corridor	Earthquakes cause direct and indirect damage to EGI. Direct Impact M>7 earthquake causes fault displacement over 20-80 km that damages EGI Indirect Impact Landslides, liquefaction or lateral spreading that damages EGI triggered by a M>6 tectonic earthquake or M>5 shallow mining-related earthquake	The Durban area is subject to local amplification and shaking. Distant moderate events have caused alarm. Liquefaction was observed following the 1932 St Lucia earthquake Areas with rugged topography in KZN are prone to landslides. These are generally triggered by high rainfall.	Disruption of electricity supply. In worst cases, the damage could trigger a cascade of other hazardous phenomena that may cause harm to the environment and people (secondary impacts). For example, fires, explosions, asphyxiation, electrocution, release of toxic and radioactive substances.	Avoid sites prone to landslides, lateral spreading and liquefaction, or the infrastructure will be strengthened or made more flexible, or the ground will be improved, or some combination of these measures will be implemented
Expanded Western Corridor		The 1969 Ceres-Tulbagh earthquake damaged buildings and triggered rockfalls. The 1809 Cape Town earthquake caused surface fissures.		

The risk posed by earthquakes to EGI in South Africa is considered to be generally low, provided local ground motion amplification, liquefaction and land slide phenomena are taken into account. For example: liquefaction was observed following the 1932 St Lucia earthquake; the Durban area seems to be subject to local amplification, and shaking due to distant moderate events has occasionally caused alarm; and soils in the Milnerton area of Cape Town could be prone to amplification and even liquefaction if subjected to shaking similar to that produced by the earthquakes that struck the region in 1809 and 1811.

Lastly, it should be noted that there are very few 'no go' areas for earthquake engineers. They have the option of either: (i) avoiding sites that are susceptible to earthquake damage; (ii) stabilising the sites e.g. driving piles, using raft foundations, dewatering potential landslides, anchoring critically-balanced rocks; or (iii) reinforcing or protecting the EGI. The decision is based on numerous factors, including environmental impacts, risk and cost.

5 BEST PRACTICE GUIDELINES AND MONITORING REQUIREMENTS FOR EARTHQUAKES

5.1 Planning phase

Map the regions within the EGI corridors that have:

- (i) Historical or instrumental records of M>5 earthquakes,
- (ii) Palaeoseismic evidence of M>6 earthquakes (age<100,000 years), or
- (iii) Seismically-active faults.

Within the corridors, map sub-regions that have either:

- (i) Steep topography prone to seismically-triggered landslides,
- (ii) Thick near-surface low-seismic-velocity layers that could cause site amplification, or
- (iii) Saturated soils and sands that could liquefy when shaken.

These regions should be designated as "sensitive".

Current knowledge, as summarised in Appendix A, is inadequate to map these regions accurately. It must be remembered that the duration of the earthquake catalogue is short compared to the likely recurrence time of M>5 events. The current national network is simply not dense or sensitive enough in these regions to relate earthquake hypocentres to any particular fault. Geological maps frequently show numerous faults, but it is important to realise that these faults are the result of tectonic forces and earthquakes that might have been active tens, hundreds or even thousands of millions of years ago. The mapping of currently active faults involves arduous palaeoseismic studies and detailed and sensitive seismic mapping.

Site effects are an important consideration (see e.g. Tamaro et al. 2013). The account of site effect (at least its first approximation) can be done by the account of average S velocity (Vs30) of the top 30 meters. Vs30 can be calculated from the topographic slope (Allen and Wald, 2007) and its implementation is easy (e.g. Atkinson and Boore, 2006). Geological and geophysical investigations should be conducted in “sensitive” regions to quantify the hazard of landslides, strong ground motion or liquefaction. Should these surveys indicate that there is a significant probability that EGI damage thresholds will be exceeded, the EGI should either be relocated, reinforced or protected (e.g. landslide mitigation measures).

The Vaalputs nuclear waste disposal site and the Thyspunt nuclear build site are examples of sites in South Africa where such studies have been conducted. For example, sensitive and dense local seismic networks have been deployed, historical records have been scoured for evidence of earthquakes, geotechnical surveys of the near surface have been conducted, and trenches have been dug for palaeoseismic studies. Similarly the detailed mapping of areas that may be prone to local site effects such as amplification, liquefaction and landslides requires detailed geological, geotechnical and geophysical mapping. This activity is known as ‘microzonation’. Such studies have been carried out at nuclear power station sites and nuclear waste disposal sites. The Council for Geoscience recently commenced seismic microzonation studies in the Johannesburg and Cape Town areas.

Some of the world’s most technologically-advanced countries are exposed to seismic hazard, for example, Italy, Japan and the USA. Standard methodologies have been developed to assess seismic hazard; numerous studies have been conducted to assess the risk posed by earthquakes to lifelines; and engineering specifications for EGI have been published. It must be emphasised that risk posed by earthquakes is generally not viewed in isolation, but as part of a multi-hazard strategy. For example:

- *Earthquake Resistant Construction of Electrical Transmission and Telecommunication Facilities Serving the Federal Government,* published by the US Federal Emergency Management Agency (FEMA, 1990)
- *Plan for Developing and Adopting Seismic Design Guidelines and Standards for Lifelines,* published by the US Federal Emergency Management Agency (FEMA, 1995)
- *Protecting Electricity Networks from Natural Hazards*, published by the Organization for Security and Co-operation in Europe (OSCE, 2016).
- *Power Grid Recovery after Natural Hazard Impact,* published by the Joint Research Centre of the European Commission (Karagiannis et al. 2017)

5.2 Construction phase

Install sensors and monitor both weak and strong ground motion in “sensitive” regions to improve hazard assessments.

5.3 Operations phase

Monitor both weak and strong ground motion in “sensitive” regions to improve hazard assessments. If necessary, increase the sensitivity and/or density of the sensors. Relocate, reinforce or protect the EGI if a significant increase in hazard or risk is indicated.

5.4 Rehabilitation and post closure

Not applicable.

5.5 Monitoring requirements

Statutory requirements for instruments to monitor ground motion are listed in Appendix C. In summary, the South African National Standard (SANS 4866:2011, based on ISO 4866:2010) specifies measuring ranges for various vibration sources, including earthquakes and blasts. These standards should be applied when carrying out surveys related to EGI.

The standard prescribes that instruments used to monitor ground-borne blast vibrations must be capable of measuring ground motions over the range 0.2 mm/s to 100 mm/s in the frequency range of 1 Hz to 300 Hz; while instruments used to monitor earthquakes must be capable of measuring ground motions over the range 0.2 mm/s to 400 mm/s in the frequency range of 0.1 Hz to 30 Hz.

6 GAPS IN KNOWLEDGE

A great deal is known about the impact of earthquakes and faults on EGI from work done in regions that are both highly-developed and tectonically-active, such as Italy, Japan and the western USA.

South Africa has a seismic monitoring network and a homogenized earthquake catalogue, although further work is required to reduce the uncertainties in hazard assessment along particular corridors and at specific sites. In particular, this would involve:

- Sensitive seismic monitoring to detect active faults.
- Strong motion monitoring to determine local ground motion prediction equations (GMPEs). However, it could take decades or even centuries to produce useful results as large earthquakes are rare.
- Determination of local site effects by geological, geotechnical and geophysical surveys.
- Analysis of ground response through amplification studies e.g. multi-channel analysis of surface waves (MASW) to determine the average shear wave velocity in the uppermost 30 metres (V_s30) and spectral ratio surveys.
- Detailed paleoseismological and geological mapping to map the length and throw of prehistoric fault ruptures, and geochronological studies to date the events.
- Detailed site-specific PSHA.
- Liquefaction potential analysis.
- Landslide susceptibility studies.
- Detailed assessment of the vulnerability of EGI.

In general, there is however sufficient information available to guide decisions on EGI development in South Africa. South Africa is regarded as a stable continental region. Earthquakes are far less frequent than in tectonically active regions such as Italy, Japan and the western USA. This does not mean that strong earthquakes cannot occur; but that the return periods are centuries or millennia. Experience in developed tectonically-active countries has shown that EGI is generally resilient to high intensities of ground motion. It is recommended that focused studies of earthquakes risk be conducted at critical EGI sites such as power stations and sub-stations situated in areas deemed to be exposed to a higher risk of damage (see Table 4).

7 CONCLUSIONS AND FURTHER RECOMMENDATIONS

Based on the findings above and provided that appropriate management actions are implemented when planning and constructing EGI, both the expanded Eastern and Western EGI corridors are deemed suitable

for power line infrastructure development. Attention should be given to local conditions that increase the earthquake hazard. For example:

- Steep slopes that are prone to landslides; and
- Thick soils and alluvium that may amplify ground motions and/or liquefy when shaken.

These sites should be avoided, or the EGI reinforced or protected appropriately.

Site specific assessments include:

- Mapping of the regions within the EGI corridors that have (i) historical or instrumental records of M>5 earthquakes, (ii) palaeoseismic evidence of M>6 earthquakes (age <100,000 years), or (iii) seismically-active faults.
- Within these regions, mapping of sub-regions that have either (i) steep topography prone to seismically-triggered landslides, (ii) thick near-surface low-seismic-velocity layers that could cause site amplification, or (iii) saturated soils and sands that could liquefy when shaken. These regions should be designated as “sensitive”.
- Geological and geophysical investigations in “sensitive” regions to quantify the hazard of landslides, strong ground motion or liquefaction.
- Installation of sensors to monitor both weak and strong ground motion in “sensitive” regions to improve hazard assessments.

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Appendix A: Seismic Hazard in South Africa

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Summary

Earthquakes were responsible for some of the most devastating disasters to occur in the early years of the 21st century. On 26 December 2004 an M_w9.1 earthquake occurred off the coast of Sumatra, triggering a tsunami that swept across the Indian Ocean, killing some 228 000 people (USGS 2012). The M_w9.0 Great Eastern Japanese earthquake and tsunami of 11 March 2011 was the costliest disaster of all time, with losses amounting to USD210 billion, not including the cost of the incident at Fukushima nuclear power station (New Scientist 2012). Fortunately, large earthquakes are relatively rare in South Africa, the most deadly earthquake on record being the M_L6.3 event that struck the Ceres-Tulbagh region on 29 September 1969, claiming the lives of nine people (Van Wyk & Kent 1974). Nevertheless, South Africans cannot afford to be complacent. A moderate-sized earthquake with a shallow focus occurring close to a town can be devastating, especially if the buildings are not designed to be earthquake-resistant, the terrain is steep and prone to landslides, or the soil is thick and prone to amplification and liquefaction.

EARLY SCIENTIFIC INVESTIGATIONS (circa 1600 to 1900)

Historical catalogues

In 1858 an Irish civil engineer named Robert Mallet (1810-1881), sometimes referred to as 'the father of seismology', published a global map of earthquake epicentres based entirely on reports of felt earthquakes (Agnew 2002). It was obvious that most earthquakes occurred in distinct zones, particularly around the Pacific Ocean and near high mountain ranges such as the Alps and Himalayas. The region surrounding the Cape of Good Hope was shaded orange, indicating that earthquakes had been felt and reported. The historical seismological catalogue for southern Africa (Brandt et al 2005, which superseded Fernández & Guzmán 1979a) lists forty-five earthquakes prior to the 20th century: four in the 17th century, three in the 18th century, and the balance in the 19th century. The catalogue is largely based on the work of Finsen (1950), Theron (1974) and De Klerk and Read (1988), who searched for reports of earthquakes in historical documents such as local newspapers and journals kept by explorers and travellers. The earliest event in the South African catalogue is dated at 1620. However, a recent re-examination of historical records by Master (2012) concluded that the event, recorded by the captain of a ship anchored in Table Bay, was most likely a thunderclap and not an earthquake. Consequently the oldest event is now dated at 1690. Discoveries of 'old' earthquakes continue to be made. For example, Master (2008) discovered a report in the *Cape Monthly Magazine* (Bright 1874) of an intensity III earthquake that was felt by many people in Maseru in February 1873, a recent study by Albini et al (2014) reviewed reports of seismic events that occurred in the Eastern Cape region between 1820 and 1936, while Singh et al (2015) were able to assign intensity values to reports of ground shaking produced by seven events felt in KwaZulu-Natal between 1927 and 1981 that were not listed in the historical database.

