Hydroseismograms from an underground hydrosensitive to seismicity site (Gran Sasso aquifer, central Italy)

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1. Introduction

Seismic monitoring by means of hydroseismograms (Figure 1), which involves high-frequency pore pressure measurements in wells drilled into rock formations, has emerged as a promising tool for understanding earthquake physics and improving seismic monitoring and prediction capabilities (De Luca et al. 2016, 2018).

This study investigates the earthquake detection capabilities of a hydraulic pressure device (HPD) installed in the Gran Sasso Aquifer (GSA), in central Italy. By comparing data from the HPD with seismic records from the nearby GIGS station, we have assessed the HPD's ability to detect a significant number of earthquakes. The HPD unique location in deep, horizontal wells intersecting a main fault network, combined with its high-frequency sampling rate, provides a sensitive tool for monitoring seismic activity and pore pressure anomalies. Our results pointed out as the utilized HPD is significantly more sensitive compared with previous studies (Montgomery and Manga, 2003; Manga and Wang, 2015, and references therein).

Our findings build upon previous research by De Luca et al. (2016, 2018), who observed anomalous signals in two boreholes (named S13 and S14) during the 2016 Amatrice seismic sequence. These studies highlighted the potential of monitoring hydro-seismograms for detecting seismic precursors and understanding the complex interplay between groundwater and seismic activity.

By analyzing long-term, high-frequency pore pressure data from the GSA, we aim to further our understanding of these phenomena. The fractured-karst geology of the GSA, coupled with the presence of the INFN underground laboratory, provides an ideal setting for studying the interaction between groundwater and seismic activity in a deep, saturated environment.

This research contributes to the advancement of earthquake science by providing valuable insights into the physical processes underlying seismic events. The findings have implications for seismic hazard assessment and early warning systems.

2. Methods

The present investigation delves into long-term high frequency pore pressure data, compared with seismic records from proximate stations (Figure 1).

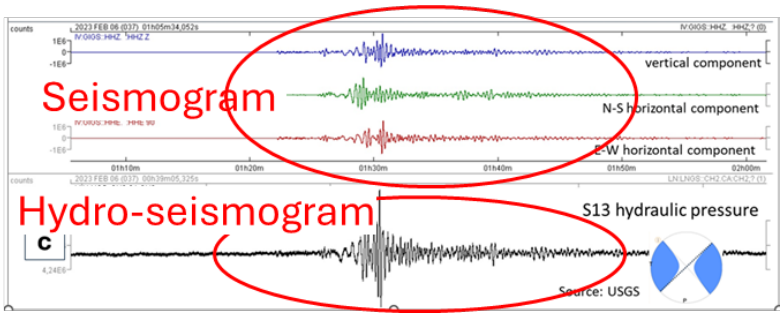


Fig. 1 – Example of seismogram and hydroseismogram.

The Gran Sasso Aquifer (GSA), characterized by its fractured-karst geology, multiple active faults, and location within Italy's high seismic hazard zone, serves as an exemplary case study. Moreover, the presence of the Italian Institute of Nuclear Physics (INFN) underground laboratory (UL) within the GSA provides a unique opportunity to study aquifer-earthquake interactions in a deep saturated environment largely unaffected by shallow hydrological processes. The UL hosts two horizontal boreholes, located within the borehole hall (Figure 2), denoted by S13 (length 190 m) and S14 (length 175 m) which are equipped with a high-frequency (20 Hz) data acquisition system specifically designed for sensitive hydraulic pressure monitoring (i.e., the HPD).Within the Gran Sasso underground laboratories (LNGS-INFN), approximately 250 meters from borehole S13, lies the INGV seismic station GIGS (De Luca et al., 2018). This station, part of the GINGER experiment (Di Virgilio et al., 2017), is equipped with two broadband seismometers, enabling the continuous monitoring of microseismic activity in the Gran Sasso range and the recording of global seismicity.

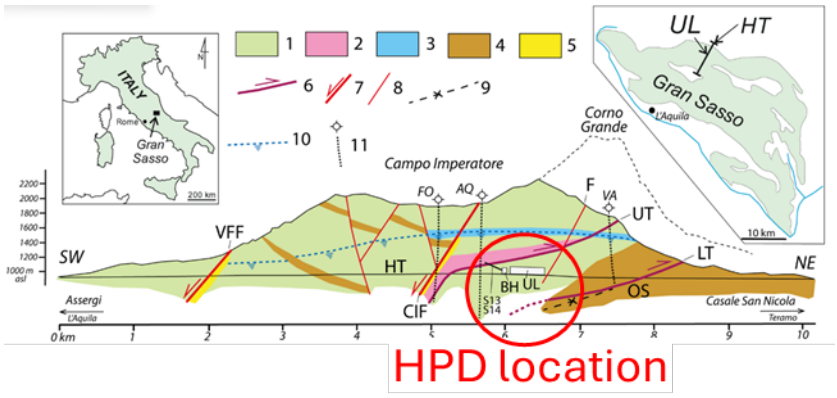


Fig. 2 –Hydrogeological section of the GSA including the highway tunnels (HT), the INFN Gran Sasso underground laboratory (UL), the borehole hall (BH) and the S13-S14 subhorizontal boreholes. Legend: (1) limestone (Upper Cretaceous - Upper Jurassic); (2) dolomite (Dolomia Principale Fm., Upper Triassic); (3) paleokarst horizon; (4) terrigenous low-permeability lithologies; (5) low-permeability fault rock; (6) main thrust (UT: upper thrust; LT: lower thrust); (7) main normal fault (CIF: Campo Imperatore fault; VFF: Valle Fredda fault); (8) minor normal fault; (9) Overturned syncline (OS) in the UT footwall; (10) water table before the tunnels excavation; (11) deep boreholes (FO: Fontari; AQ: Monte Aquila; VA: Vaduccio).

