



# Near-surface wave attenuation ( $\kappa$ ) of an earthquake near Durban, South Africa

by M.B.C. Brandt

## Synopsis

The near-surface wave attenuation factor  $\kappa$  (kappa), which describes the attenuation of seismic waves over distance in the top 1–3 km of the Earth's crust, was determined for eastern South Africa using data recorded by five stations of the South African National Seismograph Network. The author carried out the analysis on data from an earthquake with magnitude 3.8 that occurred off the coast of Durban on 6 February 2016 at 09:00:01 GMT. For the analysis, the author selected a 30-second window for the S-phase portion of the vertical component seismogram. The result was an average  $\kappa = 0.021 \pm 0.0007$  seconds, which is lower than  $\kappa = 0.048$  seconds for micro-events in the Far West Rand and much lower than  $\kappa = 0.098$  seconds for explosions at Sasolburg coal mines (Brandt, 2017). Kappa was found to be higher than for a stable continental region ( $\kappa = \text{approx. } 0.0006$  seconds). This is likely due to the narrow frequency range between 4 Hz and 9 Hz, as well as the small data-set employed during this analysis.

## Keywords

kappa, near-surface seismic attenuation, tectonic earthquake, spectral analysis.

## Introduction

Brandt (2017) recently undertook a study to determine the near-surface wave attenuation factor  $\kappa$  (kappa) of Far West Rand micro-events and Sasolburg coal mine explosions. The values of  $\kappa = 0.048$  seconds (micro-events) and  $\kappa = 0.098$  seconds (explosions) were found to be much higher than for a stable continental region where  $\kappa = \text{approximately } 0.0006$  seconds (*e.g.* Atkinson, 1996; Douglas *et al.*, 2010). Brandt (2017) ascribed this higher value obtained for  $\kappa$  to (1) additional near-surface wave attenuation at the shallow focus of both micro-events and explosions; and (2) the effect of the implosive component (micro-events) or explosive component (explosions) not accounted for in the Brune source model (Brune, 1970, 1971). These two factors differentiate mining-related events and explosions from tectonic earthquakes that have (1) deeper focal depths (Brandt, 2014) and (2) a source mechanism that may be described by a double couple (McGarr, 2002). The purpose of the initial investigation by the author (Brandt, 2017) was to derive a value for mining-related  $\kappa$  that will be useful in

determining the attenuation relation required by spectral analysis when calculating moment magnitude,  $M_w$ , for S-waves using the seismograms recorded by the South African National Seismograph Network (SANSN).

However, no analyses are available for  $\kappa$  from tectonic earthquakes in South Africa for comparison. Some doubt remains whether the value of  $\kappa = 0.048$  seconds for mining-related events is appropriate for shallow, non double-couple sources. Recently, a unique opportunity presented itself when the seismic waves, originating from a magnitude 3.8 earthquake off the coast of Durban on 6 February 2016 at 09:00:01 GMT, were clearly recorded by five stations of the SANSN, including station Parys (PRYS), with which Brandt (2017) had previously determined  $\kappa$  for micro-events and explosions. In this study, the author used the SEISAN earthquake analysis software (Havskov and Ottemöller, 2010) and Scilab open-source software (2012) to determine  $\kappa$  for eastern South Africa using data from this earthquake. The author employed a Fourier acceleration spectral analysis of the seismic signals in eastern South Africa recorded by nearby regional, suitably calibrated seismograph stations that had been properly installed on bedrock. This study follows the method by Douglas *et al.* (2010), who derived a kappa model for France, but has adapted this approach for vertical component seismograms. The advantage of using this adapted approach is that the spectral analysis will be backwardly compatible to the 1990s, when waveform recording by the SANSN was carried out on vertical-component seismographs only (Saunders *et al.*, 2008). It was envisaged that the resultant  $\kappa$  would be useful for a

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comparison with the  $\kappa$  of Far West Rand micro-events and Sasolburg coal mine explosions, as well as for the calculation of  $M_w$  for tectonic earthquakes in South Africa. However, owing to the limited frequency range of 4–9 Hz of the author’s analysis, this derived  $\kappa$  should not be extrapolated for strong ground motion engineering applications.