The most damaging event to occur in the pre-instrumental era struck the Cape Town district on 4 December 1809. Three strong quakes were felt, and many buildings suffered numerous cracks. Von Buchenröder (1830) provided an eyewitness account of the event: *In the evening, a little after ten o'clock, three shocks, each accompanied by a tremendous noise, were felt, within the space of a minute or two. .... While we were standing in the street, the second shock took place, which was felt much stronger; was accompanied by a louder, and very tremendous noise, that continued longer than the first ... The second shock roused all the inhabitants, who came running into the streets in great consternation, many of them undressed from having being in bed.* The next day Von Buchenröder undertook an inspection of the town and noted that chimneys, parapets and figurines on gables had been damaged. On 9 December he undertook an expedition to Blaauweberg's Valley (near present-day Milnerton), where he made quantitative observations of a scientific type: *[N]ear the Kraal I found rents and fissures in the ground, one of which I followed for about the extent of a mile.* The deduced intensity (on the Modified Mercalli scale) and magnitude were VII-VIII and M_L6.1, respectively (Brandt et al 2005).

The renowned explorer William Burchell provides an equally vivid account of an earthquake that struck Cape Town on 2 June 1811 in his *Travels in the Interior of Southern Africa* (Burchell 1822). He was staying in the Lutheran parsonage in Cape Town at the time: *I hastened out of doors to ascertain what had happened;[...] I came into the street and beheld all the inhabitants rushing out of doors in wild disorder and fright; [...] when I beheld this, I instantly guessed that an earthquake had happened.* Burchell goes on to describe the structural damage: *Walking afterwards about the town [...] I was told that many houses* *were exceedingly rent, and some more materially damaged; but none were actually thrown down [...] Many of the ornamental urns which had escaped the earthquake of 1809, were now tumbled from the parapets down into the street [...] and the wall of my bedroom was in the same instant divided by a crack which extended from the top of the house to the bottom.* The deduced intensity (on the Modified Mercalli scale) and magnitude were VII and M_L5.7, respectively (Brandt et al 2005).

INSTRUMENTAL SEISMOLOGY (circa 1900 – 1970)

The first seismometer installed in South Africa was a Milne-type horizontal pendulum instrument installed at the Royal Observatory in Cape Town in 1899 (Schweitzer & Lee 2003). It was deployed as part of a campaign to establish a worldwide seismograph network. Seismometers were installed in Johannesburg in 1910 to monitor earth tremors associated with mining, one in the Union Observatory and another near Ophirton. While most events were related to mining activity, some natural regional events were also recorded (Wood 1913). Over the next fifty years, seismometers were installed in Cape Town, Johannesburg, Grahamstown, Pietermaritzburg, Kimberley and Pretoria. Details of these early installations are provided by Wright and Fernández (2003).

A network of five seismographs was deployed on the northern rim of the Witwatersrand Basin in 1939 by researchers at the newly established Bernard Price Institute for Geophysics (BPI) at the University of the Witwatersrand. Data were transmitted by radio to a central point, where continuous 24-hour registration, coupled with an ingenious device that triggered distant seismographs, allowed all the larger mining-related events to be located accurately in space and time (Gane et al. 1949; 1946). This was the first use of a telemetered network anywhere, and is the only South African achievement included in the 'History of Seismology' chapter in the *International Handbook of Earthquake and Engineering Seismology*, published by the International Association for Seismology and the Physics of the Earth's Interior (IASPEI) (Agnew 2002).

It is important to note that instrumental recording does not guarantee correct location, especially in the early period. For example, the International Seismological Summary (ISS), the most comprehensive global earthquake catalogue for the time period between 1918 and 1963, lists a M6.5 earthquake on 31 October 1919 with its epicentre in Swaziland based on phase readings from 22 stations distributed around the globe. The absence of any local reports of shaking or damage led Manzunzu and Midzi (2015) to investigate its authenticity. They concluded that the event did not occur in Swaziland and should be removed from the local catalogue. The mis-location was either due to the wrong association of phases by ISS, or the simultaneous recording of phases from multiple events.

THE SOUTH AFRICAN NATIONAL SEISMOGRAPH NETWORK (1971 to the present)

The history of the South African National Seismograph Network (SANSN) is comprehensively reviewed by Saunders et al., (2008), so only a few highlights will be mentioned here. The first seven short-period (1 sec) vertical component seismic stations of the SANSN were deployed in 1971, shortly after the Ceres-Tulbagh event. Since then the SANSN has provided the essential infrastructure for the assessment of seismic hazard in South Africa. By 1997 the network had expanded to twenty-seven stations. In 1991 several digital seismographs were installed, first with dial-up landlines and later with dial-up GSM (Global System for Mobile Communications) modems.

The network was rejuvenated and modernized in 2003, partly motivated by a seismic hazard assessment programme in support of the South African government's plan to build nuclear power stations. Seven Geotech KS-2000 broadband seismometers (100 s) were installed across the network, and Guralp CMG-40T three-component extended short-period (30 s) seismometers at the other stations. There is also one very broadband Streckeisen STS-2 (120 s) seismometer at Silverton. Delays in transferring the waveforms of the Stilfontein event of 9 March 2005 triggered further upgrades to the SANSN to enable near-real-time data transmission. In 2006 seismic stations were installed in the Far West Rand (KLOF) and Central Rand (ERPM) gold fields. The KLOF station also recorded triggered data at 750 Hz, compared to the SANSN continuous recording standard of 100 Hz.

The velocity model is one of the most important factors affecting the accuracy of earthquake locations. Midzi et al. (2010) reviewed the model used by the SANSN and derived a new 1-D model by inverting P-wave travel times recorded by the SANSN. Moment tensors provide important information for seismotectonic and hazard studies. However, earthquakes with M_w<4.5 are too weak to be analysed using global moment tensor techniques. Prior to 2010, moment tensors had only been calculated for six South African earthquakes. Brandt & Saunders (2011) supplemented seismograms recorded by the SANSN with data recorded between 1996-1999 by the Southern African Seismic Experiment (SASE), conducted by the Wits University, MIT and the Carnegie Institute of Washington. The data were used to compute regional moment tensors (RMTs) for three near-regional M_w~4.0 earthquakes, two of which were mining-related events in the Far West Rand gold field, while the third was a tectonic event from the Koffiefontein cluster. The M_L scale for South Africa was recalibrated using 263 tectonic earthquakes recorded by the SANSN from 2006 to 2009 at epicentral distances of 10-1000 km, and station corrections determined for twenty-six stations (Saunders et al 2013). The anelastic term derived in this study indicated that the ground motion attenuation is significantly different from that of Southern California (which had been used previously), but comparable with other stable continental regions.

The Council for Geoscience (CGS) also operates seismographs stations and/or delivers data as a service to other organizations.

US Geological Survey National Earthquake Information Centre (NEIC) and the International Seismological Centre (ISC): The CGS releases digital seismological data, including phase readings and located epicentres, to the NEIC and ISC, where the phase readings are incorporated in international bulletins and released.

Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO): South Africa ratified the Comprehensive Nuclear Test Ban Treaty (CTBT) in 2003, and the CGS is responsible for the operation and maintenance of two stations of the International Monitoring System (IMS): a primary seismograph and infrasound station at Boshof (BOSA), and an auxiliary seismograph station at Sutherland (SUR). The stations are equipped with both short-period (1 s) and very broadband (120 s) sensors. The BOSA station is also part of the Global Telemetered Seismological Network (GTSN) of the US Air Force, while the SUR station is part of the Global Seismological Network (GSN) operated by the Incorporated Research Institutions for Seismology (IRIS).

Indian Ocean Tsunami Warning System (IOTWS): The devastating Indian Ocean tsunami of 26 December 2004 led to an initiative to establish the IOTWS by the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO). In June 2005, during the 23rd session of the IOC, the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS) was formally established. Five SANSN stations were equipped with broadband equipment and were linked to the IOTWS. In 2018 the group had 28 member states, including South Africa. Many countries participate through national tsunami warning centres. However, three Regional Tsunami Service Providers (Australia, India and Indonesia) are the primary source of tsunami advisories for the Indian Ocean (http://iotic.ioc-unesco.org/indian-ocean-tsunami-warning-system/tsunami-early-warning-centres/57/regional-tsunami-service-providers; last access 30 April 2018).

AfricaArray (2005-present): The Council for Geoscience was a founding member of the AfricaArray programme, established in 2005 (Nyblade et al 2008; Nyblade et al 2011). CGS contributes data from eleven broadband stations to the programme. The data is archived at the IRIS facility in the US.

Water Ingress Project (2008 – present): A 12-station-strong ground motion array was deployed in the Central Rand in 2008 to monitor seismicity associated with the flooding of mines.

Mine Health and Safety Council (2010-present): A 25-station-strong ground motion array was established in the Klerksdorp region to monitor mining-related seismicity in 2010. The array proved its worth when it recorded the M_L5.5 event that occurred on 5 August 2014 and its numerous aftershocks.

Observational Study in South African Mines to Mitigate Seismic Risks (2010-present): A 10-station array was deployed in 2011/12 in the Far West Rand mining district to monitor mining-related seismicity as part of a Science and Technology Research Partnership for Sustainable Development (SATREPS) project. SATREPS is a Japanese-South African collaboration funded by the Japan Science and Technology Agency (JST), Japan International Cooperation Agency (JICA), the Department of Science and Technology (DST), the Council for Geoscience, and the CSIR (Durrheim et al 2012; Durrheim et al 2010).

MEASUREMENTS OF STRESS AND STRAIN IN THE EARTH'S CRUST

Earthquakes are driven by stresses in the Earth's crust that are indirectly quantifiable by measuring strains in the rock. Crustal deformation is often extremely difficult to measure, as rates of strain and tilt are generally extremely small, especially in 'stable' continental regions.

Stress measurements in southern Africa

In the early 1970s Nick Gay of the BPI compiled in situ stress measurements made at fifteen localities in South Africa, Rhodesia (now Zimbabwe) and Zambia (Gay 1975). At that time, the most commonly used strain cell was the CSIR doorstopper developed by Leeman (1964, 1969). Measurement depths ranged from 20-2500 m. At shallow depths the horizontal stresses are generally greater than the vertical stresses, but at greater depths the vertical stresses are about double those acting horizontally. Gay subsequently published two important global reviews (McGarr & Gay 1978; Gay 1980). Stress measurements in the mining districts were compiled by Stacey & Wesseloo (1998).

Neotectonic studies

The assessment of seismic hazard at potential sites for the disposal of radioactive and toxic waste requires a detailed knowledge of any geological structures that may be active. Marco Andreoli of the Nuclear Energy Corporation of South Africa (Necsa) and his co-workers compiled observations of neotectonic faults, Landsat, SEASAT and GEOSAT imagery, aerial photography, hot springs, earthquake focal mechanisms, and detailed field mapping, amongst others (Andreoli et al., 1996). They deduced that neotectonic activity is taking place in the south-western Cape and Namaqualand, as well as in a broad region extending from the Free State to the Limpopo and Kwazulu-Natal, and also defined a broad region of NW-SE trending maximum horizontal compressive stress, which they named the Wegener Stress Anomaly.

Global and regional stress and strain models

Peter Bird of the University of California, Berkeley and his co-workers (including Marco Andreoli of Necsa) used a thin-shell finite element technique constrained by realistic heat flow and rheology to investigate the propagation of the East African Rift and compute the state of stress in the southern African crust (Bird et al., 2006). One objective of the study was to investigate the origins of the Wegener Stress Anomaly, first identified by Andreoli et al (1996). The boundary conditions of the Bird model are provided by the rates of spreading at the Mid-Atlantic and Indian Ocean Ridges, as well as various stress measurements compiled in the World Stress Map database (Reinecker et al 2004). It was concluded that the Wegener Stress Anomaly is caused primarily by resistance to the relative rotation between the Somalia and Africa plates. While the model of Bird et al (2006) certainly provides interesting results, the continental fracture that describes the East African Rift System is shown to continue along a line that joins the clusters of mining-related earthquakes in the Central and Far West Rand, Klerksdorp and Free State, before tracking through Lesotho and heading into the Indian Ocean. This plate boundary model is perpetuated in the series of earthquake posters published by the National Earthquake Information Centre at the US Geological Survey (see, for example, the poster for the M_w7.0 Machaze earthquake of 22 February 2006 (NEIC 2006)).