The primary objective of the joint analysis of well and seismic data consists in identifying and correlate coincidences between earthquakes of various scales (global, regional, and local) with the hydraulic pressure variations within the GSA detected by the HPDs installed in boreholes S13 and

S14. The data acquisition, observation, and analysis period spanned from May 1st, 2015, to December 31st, 2023, with ongoing monitoring continuing.
The HPD sensitivity was conducted according to a statistical inferential approach, by comparing the number of events identified by the HPD with those recorded by the nearby seismic station GIGS (1068 events) for various magnitude and epicentral distance values. The analysis was performed both considering all recorded events and by separately investigating crustal and deep earthquakes.
We investigated the relationship between sensitivity, magnitude, and epicentral distance of earthquakes.

3. Results and Discussion

Statistical analysis revealed that the HPD employed in this study exhibits significantly greater sensitivity compared to previous analogous studies (Dobrovolsky et al., 1979; Montgomery and Manga, 2003; Manga and Wang, 2015, and references therein). Overall, the HPD demonstrated a 13.9% success rate, detecting 148 seismic events out of 1068 identified by GIGS. However, this probability is strongly dependent on the magnitude and epicentral distance of each event. Figure 3 compares our results to those of previous studies. The threshold identified in this study is 1-2 magnitude units lower than that determined by Manga and Wang (2015). Particularly noteworthy is the comparison with the threshold defined by Montgomery and Manga (2003) according to the criterion by Dobrovolski et al. (1979), which can be viewed as a "hard" limit for detecting seismic events in a typical aquifer (Montgomery and Manga, 2003). This is supported by the findings of Montgomery and Manga (2003), who in a large dataset did not identify any events below this threshold. Figure 3 shows that, for distant events, the HPD used in this study is significantly more sensitive than predicted by the Dobrovolski et al. (1979) criterion. This finding warrants further investigation, as it highlights aspects of the mechanisms underlying hydroseismic detection that are not yet fully understood and will be the subject of future studies.

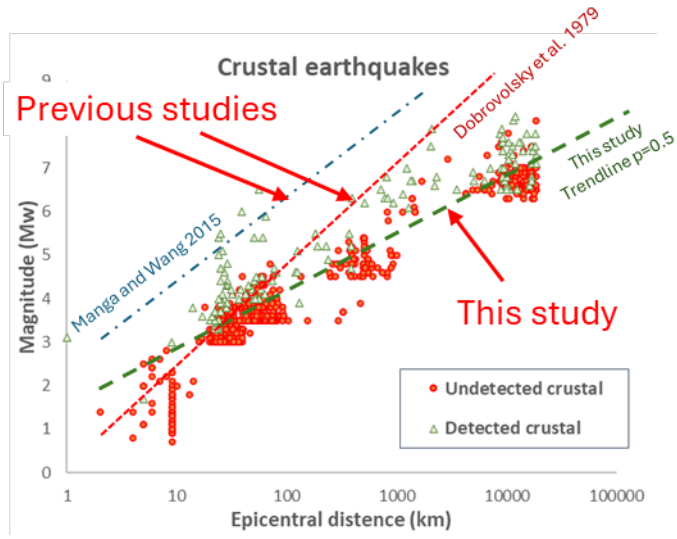


Fig. 3 – Scatterplot for crustal earthquakes; blue dashed line denotes the detection limit from Manga and Wang (2015) and red line represents the theoretical limit individuated by Montgomery and Manga (2003) according to the Dobrovolsky et al. (1979) criterion. The green dashed line denotes the detection limit for our HPD.

4. Conclusions

Our investigation into the seismic detection capabilities of HPDs installed in carbonate rock boreholes (S13 and S14), conducted from May 2015 to December 2023, has yielded promising results when compared to existing literature. The device accurately identified 148 out of 1068 analyzed seismic events. Sensitivity analysis, focusing on crustal earthquake magnitude and epicentral distance, has shown that our HPD significantly overcomes the sensitivity limit for seismic event detection reported in previous studies (Montgomery and Manga, 2003; Manga and Wang, 2015, and references therein). It has also proven particularly effective in detecting deep events, although our analysis was limited to far events due to a lack of nearby deep earthquakes. The Gran Sasso Aquifer, characterized by its complex hydrogeological and seismotectonic conditions, provides an ideal setting for deploying HPDs, both for medium-to-long-term and high-frequency pore pressure monitoring. Its strategic location within the aquifer's core, with two boreholes intersecting the main fault network, offers a unique opportunity to study the complex interplay between hydrological processes and seismic activity. Given the encouraging outcomes of this research, we intend to continue monitoring efforts using HPDs to further explore their potential as a valuable tool for seismic studies.

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