## Method

The present study is a continuation of the work previously completed by Brandt (2017). The reader is referred to that article for the definition of near-surface wave attenuation,  $\kappa$ , the two routine methods used to determine  $\kappa$ , the advanced method to determine  $\kappa$ , and how  $\kappa$  shapes the source spectrum of a small earthquake. In this study,  $\kappa$  is determined by means of definition (1) in Brandt (2017). This is the original definition given by Anderson and Hough (1984), but modified here for signals originating from a moderate size earthquake of  $M_L \geq 3.4$  rather than for events larger than magnitude 5. Figure 1 is a map showing the epicentre of the magnitude 3.8 earthquake off the coast of Durban that occurred on 6 February 2016 at 09:00:01 GMT, together with the seismograph stations that recorded the signals at the time. The analyses were performed using the signals recorded by seismograph stations in eastern South Africa with epicentral distances of 271–640 km. The stations were suitably calibrated up to a maximum frequency of 9 Hz (beyond which the anti-alias filter influences the signal, which is difficult to calibrate). Moreover, the stations had been properly installed on bedrock, the purpose of which was to ensure that no unwanted signal distortions or amplifications would occur at the site. Station Parys (PRYS) had been used in the previous study to derive  $\kappa$  for Far West Rand micro-events (Brandt, 2017) and is included in the present data-set for comparison.

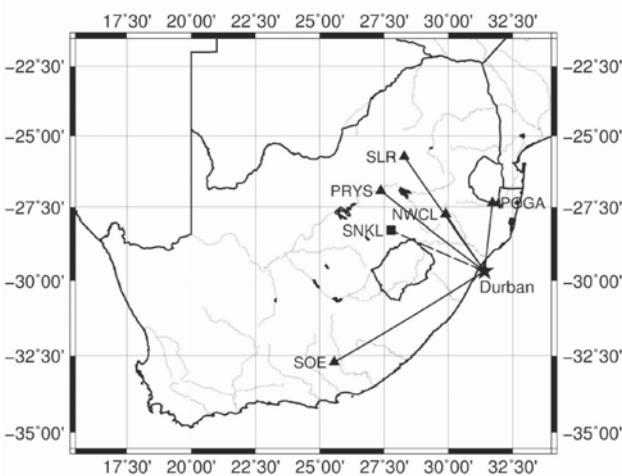


Figure 1—Location of the epicentre of the magnitude 3.8 earthquake in the Durban area and the seismograph stations at Somerset East (SOE), Parys (PRYS), Silverton (SLR), Newcastle (NWCL), and Pongola (POGA). The analysis was carried out on waves recorded by the stations (triangles with station codes) that had travelled along ray paths (lines) originating from the event near Durban on 6 February 2016 at 09:00:01 GMT (star). The waveform recorded by station Senekal (SNKL) (square) that had travelled along the dashed line ray path was rejected from the data-set

The first step in the analysis was to select suitable signals recorded by nearby regional stations for further processing. Examples of the semi-automatic selection procedure are shown Figure 2. The S-phase portion of the vertical component seismogram was identified and the corresponding Fourier acceleration spectra calculated. The Fourier acceleration S-spectrum and noise spectrum for a 30-second