InSAR

Interferometric synthetic aperture radar (InSAR) is a satellite-based method that is used to detect ground deformations associated with geophysical phenomena such as the inflation of volcanoes and earthquakes. Its application to earthquake studies in South Africa has been limited. Doyle et al. (2001) used it to assess the surface deformation associated with a M_L4.5 tremor that occurred in the Free State Gold Fields on 23 April 1999. A 5-km-long elliptical depression centred on the Eland shaft of Matjhabeng Mine was mapped, with a maximum depth at its centre of 9 cm. InSAR has also been used to assess movement along the Kango-Baviaanskloof Fault (Engelbrecht & Goedhart 2009; Goedhart & Booth 2009).

Trignet CGPS network

Starting in 2001, the National Geo-Spatial Information (NGI) Directorate deployed a network of about sixty-five continuously observing global positioning system (CGPS) stations covering South Africa. Richard Wonnacott (NGI Directorate) was the leader of this programme. The average distance between stations is 200 km, with local densifications (70 km) around Cape Town, Durban and Johannesburg. Data are freely available from the Trignet web page (www.trignet.co.za). The first findings were published by Malservisi et al. (2013) using the stations with at least a thousand days of recording by June 2011. The results show that the South African region behaves rigidly, with deformation in the order of one nanostrain/year or less. The Trignet data were compared with data for the Nubian plate, and it was found that the South African block is rotating in a clockwise direction with respect to the African continent, which is consistent with the propagation of the East African Rift along the Okavango region.

SIGNIFICANT SOUTH AFRICAN EARTHQUAKES SINCE 1900

Earthquake size is expressed in terms of the intensity of shaking, which diminishes with distance from the epicentre; and magnitude, which is proportional to the deformation caused by the earthquake rupture or the seismic energy that is radiated by the source. In South Africa, the Modified Mercalli Intensity (MMI scale) and local magnitude scale (M_L, a local implementation of the Richter scale) are commonly used, though other scales, such as surface wave (M_s) and moment magntidue (M_w) are sometime used.

At the end of 1905 the Transvaal Meteorological Department acceded to a request from the Kaiserliche Hauptstation für Erdbebenforschung to collect information on earthquakes, and postcards with printed questions were sent to meteorological observers. Wood (1913) reported that there had not been a single earthquake of great importance during seven years of observation, and only three shocks that had been widely felt.

M_L5.0 earthquake in the Zoutpansberg, 5 August 1909: The M_L5.0 earthquake in the northern Zoutpansberg was felt as far away as Bulawayo and Johannesburg. It was the first event for which macroseismic data was systematically collected over a large area, enabling an isoseismal map to be drawn. Wood (1913) provides an account given by Mr Forbes Mackenzie, a superintendent at the Seta diamond mines, not far from the epicentre. The earthquake was assigned a peak MMI of VI (Brandt et al 2005).

Earthquakes near Philipstown (M_L5.0, 21 October 1910) and Koffiefontein (M_L6.2, 20 February 1912): The Philipstown and Koffiefontein earthquakes near the border between the Cape and the Free State were amongst the first natural events to be recorded by the Wiechert seismometers installed in Johannesburg in 1910. Many farm buildings south of Koffiefontein were destroyed and buildings in Kimberley were cracked. Wood (1913) provides isoseismal maps for both these events. The MMI scale intensities of the Philipstown and Koffiefontein events were V-VI and VIII, respectively (Brandt et al 2005).

M_L6.3 earthquake off Cape St Lucia, 31 December 1932

The M_L6.3 Cape St Lucia event of 31 December 1932 occurred off the Zululand coast and was felt as far away as Port Shepstone and Johannesburg, some 500 km away (Krige & Venter 1933). The nearest point on land to the epicentre was Cape St Lucia, where a MMI of IX was assigned on the evidence of sand boils and cracks in the surface. In the severely shaken areas, poor-quality houses (built of unburned or half-burnt bricks, or other low-quality materials) were severely damaged, while cracks were occasionally seen in well-built houses. As this region falls within the extension to the Eastern EGI corridor, the description of the more intense phenomena is repeated verbatim.

The shocks reached the intensity 7 in a small area in Zululand, including Palm Ridge, Mtubatuba, St. Lucia, Estuary Lots, St. Lucia Lighthouse, Umfolosi, Eteza, Empangeni, Felixton and Mtunzini. At these centres the earthquake had the following effects:

> *Everybody was frightened and all ran outside.*
> *Movement of ground caused persons standing to stagger.*
> *The shocks appeared to come from the south-east at St. Lucia Lighthouse, from the east at Eteza, and Mtubatuba, from the south at Palm Ridge.*
> *Buildings rattled as if about to collapse.*
> *Plaster fell from ceilings.*
> *Many chimneys and walls were cracked, also cement pavements and steps at St. Lucia Lighthouse and at St. Lucia Estuary Lots.*
> *A few houses were so badly damaged that they were abandoned.*
> *One house collapsed.*
> *Crockery, bottles and glasses were smashed.*
> *Water splashed over sides of large railway tanks and out of some smaller tanks.*
> *Corrugated-iron tanks sprang leaks, burst or were dislodged.*
> *Trees and shrubs moved like waves caused by a mighty hurricane, the movement lasting three minutes. One large tree was uprooted.*
> *Water in Nyalazi River, near Palm Ridge, appeared as if boiling.*

Fissures up to four inches or more wide, and often several hundred yards long, formed in the sand hills near St. Lucia Lighthouse and in the damp ground near rivers and streams. One fissure was over two miles long and affected a railway embankment, which it crossed ten miles north of Matubatuba, to such an extent that a train was derailed.

At Mr. Shire's sugar mill, near the Umfolosi River, south-east of Mtubatuba, some of the fissures opened to a width of about two feet during the earthquake, and then closed up again partly, sending columns of water resembling geysers into the air for 10 feet or so. They left deposits of white sand on the black soil on both sides of the fissure. One of the fissures, which was parallel to the river, was followed for over a mile, but extended further in both directions. As Mr. Shire's house also suffered considerable damage, it seems that intensity 8 was reached at this locality.

At St. Lucia Lighthouse, which is built on the sand hills near the shore, 370 feet above sea level, the 30-foot iron lighthouse-tower was violently shaken for two minutes. The gas cylinders weighing between 300 and 400 lbs. were moved about. The lamp and lenses were thrown out of position. The lighthouse-keeper's wife was flung from a sofa on to the floor.

The shocks attained or exceeded intensity 8 on the rocky shore from Cape St. Lucia, to the mouth of the "Estuary" and perhaps also along the banks of the Umfolosi River during the last few miles of its course. Near the mouth of the Estuary "a low rumbling noise like underground thunder" accompanied the tremor, which was "quite violent for about 15 seconds". It appeared to be moving from S.W. to N.E. Close to the observer six or eight fountains were seen to gush up from the surface of the water to heights of 2½ or 3 feet. They spouted black, muddy water, containing lumps of black clay. Numerous cracks were also formed in the sand on the banks, some of them a foot wide. As this area is very sparsely inhabited, it seems probable that similar phenomena occurred, without being observed or reported, along the banks of the Umfolosi River as far up as Mr. Shire's sugar mill, mentioned above.

The effects of the earthquake were conspicuously displayed on the sea-shore below the St. Lucia Lighthouse, where numerous cracks had formed in the calcareous sandstone. These were generally a quarter to half an inch wide, but occasionally an inch or more. They ran in different directions, being for the most part approximately vertical, although some followed the bedding which is nearly horizontal. The cracks were seen over a distance of about a mile. It is possible that they extend somewhat further, as the rocks were not well exposed at the time of our visit, which coincided with neap tide and a strong sea breeze. The rock sometimes contains a few pebbles, and where these were in the way of a crack they were occasionally shot out of their sockets. Two or three large loose fragments were seen that had been broken off from the fixed rock along perfectly fresh fractures. The intensity of the shocks here must have reached the 9th degree.

The interpreted link between geology and the intensity of shaking is also repeated verbatim.

The isoseismal of the 8th degree runs close to the shore from Cape St. Lucia northwards, and then projects inland along the Umfolosi River. The reason for its nearness to the shore is the great thickness of sand in the costal dunes, which acted as a protective cover and reduced the intensity of the shocks. In this region, near the epicentre, the severity of the earthquake effects was seen to depend to a large extent upon the nature of the surface materials. The calcareous sandstone on the beach was cracked to a considerable extent, and it seems likely that any ordinary house built upon this rock would have collapsed entirely. And yet the lighthouse-keeper's wooden-frame residence and its brick kitchen-chimney, situated less than half a mile from the shore, suffered hardly any damage. This building stands on the sand hills at an altitude of over 350 feet. The thick cover of sand acted as a buffer and protected the house from destruction. At the St. Lucia Lots the two hotels and the other houses are all built upon sand, which is about 100 feet or more thick. They did not suffer any more than the buildings at Mtubatuba, which is about 13 miles further from the epicentre, and they also were protected by the sand.

In the moist alluvial soil along the banks of the Umfolosi River, on the other hand, the intensity of the earthquake shocks was greatly increased.

These effects are in agreement, with the common experience that a thin cover of unconsolidated material above bedrock, especially if it is wet alluvial soil, increases the destructive effects of earthquakes, while a thick cover of sand or other loose material greatly diminishes them.

M_L6.3 earthquake in the Ceres-Tulbagh region, 29 September 1969

The most destructive earthquake that has occurred in South African recorded history was a M_L6.3 event that occurred at 10:03 pm (local time) on 29 September 1969 in the Ceres-Tulbagh region of the Western Cape, killing nine people. Modern concrete-frame buildings sustained relatively minor damage, but some well-constructed brick houses were badly damaged, and many adobe-type buildings were completely destroyed. Many historical buildings, such as the Drostdy in Tulbagh, were severely damaged. Rockslides started a large number of fires on the surrounding mountains. The earthquake was felt as far as Durban, 1175 km away. No surface rupture was found. The maximum intensity was VIII on the MMI scale (Van Wyk & Kent 1974).

An array of seven continuous-recording seismographs was deployed to monitor the aftershocks (Green 1973). The first two stations (at Paarl and Tulbagh) were deployed within two days of the main shock, and the remaining five stations a week later (Green & Bloch 1971). Over 2000 events were recorded during the five weeks of operation. Aftershock activity had virtually ceased when an M_L5.7 event occurred on 14 April 1970, causing further damage in the towns of Ceres and Wolseley. A bulletin issued by the Geological Survey (Van Wyk & Kent 1974) covers many topics, including a record of disaster relief efforts; an assessment of the focal mechanisms determined by Fairhead & Girdler (1969), Green & Bloch (1971), and Green & McGarr (1972); an assessment of earthquake risk; and recommendations for the construction of earthquake-resistant buildings. A microseismic study of the area was conducted in 2012 (Smit et al 2015):

172 events with M_L<0.5 were recorded in a three month period, delineating a 5-km-wide and 15-km-deep sub-vertical zone subparallel to the 1969 aftershock zone.

The Ceres-Tulbagh earthquake had some positive results. It jolted South Africa out of complacency regarding the risks posed by earthquakes, and the National Seismograph Network was established shortly thereafter. Strong shaking was felt in Cape Town, and earthquake-resistant measures adopted in the construction of the Koeberg nuclear power plant. The buildings lining historic Church Street in Tulbagh were restored to their original splendour and a small Earthquake Museum was established.

M_L5.2 earthquake near Welkom, 8 December 1976

The M_L5.2 Welkom earthquake was the first seismic event in a mining district to cause serious damage to buildings on the surface, most dramatically the collapse of Tempest Hof, a six-storey apartment block (Fernández & Labuschagne 1979). Fortunately, it was possible to evacuate the building before it collapsed. An array of seismographs was deployed to monitor the aftershocks and investigate the origin of the event (Arnott 1981).

