Do you have a moment: The importance of instrumentation in moment magnitude estimation

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Summary

Moment magnitude is a common parameter used to define traffic light protocols in induced seismicity applications. We investigate the network design constraints associated with calculating moment magnitude using seismometers and compare it to the constraints imposed by geophones for a typical induced seismicity monitoring project. We find that seismometers are able to estimate moment magnitude in a much larger area than geophones and, as a result, far fewer instruments are needed to obtain reliable moment magnitude estimates. Additionally, there is far more flexibility with respect to station locations; the station density required by geophones may not always be achievable. We conclude that seismometers provide increased network simplicity and improved performance when compared with geophones in a network designed to estimate moment magnitude.

Introduction

Induced seismicity monitoring has become much more common in the past twenty years. In many scenarios, certain protocols must be followed when an induced seismic event occurs. This has led to traffic light operations in many induced seismicity applications. For traffic light operations to be successful, it is necessary to know the magnitude of an event accurately. It is common to use the moment magnitude scale because it scales more reliably with the energy released by an event (Hanks and Kanamori, 1979).

Networks for monitoring induced seismicity typically have a very specific set of criteria which they must meet in order to ensure that a traffic light can be correctly implemented. We seek to compare the network design constraints inherent in moment magnitude estimation with respect to instrumentation. Specifically, we compare a broadband seismometer to a 10 Hz geophone and investigate their ability to estimate moment magnitude in a generic induced seismicity setting.

Methodology

We compare a geophone and seismometer with respect to their ability to estimate moment magnitude (Hanks and Kanamori, 1979). To do so we model the NLNM and NHNM (Peterson, 1993) and the Brune (1970) spectra for specific events. We follow the approach of Ackerley (2012) to determine the response spectra at a given distance away. The Brune response spectra of an M1 event is compared to the geophone instrument noise (Strollo et al, 2008) and seismometer instrument noise.

The range at which a geophone and seismometer can estimate moment magnitude is estimated according to a nominal criterion defined below.

Estimating moment magnitude depends on imaging the flat, low frequency portion of the Brune displacement spectrum. We specify that at a signal to noise ratio of 1 (i.e. when detection first becomes possible), the Brune displacement spectrum must be within 1.5 dB of its peak value (a power decrease by a factor of ~$\sqrt{2}$). This requirement, although arbitrary and perhaps optimistic, is simple and transparent. The spectrum is still relatively flat and the response is fairly close to the peak value which should allow for accurate moment magnitude estimation. If we lose too much more than 1.5 dB of signal then we start to stray from the flat portion of the Brune spectra and may underestimate moment magnitude as a result.

A Generic Example

We consider a typical network for induced seismicity. The network employs traffic light protocols for events larger than magnitude 2, and requires a magnitude of completeness of 1 to provide a buffer zone below their traffic light operations. The traffic light is based on the moment magnitude, thus we need to be able to estimate moment magnitude for all events magnitude 1 and larger. We will assume that our site noise is specified by the NLNM. Our region of interest will be defined by a square of size 30 km by 30 km. We will further assume that events occur at a depth of 3 km and that attenuation for the region is specified by a Q of 60. As a final assumption we will restrict ourselves to surface monitoring for simplicity. (While it is becoming common to bury instruments in order to reduce site noise, the depth at which sensors are usually placed is too small in relation to typical hypocenter depths to bear heavily on the geometry of the problem.) The question that we seek to address is as follows: How do constraints on network design reflect the choice of instrument?

We begin by assessing the detection range of a geophone and a seismometer with respect to moment magnitude estimation. We will set our focus on events of magnitude 1 as that is the lowest magnitude of interest. We consider a broadband seismometer and an 10 Hz geophone. For the geophone, the signal first becomes visible when the Brune spectrum exceeds the instrument noise; for the seismometer this occurs when the Brune spectrum exceeds the NLNM. For a magnitude 1 at 4.5 km the signal exceeds the instrument noise of a geophone starting at around 2 Hz. At this point the displacement spectrum is roughly 1.4 dB lower than its peak (at 5 km this grows to 1.55 dB). Thus we will take 4.5 km as our moment magnitude estimation radius for a M1 event measured with a geophone. For a M1 at 16 km the signal exceeds the low noise model at approximately 0.6 Hz. At this point the displacement spectrum is 1.4 dB below its peak (at 17 km this grows to 1.5 dB). Thus we will take 16 km as our moment magnitude estimation radius for a M1 event measured with a seismometer. The Brune spectra of magnitude 1 events at these distances are shown in figure 1.