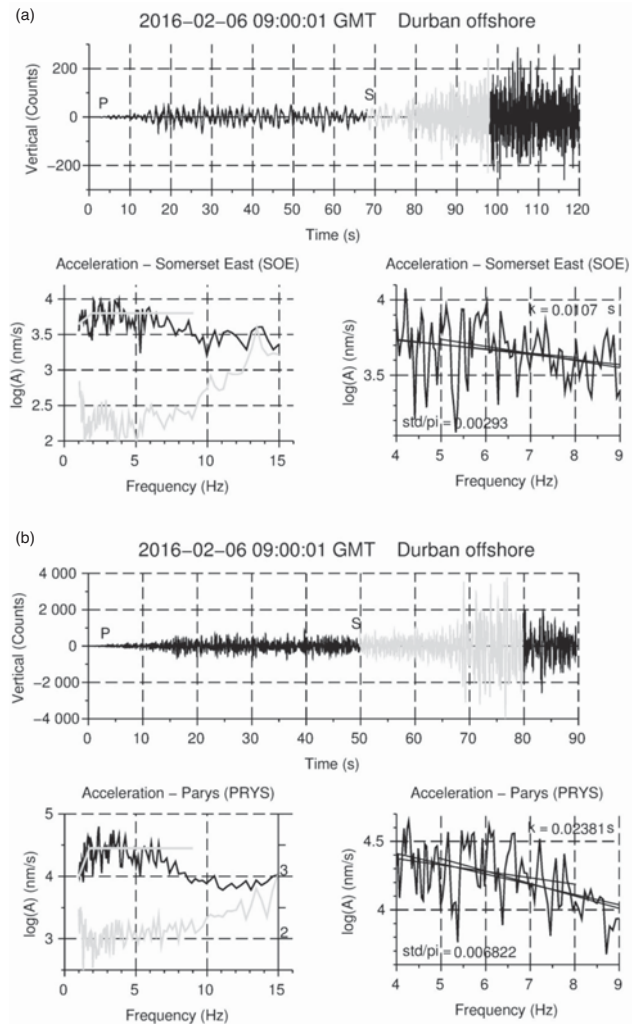


Figure 2—Examples of two analyses to select the waveforms recorded by (a) station Somerset East (SOE) with an epicentral distance of 640 km and (b) station Parys (PRYS) with an epicentral distance of 505 km, for further processing. For both seismograph stations in (a) and (b) the top trace shows the uncorrected seismogram with the 30-second long S-phase window (grey part of the time history) selected for spectral analysis. The bottom left panel shows the respective Fourier acceleration spectra for the signal (black curve with scale on left axis) and noise (grey curve with scale on left axis for SOE and right axis for PRYS) — signals selected for further processing required a minimum signal-to-noise ratio of 2. The flat level and low-frequency roll-off of the theoretical signal spectrum uncorrected for near-surface attenuation is indicated by means of grey lines. The bottom right panel shows the respective Fourier signal spectrum that has a high-frequency linear trend between 4 Hz and 9 Hz. A standard least-squares regression fits the Fourier acceleration spectrum with lines between 4–9 Hz, 5–9 Hz, and 4–8 Hz.  $\kappa$  is given for the slope between 4 Hz and 9 Hz by  $\kappa = -\lambda/\pi$  for (a) SOE  $\kappa = 0.0107$  seconds and (b) PRY  $\kappa = 0.02381$  seconds. Signals selected for further processing required a standard deviation /  $\pi$  of less than 0.01 for the three slopes

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window preceding the P-phase were plotted together to identify signals with a signal-to-noise ratio of at least 2. Next, the high-frequency linear downward trend (above 4 Hz) in the acceleration spectrum was identified visually by comparing this spectrum to the theoretical signal spectrum that had not been corrected for near-surface attenuation. Based on this comparison, Fourier acceleration spectra without an obvious high-frequency linear trend were rejected. Finally, three lines were semi-automatically fitted (with a linear regression) over the high-frequency linear trend between 4–9 Hz, 5–9 Hz, and 4–8 Hz, with  $\kappa = -\lambda/\pi$ , where  $\lambda$  is the measured slope of the fitted line.  $\kappa$  was determined over the frequency range 4–9 Hz. Signals with an unacceptable high-frequency linear downward trend were rejected from further processing if the standard deviation  $/\pi$  of the three slopes exceeded 0.01. Figure 3 demonstrates how a signal recorded at station Senekal was rejected. The noise spectrum displayed unwanted signal distortions at 1 Hz, 2.5 Hz, and 8 Hz, which were attributed to a local factor (man-made or geological) that distorted the signal acceleration spectrum.