M_L5.3 earthquake near Stilfontein, 9 March 2005

An M_L5.3 earthquake occurred at 12:15 pm on 9 March 2005 at Durban Roodepoort Deep's (DRD) Northwest operations (Durrheim et al 2006). The event and its aftershocks shook the nearby town of Stilfontein, causing serious damage to some buildings. Shattered glass and falling masonry caused minor injuries to fifty-eight people. The underground workings were severely damaged: two mine workers died, and 3 200 were evacuated under difficult circumstances. The mine went into liquidation soon afterwards and some 6 500 mine workers lost their jobs. Some R500 million was claimed from insurers for damage to mine infrastructure and loss of production.

Shortly thereafter, the Chief Inspector of Mines initiated an 'Investigation into the risks to miners, mines and the public associated with large seismic events in gold mining districts' (Durrheim et al 2006). The terms of reference listed nine specific issues that were to be addressed, top of the list being whether the events of 9 March 2005 could be attributed to mining activity. The team considered both statistical and mechanistic evidence. Andrzej Kijko (Council for Geoscience) presented evidence that the number of events with M>3 in the Klerksdorp mining district exceeded the average for the rest of South Africa by a factor of 700. Analysis of seismic records for the main event and its aftershocks showed that the source was close to the Number 5 Shaft fault and the reef horizon. Art McGarr (United States Geological Survey) showed that the dewatering of the rock mass during mining operations will tend to stabilize natural faults that might be close to failure. The team found that: *The magnitude 5.3 event and its aftershocks can be ascribed to past mining. The event was caused by rejuvenated slippage on an existing major fault, with extensive mining activities in the region contributing most of the strain energy. The chance of the events being solely due to natural forces is considered to be extremely small.*

M_w7.0 earthquake, Machaze district, Mozambique, 23 February 2006

The M_w7.0 earthquake struck Mozambique just after midnight, local time (Saunders et al., 2010). The shaking was sufficiently strong to cause many residents of Maputo and Beira to flee into the streets, and was felt in South Africa (Durban, Johannesburg and Pretoria), Zambia and Zimbabwe. The epicentral region is sparsely populated, but four people were killed and thirty-six injured, and at least 288 houses, six schools and two small bridges were destroyed (UNOCHA 2006). Fenton & Bommer (2006) surveyed three segments of the fault rupture with a combined length of some 15 km (the total rupture length is expected to be in the order of 30-40 km). The surface rupture, although visible in the field, could not be followed along its entire length due to the danger posed by buried land mines. They observed average vertical displacements of 1.0-1.5 m, and in one segment left-lateral offsets of 0.7 m. They also observed spectacular liquefaction features, such as sand blows with diameters of 5-8 m, and a 318-m-long liquefaction fissure. Fenton & Bommer (2006) were unable to decide if the earthquake was on an 'old, slow fault', similar to those found in intraplate regions, or a new structure related to the southward propagation of the East African Rift (NEIC 2006). Satellite radar interferometry allowed both the co-seismic and post-seismic displacement along the entire surface rupture to be measured (Raucoules et al., 2010).

M_L5.5 earthquake near Orkney, 5 August 2014

The M_L5.5 earthquake, with its epicentre near Orkney in the North West Province, occurred at 12:22 local time (Midzi et al 2015b). The earthquake shaking was felt as far away as Cape Town. More than 600 houses were damaged and one person was killed. Many people completed an online questionnaire administered by the Council for Geoscience (CGS), whilst others reported the event and its effects on social networks and in newspapers (Midzi et al 2015b). The CGS also sent out a team of scientists to further assess the effects of the event by interviewing members of the public and completing additional questionnaires. A total of 866 observations were collected. Analysis of the macroseismic data produced 170 intensity data points which showed a maximum MMI of VII in the epicentral area (Midzi et al 2015b).

This earthquake, being the largest recorded to date around the mining regions of South Africa, is mysterious for several reasons (Ogasawara 2015; Moyer et al., 2017). The mechanism was a left-lateral strike-slip on a NNW-SSE striking and nearly vertically dipping plane. This differs significantly from typical mining-induced earthquakes in the region, which usually exhibit dip-slip on NE-SW striking normal faults close to the mining horizon. The geological structures mapped on the mining horizon in the Orkney district are characterized by a horst and graben structure trending NE-SW, intruded by multiple dykes trending NNW-SSE. So, the strike-slip might be on a dyke. However, the hypocenter was significantly deeper than the mining horizon (at least 1-2 km deeper), and no dyke or seismic fault rupture was reported on the mining horizon. The maximum principal stress measured in situ at 3.0 km depth and several km from the hypocenter was almost vertical, while the intermediate principal stress was horizontal, trending NNW-SSE almost parallel to the M5.5 fault plane.

In order to assess the seismic hazard posed by such earthquakes as this, it is very important to understand stress field and loading mechanism (or tectonics) to address the above mysteries, because such dykes may prevail elsewhere. A proposal was submitted to the International Continental scientific Drilling Programme (ICDP) by a South African – Japanese team to investigate the source zone directly by drilling (Ogaswara et al. 2015). The ICDP granted funds to hold a workshop to form an international consortium and prepare a full proposal. The proposal was approved, and drilling commenced in 2017.

M_w6.5 earthquake in Botswana, 3 April 2017

The M_w6.5 earthquake occurred on the evening of 3 April 2017 in Central Botswana, southern Africa (Midzi et al 2018a). Its effects were felt widely in southern Africa and were especially pronounced for residents of Gauteng and the North West Province in South Africa. In total 181 questionnaires were obtained by the Council for Geoscience through interviews and 151 online from South Africa, Zimbabwe and Namibia in collaboration with the Meteorological Services Department, Zimbabwe and the Geological Survey of Namibia. All data were analysed to produce 79 intensity data points located all over the region, with maximum MMI values of VI observed near the epicentre. These are quite low values of intensity for such a large event, but are to be expected given that the epicentral region is in a national park which is sparsely populated. The CGS and Botswana Geoscience Institute deployed a network of aftershock recorders. More than 450 aftershock events of magnitude M_L> 0.5 were recorded and analysed for this period. All the events are located at the eastern edge of the Central Kgalagadi Park near the location of the main event in two clear clusters. The observed clusters imply that a segmented fault is the source of these earthquakes and is oriented in a NW-SE direction, similar to the direction inferred from the fault plane solution of the main event.

Reservoir-induced earthquakes

The impoundment of large reservoirs may trigger local earthquakes as a result of increases in the surface load and the pore fluid pressure, and seismic hazard should be taken into account when designing any large dam, regardless of whether the seismic loading is due to natural tectonic earthquakes or reservoir-induced seismicity (World Commission on Dams 2000).

Kariba Dam, Zimbabwe: The filling of Lake Kariba on the Zambezi River and subsequent fluctuations in water level has been accompanied by seismicity. The Kariba Dam was built from 1955 to 1959, and is one of the world's largest dams. The wall of the Kariba Dam is 128 m high, and the reservoir is 280 km long and has a storage capacity of 180 km^3. Seismic loading was not taken into account during the design of the dam, even though the reservoir is located in a tectonically active branch of the East African Rift system and an M_s6.0 earthquake had occurred in the region in 1910. (M_s denotes the surface wave magnitude, which is similar to other magnitudes.) No local measurements of seismicity were carried out prior to the impoundment, but many studies were carried out after 1959 (World Commission on Dams 2000). Geophysical work in Rhodesia (now Zimbabwe) did not begin in earnest until 1958 when seismograph stations were deployed around the Zambezi Valley to monitor seismic activity as Lake Kariba filled behind the Kariba Dam. Substantial seismic activity was recorded, increasing as the dam filled and peaking in 1963 (Gough & Gough 1970a; 1970b). The larger earthquakes (M>5) occurred in the vicinity of the dam wall. The largest event (M_L6.1, which occurred in 1963) caused damage to the dam structure and some property in nearby settlements, but no casualties were reported. Since 1963 there has been a general decline in seismic activity. It was initially thought that the loading of the water filling the dam on the crust was the cause of the seismic events. Consensus later swung towards the increase in hydrostatic pressure in faults as the likely cause of the seismicity.

Gariep Dam, South Africa: The 61-m-high and 600-m-long Gariep Dam (previously known as the HF Verwoerd Dam) on the Orange River was impounded in 1970. Seismicity was monitored by Milner (1973). A seismometer array comprising one three-component and six vertical component stations was deployed prior to impoundment. Seismicity was first recorded in February 1971, six months after impoundment, when the water level reached 40 m. During the next ten months 93 events were recorded, the largest of which being an M2.1 event. Seismicity declined after December 1971.

Katse Dam, Lesotho: Seismicity was also associated with the filling of the 185-m-high Katse Dam on the Malibamat'so River in Lesotho, which was completed in 1996 (Brandt 2000, 2001). Seismicity was monitored from 1995 to 1999. The first recorded event occurred when the water level in the reservoir had risen by 45 m. The largest event had a magnitude of M_L3.0, when fresh fissures opened along a shear zone adjacent to the dam; dwellings in the village of Mapeleng suffered minor damage. The ground motion expected by a hypothetical M5 reservoir-induced seismic event was modelled by Brandt (2004). It was concluded that such an event does not pose any risk to the dam wall. Although it may pose a risk to the villages built on the steep slopes surrounding the dam.

SEISMIC HAZARD ASSESSMENT

The African continent is largely a tectonically stable intraplate region and has been surrounded by spreading ridges since the break-up of Gondwana, about 120 million years ago. The only parts of Africa that do not display the characteristics of an intra-plate region are the Africa-Eurasia collision zone, the Cameroon Volcanic Line, and the East African Rift System and its continuations into Botswana and Mozambique. The rest of Africa and South Africa (apart from the mining regions) is characterised by a relatively low level of seismic activity, with earthquakes randomly distributed in space and time. However, it is important to note that global observations have shown that intraplate earthquakes, while rare, can occur even without significant precursory seismic activity; moreover, they may have large magnitudes and cause considerable damage.

Hazard assessment is the process of determining the likelihood that a given event will take place. Probabilistic seismic hazard assessment (PSHA) is generally expressed in terms of the ground motion (for example, peak ground acceleration (PGA)) that has a certain likelihood of exceedance (say 10%) in a given period (say fifty years). There are many PSHA schemes, but all require a catalogue of earthquakes (size, time, location); the characterisation of seismically active faults and areas (usually in terms of the maximum credible magnitude and recurrence periods); and a prediction of variation in ground motion with distance from the epicentre. The longer the duration of the catalogue, the smaller the magnitude of completeness, and the better the zonation, the more reliable is the PSHA.

Palaeoseismology

In order to assess the risk posed by earthquakes, it is important to have a record of past earthquake activity. These parameters are best known if earthquakes are recorded by seismographs. However, the global instrumental catalogue does not go back much further than a century, and, in many parts of the world, the recurrence times of the largest plausible earthquake is much longer than this. Thus historical records of earthquakes, while less accurate and complete, are a vital supplement to instrumental catalogues. However, the historical record often only covers a few centuries and is inevitably incomplete. Thus palaeoseismologists seek to extend the catalogue back in time by discovering and deciphering clues left by prehistoric earthquakes (say events occurring during the last 100 000 years). For example, geomorphological features such as fault scarps and knick points in rivers can be used to deduce the length and displacement of the rupture caused by a particular earthquake, while geochronological techniques can be used to determine the age of sediments deposited along fault scarps, and hence the minimum age of the earthquake.

Soutpansberg M8.0 event: A project was commissioned by Eskom (1998) to investigate palaeo-seismic movement of Tshipise and Bosbokpoort faults, this was then used to investigate as part of a study of the slope stability within Mutale upper dam basin. Evidence for the recent reactivation of the faults was first reported in 1977 by Tim Partridge (Eskom 1998). Different fault zones were mapped, and the length, throw and age of the palaeoseismic fault ruptures estimated. The biggest event, based on rupture length and throw, was estimated to have been an M8.0 earthquake that occurred about 100 000 years ago.