The radius of moment magnitude estimation defined above is taken from the hypocenter. Since we are considering only surface monitoring, we must determine an epicentral radius in which moment magnitude estimation is possible. Recall the earlier assumption that our event depth is 3 km. First consider the geophone with hypocentral estimation radius 4.5 km. By Pythagorean Theorem this yields an epicentral estimation radius of 3.35 km or a total area in which moment magnitude can be estimated of 35 km^2. The seismometer has a hypocentral moment magnitude estimation radius of 16 km. Applying the same technique this translates to an epicentral estimation radius of 15.7 km or a total area of 776 km^2.

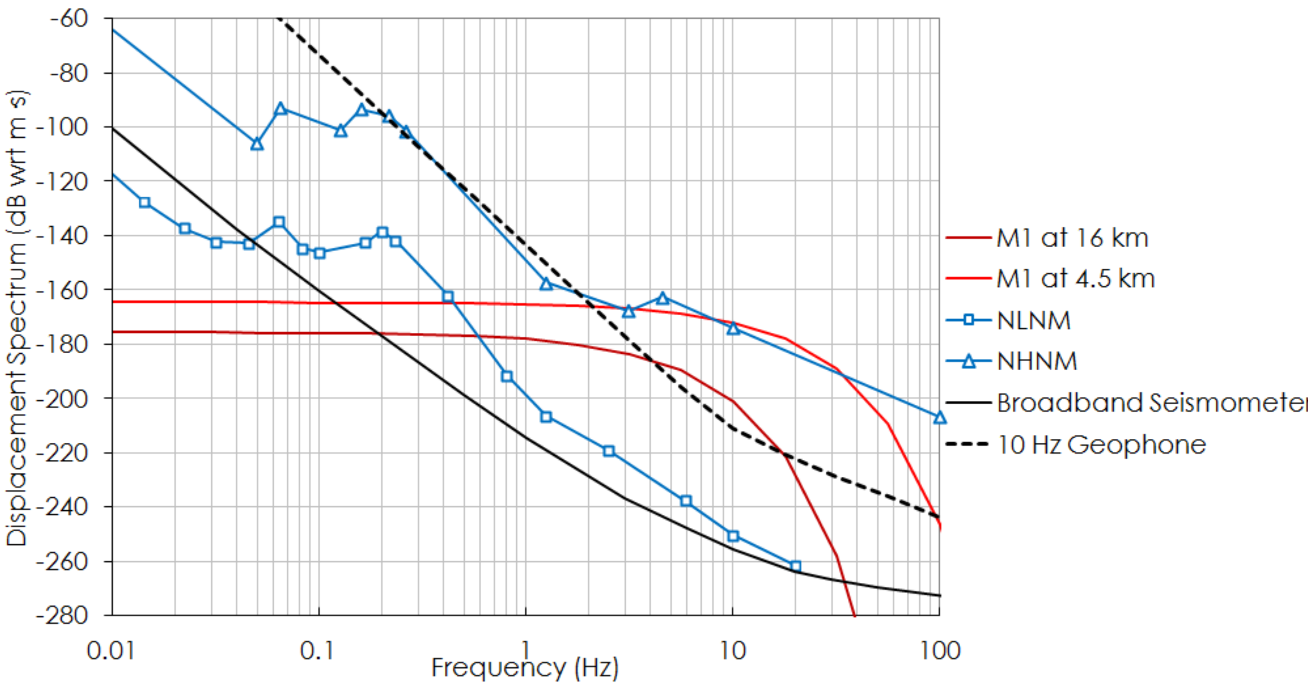

Figure 1: *Brune displacement spectra for magnitude 1 events at 4.5 km and 16 km. A seismometer can estimate moment magnitude for events up to 16 km away, a geophone up to 4.5 km away.*

Location algorithms typically require four station detections for event location. It is reasonable to apply the same requirement to the estimation of moment magnitude. We are interested in monitoring a 30 km by 30 km box (a 900 km^2 area); the entire region must be visible to 4 instruments. Thus we effectively need to cover 3600 km^2 with our sensors. We previously determined the area of reliable moment magnitude estimation of a geophone to be 35 km^2. Thus a minimum of 103 instruments are necessary to fulfill the network requirements. For a seismometer the area was found to be 776 km^2. As such we need a minimum of 5 seismometers to fulfill the network requirements. Because we are interested in a box and our instruments detect events within a circle, we will need some additional stations to compensate for lost area from the geometry of the problem. This geometry problem will be more challenging for seismometers because the detection circles are larger, however if we double the number of seismometers to 10 then we should have no trouble obtaining four station coverage of the region. We also apply a similar penalty to geophones. Optimistically, we will estimate that an additional seven geophones, bringing the total to 110, will be able to overcome the geometry problem.