The average spectrum of all five selected Fourier acceleration spectra (in view of deriving the average  $\kappa = 0.021 \pm 0.0007$  seconds) is shown in Figure 4, together with the linear fits to the acceleration spectra for those seismograph stations not included in Figure 2. Three lines were again semi-automatically fitted over the average spectrum high-frequency linear trend to derive average  $\kappa$ . Lines were also fitted over the standard deviation per frequency of the average spectrum and compared with the

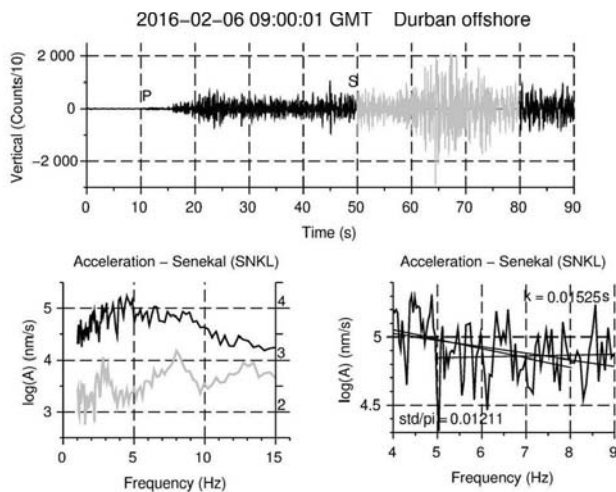


Figure 3—Example of the analysis which led to the rejection of the waveform recorded by station Senekal (SNKL) with an epicentral distance of 389 km for further processing. The top trace shows the uncorrected seismogram with the 30-second long S-phase window (grey part of the time history) selected for spectral analysis. The bottom left panel shows the Fourier acceleration spectrum for the signal (black curve with scale on left axis) and noise (grey curve with scale on right axis). The bottom right panel shows the Fourier signal spectrum that has a high-frequency linear trend between 4 Hz and 9 Hz. A standard least-squares regression fits the Fourier acceleration spectrum with lines between 4–9 Hz, 5–9 Hz, and 4–8 Hz.  $\kappa$  is given for the slope between 4 Hz and 9 Hz by  $\kappa = -\lambda/\pi$  where  $\kappa = 0.01525$  seconds. This signal was rejected from further processing since the standard deviation  $/\pi$  for the three slopes exceeded 0.01

arithmetic mean of  $\kappa$  for stations SOE, PRYS, SLR, NWCL, and POGA to test the consistency of average  $\kappa$  (*i.e.* the slope of the fitted line) with individual analyses. This test required the normalization of the different signal amplitudes to a common level to account for the attenuation over the epicentral distances ranging from 271–640 km.

## Discussion and conclusion

Determining average  $\kappa$  from a tectonic earthquake has provided a viable comparison to evaluate whether the value of  $\kappa = 0.048$  seconds is appropriate for mining-related events with shallow, non double-couple sources. The result of this analysis has yielded a  $\kappa = 0.021$  seconds, which is lower than  $\kappa$  for micro-events in the Far West Rand, and much lower than  $\kappa$  for explosions at Sasolburg coal mines. However,  $\kappa$  is higher than for a stable continental region where  $\kappa =$  approximately 0.0006 seconds (Atkinson, 1996; Douglas *et al.*, 2010). This may be ascribed to the narrow frequency range between 4 Hz and 9 Hz as well as the small data-set employed during the present analysis. Douglas *et al.* (2010) determined  $\kappa$  over a broad frequency range between 3 Hz and 50 Hz. For their study, the start of the linear downward trend in the acceleration signal spectrum ( $f_E$ ) was generally at 3 Hz, but with a large scatter within the 2–12 Hz range, as had originally been observed by Anderson and Hough (1984). However, it would appear from the present study that  $f_E$  is