Kango fault M7.4 event: Palaeoseismic studies have been carried out as part of an investigation into the Quaternary tectonic history of the south-eastern continental margin, in support of the assessment of seismic hazard at proposed sites for nuclear power stations (Engelbrecht & Goedhart 2009; Goedhart & Booth 2009; Midzi & Goedhart 2009; Goedhart & Booth 2016a, 2016b). There is little seismic information for this region, and the record is too short to include the long recurrence intervals typical of large, surfacerupturing earthquakes in intraplate regions. Goedhart & Booth (2016a) interpreted a scarp running parallel to the Kango fault in the Cape Fold Belt to be the surface expression of an 84-km-long extensional surface rupture (Figure 1). An 80-m-long, 6-m-deep and 2.5-m-wide trench was dug across the fault, exposing twenty-one lithological units, six soil horizons, and nineteen faults strands. Vertical displacement indicated a fault throw of about 2 m. Optically stimulated luminescence dating indicated that the fault was active between 12 200 and 8 800 years ago, and most probably around 10 600 years ago. Goedhart and Booth (2016b) used published relations between surface rupture length, displacement and magnitude to estimate the magnitude of the event at M_w7.4.

Figure 1: The Kango fault, showing part of a 84-km-long and 2-m-high fault scarp produced by an M_w7.4 event about 10 600 years ago (Source: Midzi & Goedhart 2009)

Early efforts to quantify seismic hazard

The 1969 M_L6.3 Ceres-Tulbagh earthquake gave impetus to the establishment of the Southern African Seismograph Network. The number of stations increased from five in 1969 to 11 in 1973, and in 1992 consisted of 25 stations in South Africa and five in neighbouring countries (Fernández & Du Plessis 1992). Monthly bulletins and annual catalogues were published from 1971 onwards, and in 1979 a bulletin was published containing several maps depicting earthquake hazard levels in South Africa based on the distribution of annual extreme values (Fernández & Guzmán 1979b).

The *Seismic Hazard Maps for Southern Africa* poster was published in 1992 (Fernández & Du Plessis 1992). The poster features explanatory notes and three maps: a plot of the maximum reported Modified Mercalli scale intensities from 1620-1988; a contour plot of the Modified Mercalli scale intensity with a 10% probability of being exceeded at least once in fifty years; and a contour plot of the PGA with a 10% probability of being exceeded at least once in 50 years. The areas exposed to the greatest natural hazard (where PGAs were considered to have a 10% probability of exceeding 100 cm/sec^2 (0.1 g) at least once in fifty years) are the south-western Cape, the southern Free State and Lesotho, and Swaziland. In 1990 the South African Bureau of Standards (SABS) issued the *Code of practice for the general procedures and loadings to be adopted for the design of buildings* (SABS 1990). The Code designated two zones: Zone 1, corresponding to the three areas noted above; and Zone 2, regions exposed to mining-related seismicity.

In 1996, Luiz Fernández, head of the Seismology Unit at the Geological Survey, summarized the state of the art with regard to seismic hazard evaluation in a report entitled *The seismic climate of Southern Africa: Peak ground accelerations to be expected from tectonic and mining seismicity* (Fernández 1996). Standard methods (for example, McGuire 1993; Cornell 1968; Kijko 2011) of assessing seismic hazard required a priori knowledge of the seismogenic regions, including a clear demarcation of their borders and their activity rates. In regions that have low seismic activity rates, such as the interior of the global plates, this knowledge is rudimentary, especially when the time window of data is very short. This is the case for South Africa.

One of the first attempts to estimate the maximum credible magnitudes of earthquakes in South Africa was made by Shapira et al. (1989). It was concluded that the catalogue of earthquakes was complete for $M_L \geq 4.6$ events since 1950; for $M_L \geq 4.9$ events since 1910; and for $M_L \geq 5.3$ events since 1906, and that the maximum credible magnitudes of tectonic and mining-related earthquakes were M7.5 and M5.5, respectively. Shapira and Fernández (1989) also estimated the probability that a defined horizontal PGA will be exceeded at fourteen cities in southern Africa.

Ideally, the historical and instrumental catalogue used to assess seismic hazard should be complete; that is, there should be no data gaps or changes in the threshold of completeness. However, this ideal is often not met, particularly in the developing world. A 'parametric-historic method' that compensates for these difficulties was developed by Professor Kijko, previously at the Council for Geoscience and now at the University of Pretoria (Kijko & Graham 1998; 1999; Kijko & Sellevol 1989; 1992; Kijko et al 2016) and is used in many countries. Kijko also applied his formidable statistical skills to the related important problem of estimating the maximum credible earthquake magnitude m_{max} (Kijko 2004, 2012; Kijko & Singh 2011; Kijko & Smit 2012). In 2003 the Council for Geoscience published seismic hazard maps showing the 10% probability of exceeding the calculated PGA at least once in fifty years at 1, 3, 5 and 10 Hz, frequencies that are important for the fragility of buildings (Kijko et al 2003; Kijko 2008). The parametric-historic procedure of Kijko and Graham (1998; 1999) was used.

Recent efforts to quantify seismic hazard

During the 1990s the Global Seismic Hazard Assessment Programme (GSHAP 2013) compiled and published a seismic hazard map of the world (Giardini et al 1999). The GSHAP map for Africa (Grünthal et al 1999; Midzi et al 1999) is currently being updated under the auspices of the Global Earthquake Model initiative (GEM-SSA 2013).

The first step in assessing the seismic hazard and risk for any site is to develop a seismotectonic model. The area under investigation is divided into smaller zones or regions that have a similar tectonic setting and similar seismic potential. These zones are then used in a seismic hazard assessment model to determine the return periods of certain levels of ground motion at a given site in the area in question. Mayshree Singh (née Bejaichund) of the Seismology Unit of the Council for Geoscience developed a first-order seismotectonic model for South Africa. The outputs of the project were first reported in an unpublished MSc dissertation (Bejaichund 2010) and published in a series of three papers (Singh et al 2009; Singh & Hattingh 2009; Singh et al 2011). The inputs to the seismotectonic model include the historical and instrumental earthquake catalogue for South Africa, maps of geological and geophysical terrains, evidence of Quaternary fault activity, thermal springs, and so forth (Singh et al 2009). Isoseismal maps are extremely useful for assessing seismic hazard, in particular for determining parameters such as crustal attenuation and identifying local site effects. If possible, surveys of macroseismic effects (damage to buildings, surface ruptures, liquefaction, and so forth) are conducted immediately after an earthquake, but historical documents can also be used. Singh and Hattingh (2009) compiled thirty-two isoseismal maps for South Africa, the earliest being for the 1932 earthquake with its epicentre offshore from St Lucia (M_L6.3, intensity VIII). Eighteen seismotectonic zones were defined. Finally, the frequency-magnitude relations were analysed using ten different procedures. Estimates of the earthquake recurrence parameters and maximum possible earthquake magnitudes m_{max} were obtained for each seismotectonic zone (Singh et al 2011). This work has been extended with a more detailed study of KwaZulu-Natal (Singh et al., 2015; Singh 2016).

As part of CGS's effort to improve hazard assessment in South Africa, a database of the intensity of earthquakes occurring between 1912 and 2011 was compiled (Midzi et al., 2013), as well as intensity surveys of two moderate-sized earthquakes that occurred in 2013 (Midzi et al 2015a). The CGS made use of GEM products and tools (notably the OpenQuake software package), coupled with a new zonation model for South Africa, to compute the seismic hazard (Midzi et al 2018b). Seismotectonic data was compiled and interpreted by Manzunzu et al (2019). The outputs of these studies are used for this assessment (see Appendix B of this report).

SEISMIC RISK ASSESSMENT

A risk assessment is an attempt to quantify the losses that could be caused by a particular hazard. It is calculated as follows:

Risk = likelihood of the hazard occurring X seriousness of consequences

The consequences of an earthquake depend on four main factors: the vulnerability of structures (e.g. EGI infrastructure or gas pipelines) to damage, the exposure of persons and other assets to harm, the cost of reconstruction, and the cost of lost economic production. Risk assessments are useful for raising awareness of possible disasters and motivating policies and actions to mitigate losses and avoid disasters. For example, vulnerable structures may be reinforced, building codes enforced and insurance taken out to cover possible losses. An important input into the assessment of consequences is the vulnerability of structures subjected to shaking. The vulnerability curves for typical South African buildings have been published by Pule et al (2015).

Insuring against earthquake risk: In 2001 a global reinsurance company, Hannover Re, published a report assessing the risk posed by seismicity to the South African insurance industry (Hannover Re 2001). The seismic research was performed by Andrzej Kijko and Paul Retief of the CGS, while the application to the insurance industry was carried out by Nicholas Davies of Hannover Re. The main findings of these studies were translated into the language of the insurance industry and published in the *South African Actuarial Journal* (Davies & Kijko 2003).

Quantifying earthquake risk in the Tulbagh region: A comprehensive study of seismic hazard and risk in the Tulbagh area was conducted by Kijko et al 2002, 2003). The worst case scenario is an event that produces shaking with a PGA of 0.3 g.

FIFA 2010 Soccer World Cup stadia: In 2010 South Africa hosted the FIFA Soccer World Cup. To coincide with this event, the global reinsurance company, Aon Benfield, issued its report *South Africa Spotlight on Earthquake* in conjunction with the Aon Benfield Natural Hazard Centre Africa (Aon Benfield 2010). According to the report, earthquake is "regarded as the natural hazard most likely to trigger the country's largest financial loss" (Aon Benfield 2010). The objective of the report was to enable insurers to obtain a more accurate estimate of their exposure and in turn purchase appropriate reinsurance cover. Earthquake risk was assessed in Cape Town and Durban, two cities where major new stadia had been built and which had experienced the largest seismic events recorded in South African history, and hence where risk would most likely be greatest. The losses associated with a scenario earthquake similar to the M_L6.1 1809 Cape Town earthquake were considered. The worst case scenario, a M6.9 earthquake on the Milnerton Fault, would produce a MMI of about IX, which would be "ruinous" (Aon Benfield 2010) to the Cape Town CBD and Cape Town Stadium, only 10 km away. Fortunately, the probability of such an event is low, in the order of one in 1000 years. While a M6.3 earthquake occurred near St Lucia, 220 km north of Durban, on New Year's Eve 1932, Durban is not regarded as being exposed to high seismic risk as no active faults are known to exist close to the city. The report concluded that M5.0 and M6.0 events would only cause structural damage if their epicentres were closer than 45 and 90 km, respectively. The return periods of such events was estimated to be 735 and 5000 years, respectively.

Risk posed by tsunamis: Numerical tsunami simulations have been conducted to investigate the realistic and worst-case scenarios that could be generated by the nearest (but distant) subduction zones, *viz.* Makran, South Sandwich Islands, Sumatra and Andaman (Okal & Hartnady, 2009; Okal et al., 2009; Kijko et al. 2018). The simulated tsunami amplitudes and run-up heights calculated for the coastal cities of Cape Town, Durban, and Port Elizabeth are relatively small and therefore pose no real risk to the South African coast.

Nuclear power stations: The damage to the Fukushima nuclear power station caused by the M_w9.0 Great Eastern Japanese earthquake and tsunami of 11 March 2011 naturally raised concerns about the safety of the Koeberg nuclear power station, situated on the Atlantic seaboard 30 km north-west of Cape Town. The managing director of Eskom's operations and planning division, Kannan Lakmeeharam, promptly assured parliament and the public that Koeberg was designed to withstand both earthquakes and tsunamis (News24, 2011). The construction of the 1800-megawatt power station began in 1976. The pressurized water reactors are housed within a containment building mounted on a base-isolated raft. It is designed to withstand an M_L7 earthquake without any risk of rupture.

In 2006 the South African government announced plans to build several more nuclear power stations, and a programme to identify suitable sites was launched. Five potential sites were identified, two on the Indian Ocean coastline (Thyspunt near Jeffrey's Bay, and Bantamsklip near Gansbaai) and three on the Atlantic coastline (Duynefontein (Koeberg), and two sites in Namaqualand). Environmental Impact Assessments (EIAs) were commissioned and published on the internet (http://www.eskom.co.za/c/article/1719/nuclear-1-eia-documentation/). The EIAs addressed a wide range of issues, including geology, seismology, hydrology and geotechnics (addressing issues such as liquefaction potential). Neotectonic and palaeoseismic investigations were undertaken and field measurements of Vs30 were made (Park 2013). The earthquake catalogue for each site was updated, the maximum ground velocity determined deterministically for each site, and the expected PGA determined probabilistically for each site. Site-specific SHAs were previously undertaken for the three sites by the Council for Geoscience (CGS), employing a methodology called the Parametric-Historic SHA. Using this methodology, median PGA values of 0.16 g, 0.23 g and 0.30 g were calculated for the Thyspunt, Bantamsklip and Duynefontein sites, respectively (CGS 2011). In order to enhance the probability that the assessment of the hazard associated with vibratory ground motion (due to natural earthquakes) will be accepted by the National Nuclear Regulator, methodologies with considerable precedence and recognition by the US Nuclear Regulatory Commission (USNRC) and regulators from other countries were used, in particular a process that was drafted by the USNRC Senior Seismic Hazard Committee (SSHAC). The SSHAC process is documented by Budnitz et al (1997) and Hanks et al (2009), and the application to Thyspunt by Strasser & Mangongolo (2012), Bommer et al (2013) and Bommer et al (2015).

