SnT 2025
8 SEPTEMBER ONLINE DAY
9 TO 12 SEPTEMBER AT HOFBURG PALACE, VIENNA & ONLINE
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Neutralization of a WWII Aerial Bomb in the Port of Rijeka: Seismological Data Analysis

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University of Zagreb - Faculty of Science - Croatian Seismological Survey

CROATIAN SEISMOLOGICAL SURVEY

INTRODUCTION AND MAIN RESULTS

During infrastructure works in the Port of Rijeka, an unexploded World War II aerial bomb was discovered at a depth of 19 meters. The controlled neutralization was carried out on March 19, 2023, at 1:15 p.m. (UTC+1) at a secure offshore location. Prior to the operation, residents were evacuated from the city center near the port to ensure public safety.

Seismological data enabled precise determination of the explosion's location. This confirmed the successful neutralization of the bomb while minimizing risks to surrounding areas.

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Introduction

During infrastructure works in the Port of Rijeka, an unexploded aerial bomb from World War II was discovered at a depth of 19 meters, covered in sediment. Following a detailed technical assessment, the device was measured to be 298 cm in length and 70 cm in diameter, with a total weight of 986 kg, including 690 kg of high explosives. Due to its considerable size and location, authorities decided to relocate the bomb to a designated offshore site for controlled detonation. To mitigate potential risks and ensure the highest level of public safety, the Civil Protection Headquarters of the City of Rijeka implemented extensive protective measures. These included the suspension of road, rail, air, and maritime traffic, as well as the evacuation of residents from designated zones within the city center near the port (*Figure 1*).

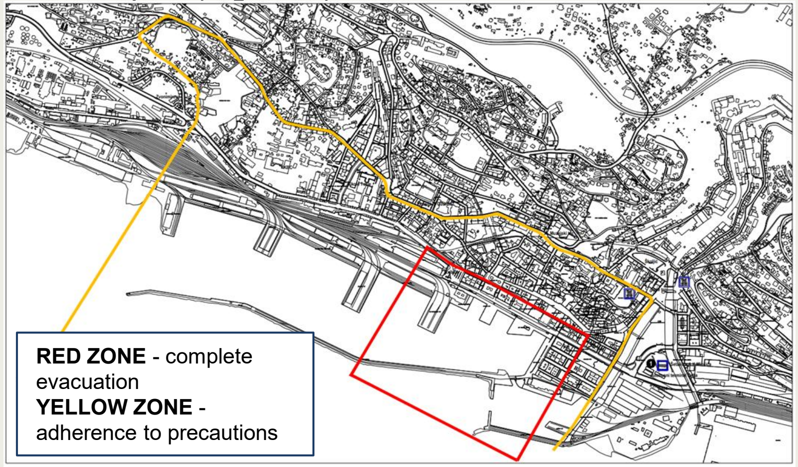

Figure 1: Ground plan of the Port of Rijeka

The neutralization operation was successfully conducted on March 19, 2023, at 13:15 local time (UTC+1), at a secure maritime location situated 8.3 km from the nearest point on the mainland (*Figure 2, 3*).

Figure 2: Photo courtesy of the Primorje-Gorski Kotar Police Department

Figure 3: Photo courtesy of the Primorje-Gorski Kotar Police Department

Data

Seismic stations from the Croatian and Slovenian networks were used to analyze the detonation. These stations were equipped with three-component broadband seismometers and accelerometers. The stations included: AKK04, PA25, PS27, PA27, QBSK, PS06, BOJS, CADS, CEY, CRES, CRNS, GBAS, GBRS, GCIS, GORS, GROS, JAVS, KNDS, SKDS, VISS, OZLJ, SAVD, RICI and VNDS (*Figure 4, 5*).