A network designed using seismometers instead of geophones can reduce the number of instruments required by more than a factor of 10. This has the potential to greatly reduce the time and costs associated with installation and continued maintenance of the network. Furthermore, because the instrument density required when using seismometers is so much less than for a geophone, it provides considerably greater flexibility for station locations. It may not even be possible to place geophones at the required density to meet the network requirements. A large body of water or swamp may make it impossible to place geophones within a region, resulting in a blind spot in the network where moment magnitude cannot be determined. This is less likely to be a problem for a seismometer.

The above analysis has all been done for a magnitude 1 event, but the same principles apply to other magnitudes as do the general findings. For example, the above procedure is repeated and briefly summarized for a magnitude 2. Figure 2 shows the Brune spectra at the threshold of moment magnitude estimation according to the previously defined criterion. The hypocentral estimation radius has increased to 9 km for a geophone and 30 km for a seismometer, resulting in moment magnitude estimation areas of 226 km^2 and 2800 km^2 respectively. It will still be necessary to have considerably more geophones than seismometers.

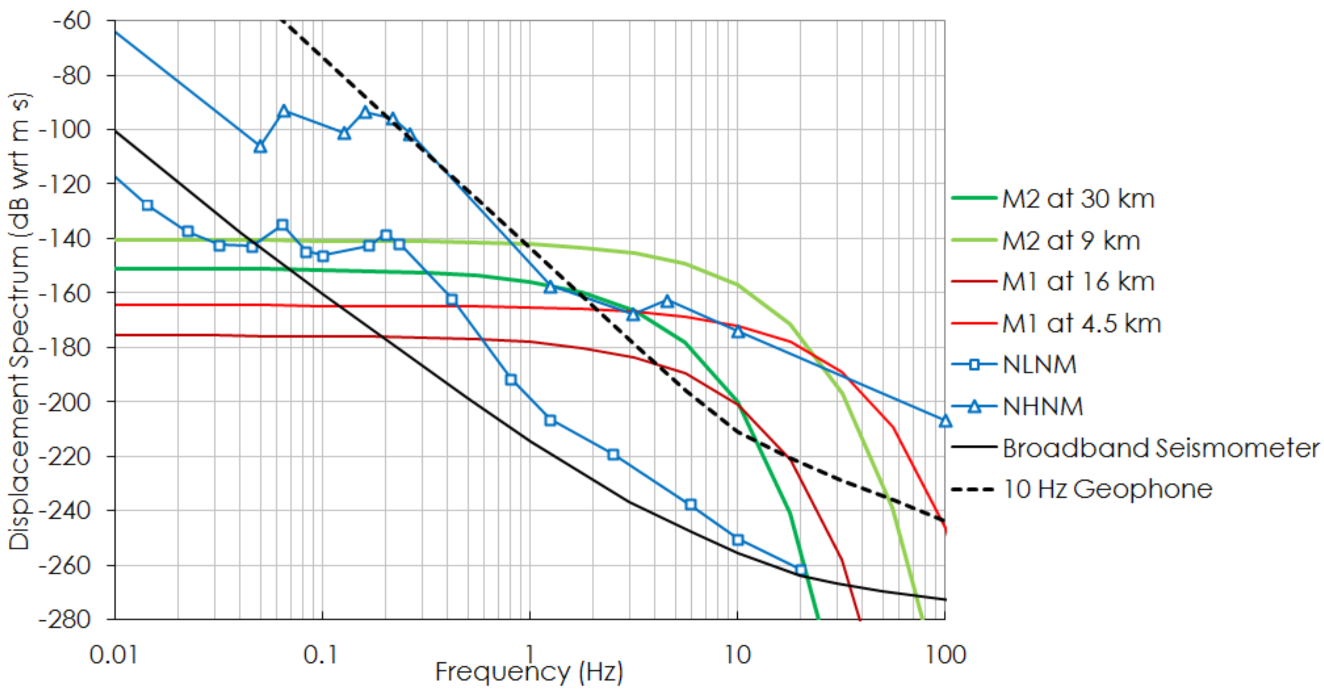

Figure 2: *Plot of the Brune displacement spectra for magnitude 1 and 2 events. A seismometer can estimate moment magnitude forM1 events within 16 km and M2 events within 30 km. A geophone can estimate moment magnitude for M1 events within 4.5 km and M2 events within 9 km.*