Nuclear waste disposal facilities: The Namaqualand-Bushmanland region has numerous features that make it attractive for the storage of radioactive waste. In the late 1970s a programme was launched to find a suitable site for low- and intermediate-level waste. The Vaalputs facility, approximately 100 km south of Springbok, was opened in 1986. Seismicity is one of several key factors that are monitored as part of the ongoing operations. A two-station network of short-period seismometers was installed in 1989 and replaced in 2012 with a three-station network comprising one broadband and two short-period seismometers (Malephane, Durrheim & Andreoli 2013). Data from these networks, the South African National Seismological Network, and the International Seismological Centre has been used to compile a catalogue of the general seismicity of the region.

Large dams: A seismic risk classification was performed for 101 large (wall height >30 m) state-owned dams (Singh et al 2011). The risk is strongly dependent on the method used to construct the dam wall, with gravity and earth-fill dams being the most vulnerable to ground shaking.

Fracking: The risk posed by fracking-induced earthquakes in the Karoo basin was assessed as part of a Strategic Environmental Assessment commissioned by the Department of Environmental Affairs (Durrheim et al 2016).

Open-pit mine blasting: The risk posed by open pit blasting was assessed in a study commissioned by the Mine Health and Safety Council (Milev et al 2016).

CONCLUSIONS

South Africa is fortunate to be situated far from a plate boundary. Large, damaging tectonic earthquakes (6.5<M<7.5) are rare and losses due to earthquakes have been small. However, it should be noted that a damaging earthquake (5.0<M<6.5) could occur anywhere in South Africa. Mining-related earthquakes are restricted to the regions where deep and extensive gold mining has taken place, notably the Welkom and Klerksdorp districts. Earthquakes have been identified as the natural hazard with the potential to cause the greatest financial losses. A low rate of seismicity does not mean that the maximum size of an earthquake will be small, just that earthquakes are less frequent. A moderate-sized earthquake (such as those that occurred near Cape Town in 1809 and Ceres in 1969) can prove disastrous if it occurs beneath a town with many vulnerable buildings.

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Appendix B: OpenQuake PSHA computation for South Africa and the energy corridors

Primary references:

Midzi V, Manzunzu B, Mulabisana TF, Zulu BS, Pule T, Myendeki S & Rathod, G. 2018. The Probabilistic Seismic Hazard Assessment of South Africa. *Journal of Seismology* (in review).

Manzunzu B, Midzi V, Mulabisana TF, Zulu BS, Pule T, Myendeki S & Rathod, G. 2019. Seismotectonics of South Africa. *Journal of Africa Earth Sciences,* 149:271-279.

Summary:

More than 20 years has passed since previous national seismic hazard maps were prepared for South Africa. In those maps, zone-less techniques were applied. The availability of more reliable seismicity and geological data has made it possible to update those maps using state of the art probabilistic seismic hazard assessment methodologies that take into consideration all available data. This paper presents a summary of the work conducted to produce the latest seismic hazard maps for South Africa. This involved the systematic compilation and homogenisation of an earthquake catalogue, which comprised both historical and instrumental events. The catalogue played a prominent role in the preparation and characterisation of the seismic source model. Two ground motion prediction equations were identified from available international models for regions that are tectonically similar to South Africa. These two models were then implemented in the hazard calculations, which were done using the OPENQUAKE software. Uncertainties associated with input parameters in both the seismic source and ground motion models were taken into account and implemented using the logic tree technique. Maps showing the distribution of acceleration at three periods (0.0s, 0.15s and 2.0s) computed for 10% probability of exceedance in 50 years were produced. These maps constitute a valuable product of this study that can be useful in updating South African building codes.

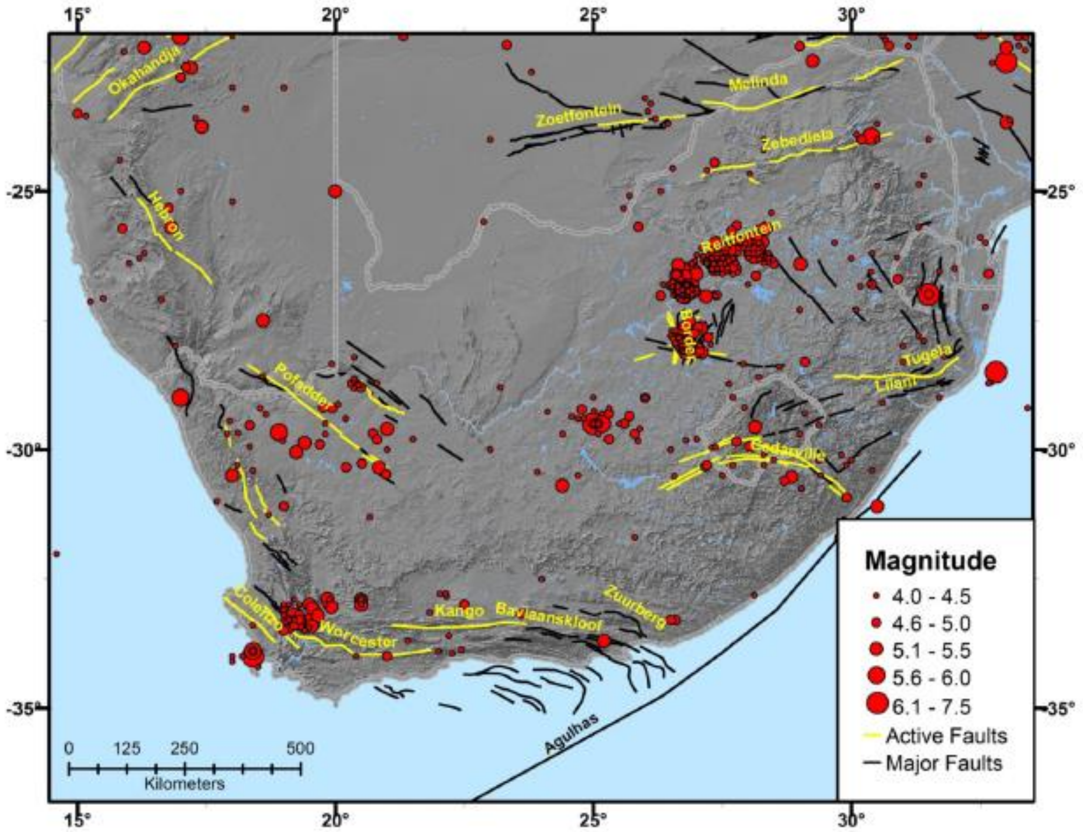

Figure 1: Major faults of southern Africa (Manzunzu et al., 2019). Faults that were potentially active during the Quaternary (2.588 ± 0.005 million years ago to the present) are shown in yellow. It should be noted that the time period is considerably longer than that commonly used in the definition of an "active fault". For example, the glossary in the International Handbook of Earthquake and Engineering Seismology (Aki and Lee, 2003) define an active fault as "a fault that has moved in historic (e.g., past 10,000 years) or recent geological time (e.g., past 500,000 years)". Also included in red circles are southern African earthquakes of magnitude greater than or equal to 4.0.

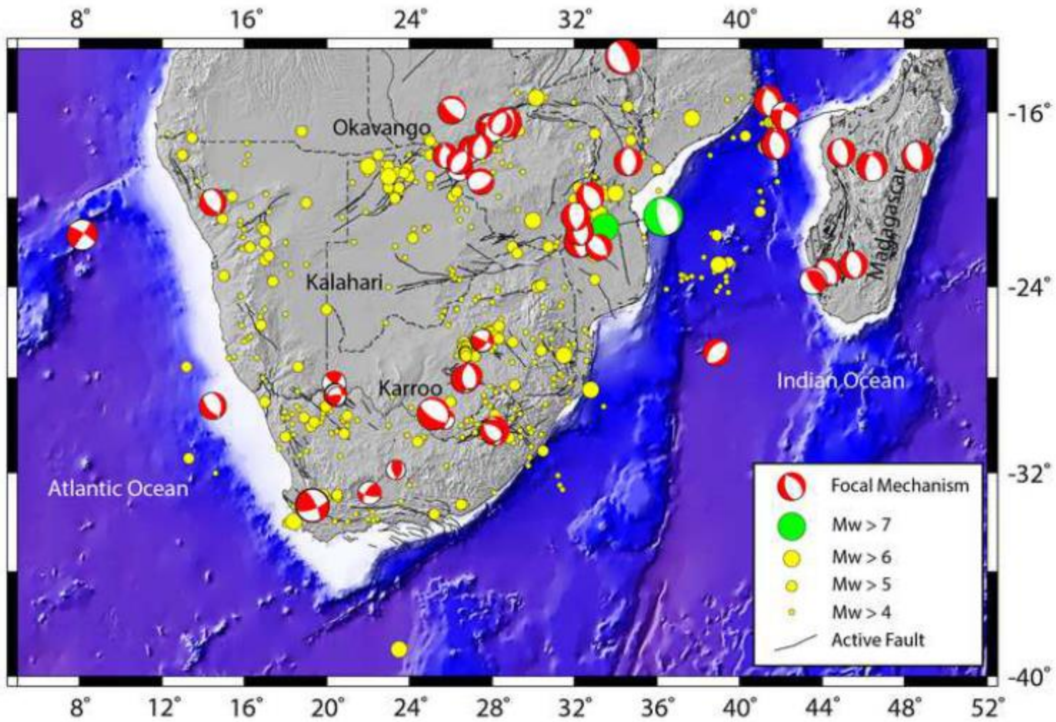

Figure 2: A seismotectonic map of southern Africa combining available information used in the identification of seismic sources

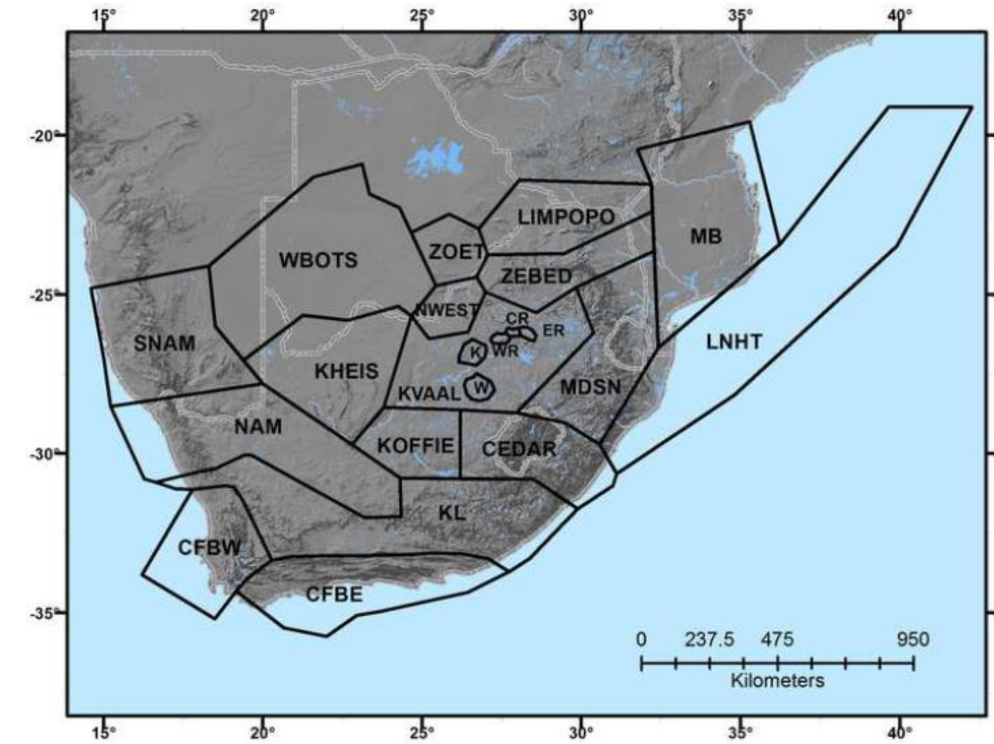

Figure 3: Illustration of the individual area source zones used in this study. ER- ERAND, WR – WRAND, CR – CRAND, K – KOSH and W – Welkom