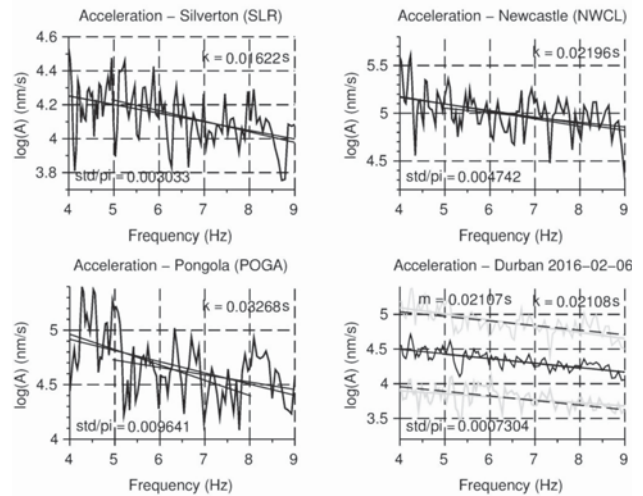


Figure 4—Analysis to determine average  $\kappa$  with standard deviation. The Fourier acceleration signal spectra (black curves) for stations Silvertown (SLR), Newcastle (NWCL), and Pongola (POGA) (not included in Figure 2) are shown in the top left, top right, and bottom left panels, respectively. A standard least-squares regression fits each spectrum with lines between 4–9 Hz, 5–9 Hz, and 4–8 Hz.  $\kappa$  is given by  $\kappa = -\lambda/\pi$  for the slope between 4 Hz and 9 Hz. Signals selected for further processing required a standard deviation  $/\pi$  of less than 0.01 for the three slopes. The bottom right panel shows the average of all the acceleration spectra (black curves) of stations SOE, PRYS, SLR, NWCL, and POGA with standard deviation per frequency (grey curves). A standard least-squares regression fits the average spectrum with lines between 4–9 Hz, 5–9 Hz, and 4–8 Hz.  $\kappa$  is given by  $\kappa = -\lambda/\pi$  for the slope between 4 Hz and 9 Hz where  $\kappa = 0.02108$  seconds. The standard least-squares regression fits of the standard deviation spectra are represented by grey lines. Dashed lines represent the projected arithmetic mean of  $\kappa$  for stations SOE, PRYS, SLR, NWCL, and POGA where slope  $m = 0.02107$  seconds



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consistently at 4 Hz for all five the stations and that the narrow frequency range between 4 Hz and 9 Hz is likely detrimentally affected by broad, local signal distortions (in comparison to the 2 Hz–50 Hz range). Nevertheless, since the moment magnitude for regional earthquakes is calculated by means of a spectral analysis of the S-wave using frequencies below 9 Hz,  $M_w$  for tectonic earthquakes can now be assigned with more confidence than before.

The result of  $\kappa = 0.024$  seconds for a tectonic earthquake, derived by station Parys (PRYS), as shown in Figure 2b, is in agreement (*i.e.* is lower) with the analysis of Brandt (2017), which yielded a value of  $\kappa = 0.048$  seconds for Far West Rand micro-events, using the same station.

The result of the present study is based on a small data-set derived from one earthquake with hypocentre near Durban, South Africa, and narrow frequency range signals recorded by five nearby regional stations. However, the comparison of  $\kappa$  derived before for Far West Rand micro-events and Sasolburg coal mine explosions with  $\kappa$  derived in this study for the tectonic earthquake using the same station, PRYS, indicates that the analysis techniques are sound. Once more earthquake signals are analysed, and specifically when signals over the frequency range between 3 Hz and 50 Hz become available for analysis from suitable tectonic and mine-related events, a more accurate understanding of near-surface wave attenuation for South Africa will emerge.

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