It is interesting to revisit the assumed area of interest (a 900 km^2 square). Some may argue that if an operation contains a single injection well, then the area that must be monitored is much smaller. This is simply not the case. Our understanding of fault mechanics is not detailed enough to be able to predict where an induced seismic event will occur. The induced seismicity near Guy, Arkansas is a good example. Two injection sites placed approximately 5 km apart triggered induced events distributed over nearly 20 km (Horton, 2012; see figure 3). Similarly, induced seismicity in Paradox valley has been shown to occur in several kilometres from injection sites (Ake et al, 2005). Induced seismicity is unpredictable and has the potential to occur in a large area regardless of its cause.

One final consideration is given to the depth of the event. If the event is shallower than 3 km, then the geophone's performance will slightly improve. Changing the depth to 0 km increases the geophones moment magnitude estimation area for M1 to 64 km^2 from 35, and the seismometers to 804 km^2 from 776. Though this reduces the number of geophones required considerably the seismometer still has vastly superior performance and still requires far fewer instruments. If, on the other hand, the depth is increased, then at depths larger than 4.5 km the geophone is no longer able to estimate moment magnitude reliably. In this case only a seismometer will be able to estimate moment magnitude of magnitude 1 events.

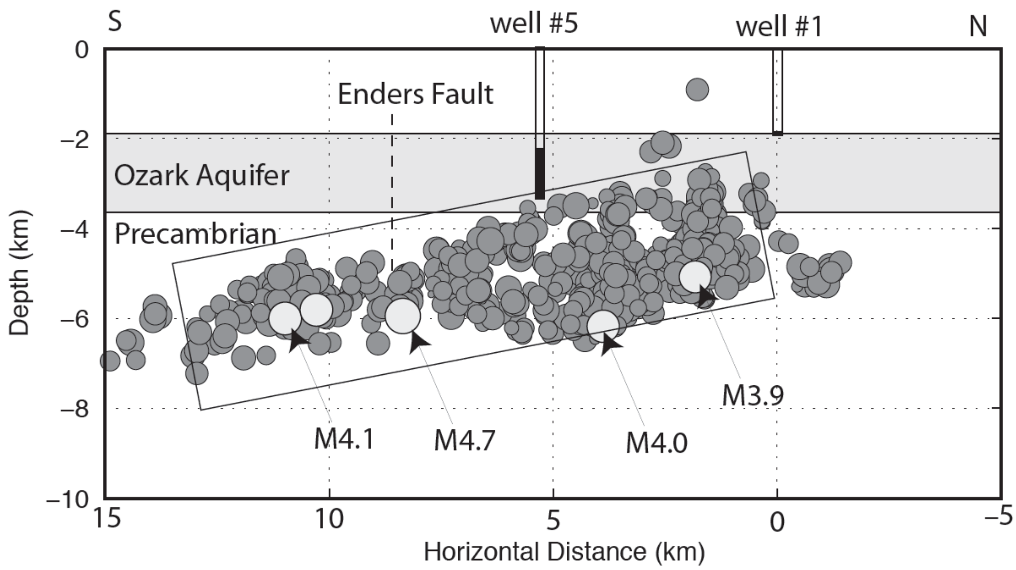

Figure 3 (from Horton, 2012): *Induced events from injection wells have occurred more than 10 km from the injection site.*

Conclusions

The broadband seismometer has a much larger range in which it can estimate moment magnitude than the 10 Hz geophone. For a M1 event, the seismometer will provide more than 750 km^2 of coverage whereas a geophone provides less than 40 km^2. The result is that a geophone network will require far more stations than a network of seismometers. This is not just true for M1 events, but for smaller and larger events as well. The constraints placed on network design using geophones are highly restrictive and may be impossible to meet. If, however, seismometers are used then there is considerably more freedom in design of the network. In induced seismicity applications the use of seismometers provides increased network simplicity and improved performance over a geophone.

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