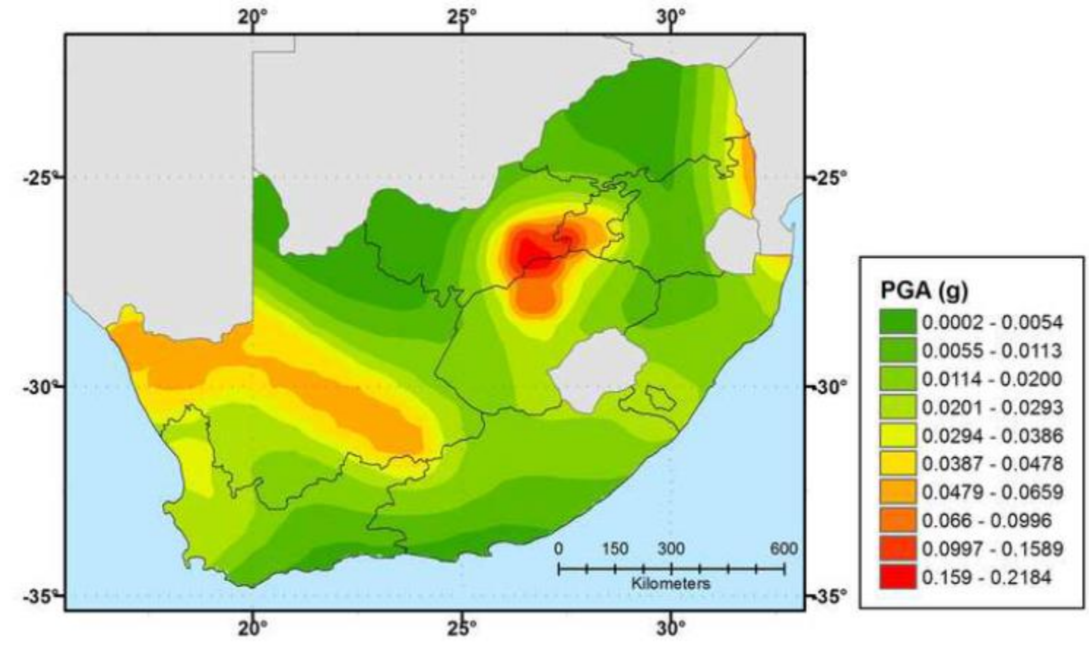

Figure 4. Distribution of mean PGA values in South Africa computed for 10% probability of exceedance in 50 years (return period of 475 years)

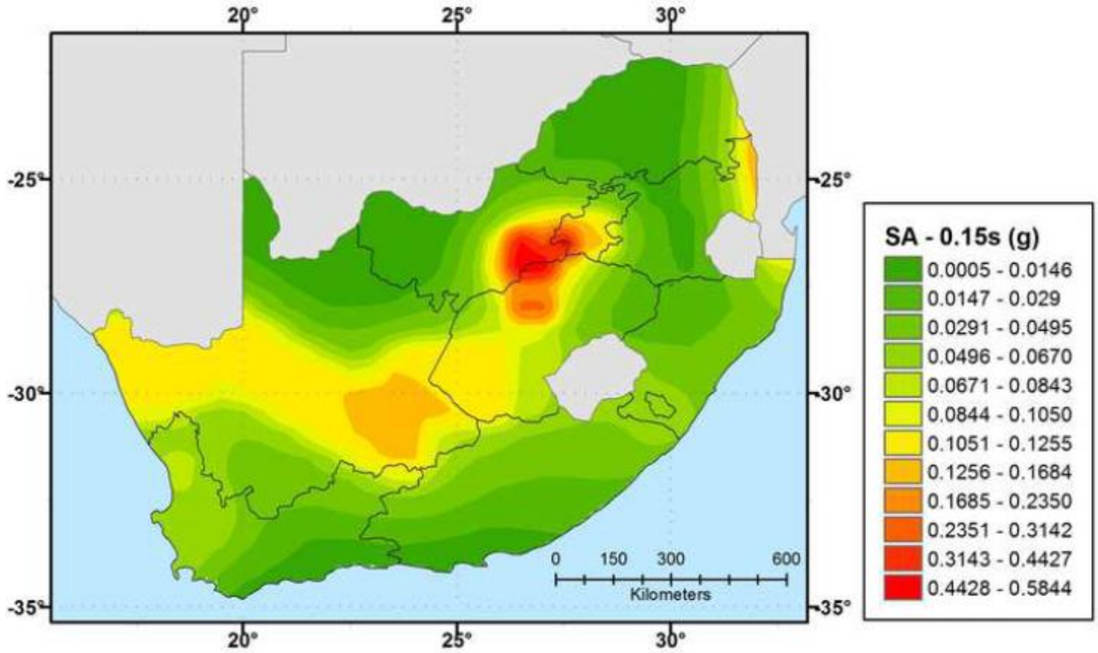

Figure 5. Distribution of spectral acceleration (period of 0.15s) values in South Africa computed for 10% probability of exceedance in 50 years (return period of 475 years)

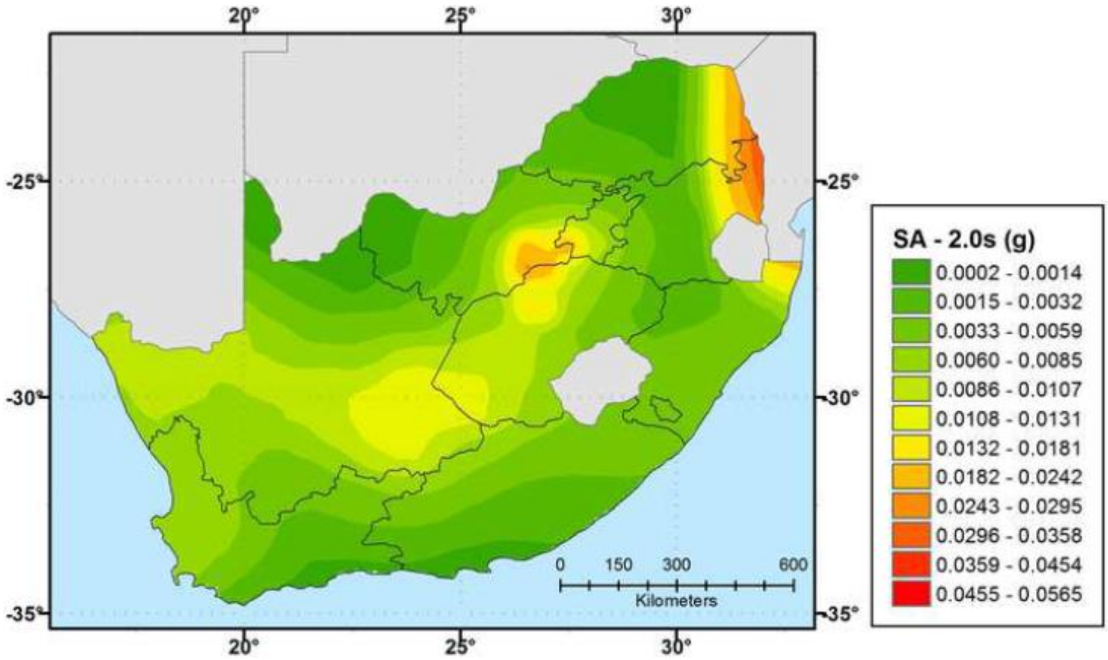

Figure 6. Distribution of spectral acceleration (period of 2.0s) values in South Africa computed for 10% probability of exceedance in 50 years (return period of 475 years)

Appendix C: Vulnerability of EGI and Monitoring

Primary reference: Milev, A, Durrheim, R, Brovko, F, Kgarume, T, Singh, N, Lumbwe, T, Wekesa, B, Pandelany, T & Mwila, M, 2016. *Development of a South African Minimum Standard on Ground Vibration, Noise, Air-blast and Flyrock near Surface Structures to be Protected.* Final Report, Project SIM14-09-01, South African Mine Health and Safety Council Report.

GROUND SHAKING

Ground vibrations are the inevitable results of earthquakes. The rock close to the fault zone may be crushed or fractured, but a proportion of the energy is radiated as elastic energy in the form of compressional (P) and shear (S) waves. The class of seismic waves that distort the Earth's surface most severely are known as 'surface waves', and are formed by the 'trapping' of P- and S-wave energy in near-surface layers. Surface waves have both compressional (and dilatational) components and vertical and horizontal components of shear. Their effect on buildings and other structures depends on the wavelength of the waves and the footprint and height of the structures. The seismic wavelength, in turn, depends on:

i. the size of the earthquake, and
ii. the seismic velocity of the rock, weathered material, alluvium or soil that comprises the near-surface layer of the Earth (say the uppermost 10-30 m).

Surface wave velocities (c) for near surface materials typically range from 200 m/s (alluvium) to 2000 m/s (slightly weathered granite); while the frequencies (f) produced by a typical blast in an open cast mine range from 5-200 Hz. The wavelength ($\lambda = c/f$) thus ranges from 1 m to 400 m. The potential to cause damage to buildings is greatest when the wavelength is of the same order as the footprint of the building (Figure 1).

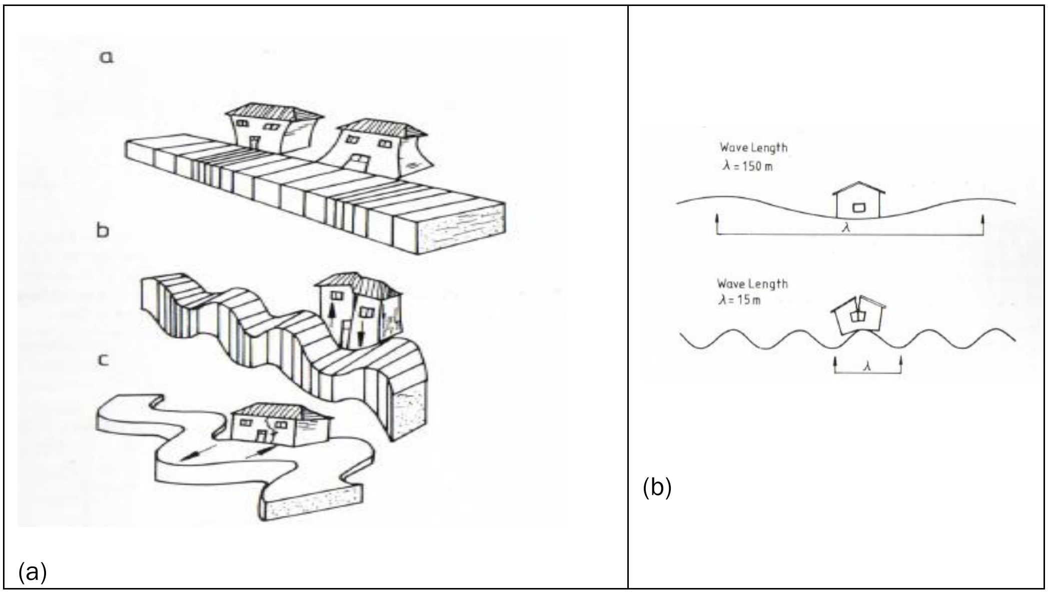

Figure 1: (a) How seismic waves distort structures; (b) The effect of wavelength
(Source: Tamrock, 1984, p. 166-167)

Earthquake-induced ground vibration can be measured using three different parameters: ground displacement (u), particle velocity (V) or acceleration (a). These parameters are related by the frequency (f) and π:

$$V = 2\pi f u$$

$$a = 2\pi f V = 4\pi^2 f^2 u$$

- **Acceleration (a)** is a measure of how quickly the point of interest changes velocity over a set period of time. This is usually expressed in millimetres per second per second (mm/s^2) or as a multiple of gravitational acceleration (9.8 m/s^2, or "g"). Acceleration on its own does not necessarily cause damage, but differential acceleration between objects or structures can create dynamic stresses and strains, causing damage.

- **Velocity (V)** is a measure of how far the point of interest moves in a set period of time. It is usually expressed in millimetres per second (mm/s). Like acceleration, velocity on its own does not cause damage. A house, car or person can sustain high speeds without damage; we see this every time we fly in a passenger jet.
- **Displacement (u)** is the distance that the point of interest moves from a certain reference point. This is usually expressed in millimetres (mm). Displacement alone does not cause damage; a house on the back of truck can be moved kilometres without being damaged. It is differential displacement (strain) that ultimately causes damage.

The potential to cause damage to buildings is most closely correlated with the Peak Particle Velocity (PPV). People can detect ground motions with PPVs as low as 0.8 mm/s; buildings may experience cosmetic damage at PPVs of 10 mm/s at frequencies of 10 Hz; while severe structural damage may occur when PPVs exceed 200 mm/s.

The methods used to record and analyse vibrations produced by earthquakes and mine blasts are similar, but there are important differences (Table 1). This means that the relationships and conclusions that are valid in earthquake engineering do not necessarily apply to mine blasting (JKMRC, 1996, p. 270).

Table 1: Comparison of blast-induced and earthquake ground vibrations

	Typical opencast blast	Damaging Earthquake (M>6)
Frequency (Hz)	5 - 200	0.1 – 5
Duration (sec)	0.5 - 5	10s of seconds to minutes
Displacement (mm)	0.001 - 2	100s of mm
Peak velocity (mm/s)	0.1 - 1000	Up to 1000
Peak acceleration (m/s^2)	0.01 - 100	Seldom > 10

SAFE LIMITS OF GROUND VIBRATION FOR EGI AND OTHER ENGINEERED STRUCTURES

Vibration limits have been published in the literature for different types of equipment and structures. Although these may differ slightly from application to application, the guidelines by Bauer and Calder (1977) are based on empirical information (Table 2).

Table 2: Vibration amplitudes for structures and equipment other than buildings
(Rorke, 2011; citing Bauer and Calder, 1977)

Type of Structure	Type of Damage	PPV at which Damage starts (mm/s)
Rigidly mounted mercury switches	Trip-out	12.7
Concrete blocks (e.g. floor slabs)	Hairline cracks in concrete	203
Cased drill holes	Horizontal offset	381
Mechanical equipment (e.g. pumps and compressors)	Shaft misalignment	1016
Prefabricated metal buildings on concrete pads	Cracked floor, building twisted and distorted	1524

The Australian Coal Association Research Programme (ACARP) project C14057 investigated methodologies for the assessment of the strength of infrastructure types and established limits for installations such as conveyors, power transmission towers, wooden power poles, electrical substations, pipelines, bridges, public access roads and underground working (Richards and Moore, 2007 and 2008). Some of the conclusions are listed below:

- **Power transmission towers:** Transgrid had commonly specified a limit of 50 mm/s. The study showed that this was conservative and a higher limit of 100 mm/s was validated, subject to effective measurement and control.
- **Wooden power poles:** Investigations showed that vibrations up to 240 mm/s did not adversely affect the poles.

- **Electrical substations:** The vibration limit is determined by the sensitivity of the trip switches in the substations, and the sensitivity of the switches varies considerably.
- **Conveyor structures:** Tests were limited to 25 mm/s. It was found that no significant additional stresses were imparted to the structure. Based on conservative assumptions, it is predicted that the conveyor will remain within serviceability limits at ground vibrations of 50 mm/s.

Vibration limits for civil and engineering structures such as power lines, roads, pipelines and conveyors are provided by Rorke (2011):

- **Eskom Power Lines:** Eskom places a limit of 75 mm/s at its pylons. This is a conservative limit as the steel structure of each pylon and the concrete foundation blocks can both withstand significantly higher vibrations.
- **Public Roads:** For public roads, such as the regional and national roads (e.g. R545, N4), the risk of disaggregation of the road material will start to appear at vibration amplitudes of the vertical component above 150 mm/s. Thus vibration levels at these structures need to be kept below 150 mm/s.
- **Telkom Relay Tower:** Structurally, towers will be able to withstand relatively high vibration at frequencies above 5 Hz. However, the electronic circuitry will be more sensitive, and a ground vibration limit of 10 mm/s is applicable.
- **Pipelines (Water and Transnet):** The limit at which pipelines will start to become damaged is high. Blasting near pressurized steel pipelines has taken place safely at PPV's in excess of 50 mm/s in South Africa. Unless the pipelines are in very poor condition or made of old concrete/asbestos, a level of 50 mm/s is considered to be safe. Transnet prescribed a limit of 25 mm/s on their pipeline that runs close to blasting operations along the N12 highway. (The purpose of the pipeline is not specified).
- **Conveyors:** A steel conveyor structure will withstand very high vibrations and the concrete plinths will remain undamaged by ground vibration up to 200 mm/s.

A similar compilation of vibration limits for civil and engineering structures such as power lines, roads, pipelines and conveyors is given in Table 3.

Table 3: Vibration limits for civil infrastructure used in South Africa
(Source: Blast Management & Consulting, 2015):

Structure Description	Ground Vibration Limit (mm/s)
National Roads/Tar Roads	150
Electrical Lines (Pylons)	75
Railway	150
Transformers	25
Water Wells	50
Telecoms Tower	50
General Houses of proper construction	USBM Criteria or 25 mm/s
Houses of lesser proper construction	12.5
Rural building – Mud houses	6

MONITORING OF VIBRATIONS

The South African National Standard (SANS 4866:2011, based on ISO 4866:2010) specifies measuring ranges for various vibration sources, including earthquakes and blasts (Table 4). These standards should be applied when carrying out surveys related to EGI.

The standard prescribes that instruments used to monitor ground-borne blast vibrations must be capable of measuring ground motions over the range 0.2 mm/s to 100 mm/s in the frequency range of 1 Hz to 300 Hz; while instruments used to monitor earthquakes must be capable of measuring ground motions over the range 0.2 mm/s to 400 mm/s in the frequency range of 0.1 Hz to 30 Hz.

Table 4: South African standards for measuring mechanical vibrations
(South African National Standard (SANS) 4866:2011)

Vibration source	Frequency range[a] Hz	Amplitude range µm	Particle velocity range mm/s	Particle acceleration range m/s^2	Time characteristic
Traffic road, rail, ground-borne	1 to 100	1 to 200	0,2 to 50	0,02 to 1	C[b]/T[c]
Blasting vibration ground-borne	1 to 300	100 to 2 500	0,2 to 100	0,02 to 50	T
Air over pressure	1 to 40	1 to 30	0,2 to 3	0,02 to 0,5	T
Pile driving ground-borne	1 to 100	10 to 50	0,2 to 100	0,02 to 2	T
Machinery outside ground-borne	1 to 100	10 to 1 000	0,2 to 100	0,02 to 1	C/T
Machinery inside	1 to 300	1 to 100	0,2 to 30	0,02 to 1	C/T
Human activities inside	0,1 to 30	5 to 500	0,2 to 20	0,02 to 0,2	T
Earthquakes	0,1 to 30	10 to 10^5	0,2 to 400	0,02 to 20	T
Wind	0,1 to 10	10 to 10^5	—	—	T
Acoustic (inside)	5 to 500	—	—	—	C/T

NOTE 1 The ranges quoted are extreme, but they still indicate the values which may be experienced and which may have to be measured (see also Note 2). Extreme ranges of displacement amplitudes and frequencies have not been used to derive particle velocities and accelerations. Values lower than 0,2 mm/s can also be considered. For building security and human annoyance, these values may be insignificant, but for sensitive equipments they are significant.

NOTE 2 Vibration values within the given ranges may cause concern. There are no standards which cover all varieties of structures, conditions and durations of exposure, but many national codes associate the threshold of visible (or otherwise noticeable) effects with peak particle velocities at the foundation of a structure of more than a few millimetres per second. A significant damage is linked to peak particle velocities of several hundred millimetres per second. Vibration levels below the threshold of human perception may be of concern in delicate and industrial processes.

[a] Ranges quoted refer to the response of structures and structural elements to a particular type of excitation and are indicative only.

[b] Continuous.

[c] Transient.

The guideline *Noise and Vibration from Blasting* issued by the Queensland Department of Environment and Heritage Protection (EM2402, version 3.00, approved 22 January 2016) differs slightly from SANS 4866:2011, recommending that ground vibration instrumentation used for compliance monitoring must be capable of measurement over the range 0.1 mm/s to 300 mm/s with an accuracy of not less than 5% and have a flat frequency response to within 5% over the frequency range of 4.5 Hz to 250 Hz.

Field Practice Guidelines for Blasting Seismographs, published by the International Society of Explosives Engineers (ISEE, 2015), is the industry standard for the correct monitoring of blast vibrations. It can be downloaded at https://www.isee.org/digital-downloads/290-isee-field-practice-guidelines-for-blasting-seismographs-2015. It notes that the following issues require special attention:

- **Coupling of vibration sensors:** If transducers are placed on the ground alongside the building being monitored, the recorded vibrations can be significantly affected by surface or near-surface features which may have a very localised affect. At high levels of vibration which occur at certain frequencies, it is also possible for transducers to leave the ground. In principle, this can be addressed by driving a stiff steel rod into the ground through the loose surface layer and attaching the transducer to it, but good coupling is often difficult to achieve. Alternatively, the transducer can be fixed to a rigid surface plate such as a well-bedded paving slab. Some equipment manufacturers suggest placing the transducer on a hard surface with a small sandbag on top of it. However, even if good coupling is achieved, the nature of the ground under the hard surface is unknown, and it might be very broken and affect the vibrations. Better coupling can be achieved if the transducers are buried in a density-matching box, but this is only practicable for permanent monitoring stations.
- **Calibration of vibration sensors:** The detectors commonly used to measure ground vibrations are either geophones (velocity transducers) or accelerometers. The vibrations produced by mining operations generally occur over the frequency range of 2-200 Hz and thus the detectors should be capable of

accurately monitoring vibrations across this range. Geophones require regular re-calibration over a period of time and if shaken violently. Geophones should be calibrated annually at least.

- Orientation of vibration sensors:
    - Some sensors are sensitive to orientation; a vertical 2 Hz geophone cannot be used as a horizontal sensor and vice-versa.
    - In a permanent array, sensors are usually orientated with respect to geographic north; while for a temporary measurement, the radial component is pointed towards the blast.
    - The three axes (directions) of measurement, the longitudinal (or "radial", the vector connecting the seismograph transducer and source of vibration), transverse (the vector in the same plane as, but perpendicular to, the longitudinal) and vertical (up and down) vectors, are always measured and reported separately. One reason for this is that they have different degrees of importance in causing damage. Structures are built to withstand vertical forces. For that reason, vibrations along the vertical vector are usually of lesser importance in causing damage, though not always benign. Vibrations in both the longitudinal and transverse directions have the potential for causing shear in the structure, which is a major contributor to damage effects. When in shear, various parts of the house move at different speeds or even in different directions, which can cause cosmetic cracking or even structural damage.
    - Vibration standards generally do not take these differences in damage potential between vibration direction components into account, but simply specify a single limit that applies to all three axes of measurement.
- Parameter(s) to measure
    - PPV is a "vector" quantity (i.e. it has both a value and an associated direction).
    - The Peak Vector Sum (PVS) is usually also quoted; it is simply the square root of the sum of the squares of the PPV values in all three vector directions measured by the geophones. PVS is a "scalar" quantity, i.e. one with only a value, which is always larger than the individual PPV vector values.
    - Scientific studies have shown that the PPV, of all the tested characterizations of ground movement (e.g. acceleration, displacement, or strain), correlates best with damage potential.
    - All the standards are quoted in PPV values, not PVS or other measures of movement, although the "acceptable" values of PPV differ with the standard applied and with the frequency of the vibration components.

It is important that ground and structure vibrations should be measured properly to ensure the receipt of correct records. A contemporary transducer for velocity measurement is a tri-axial pack of geophones with the frequency response from 1-300 Hz.

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