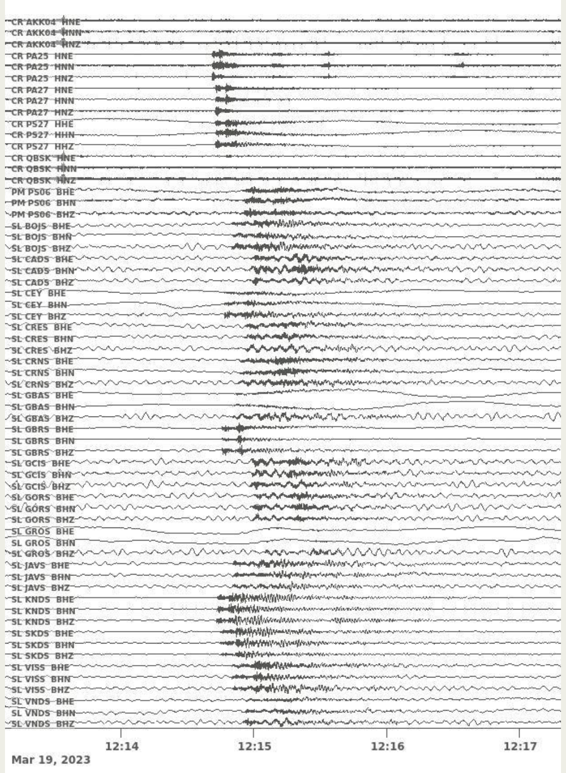

Figure 4: Seismograms from Croatian and Slovenian seismic stations used to determine the location of the controlled detonation of a naval mine in the Bay of Rijeka

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Data (cont.)

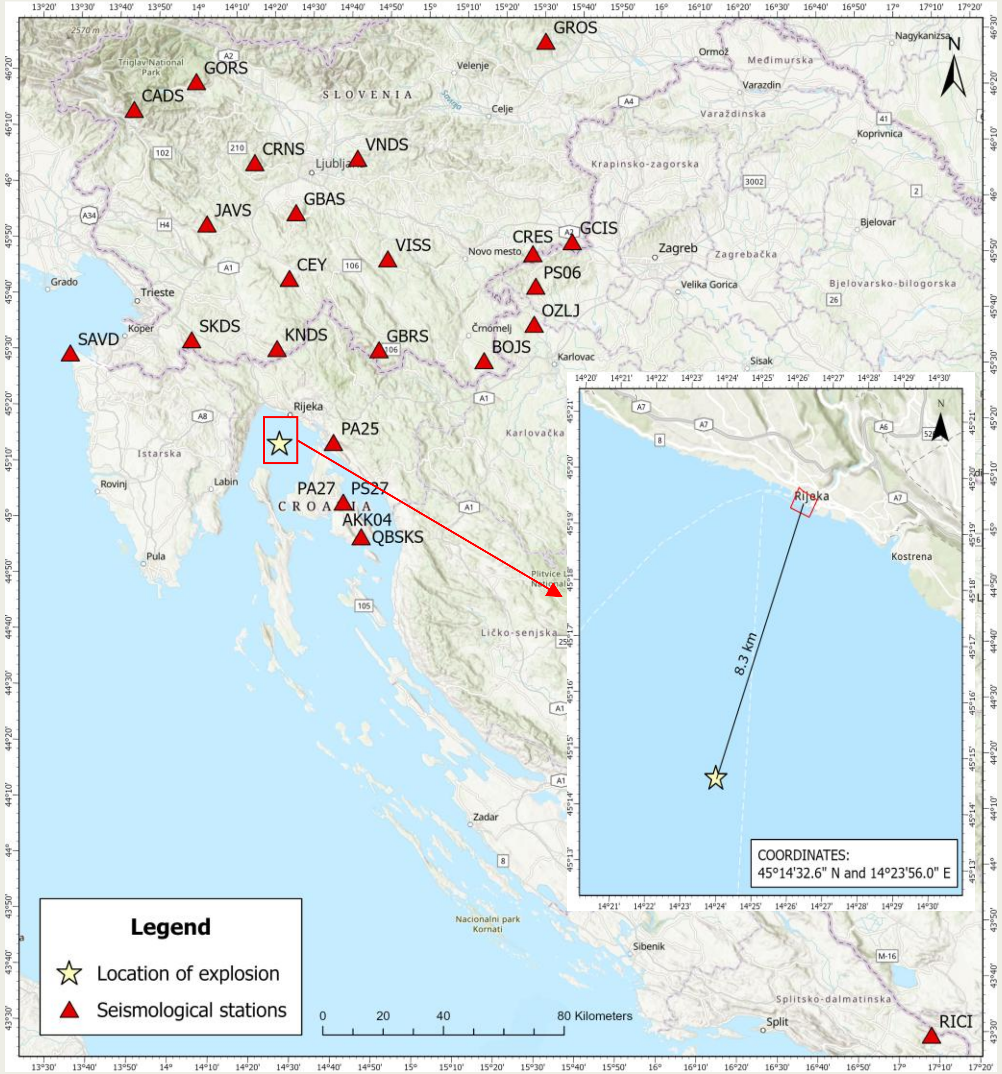

Figure 5: Map of the Croatian and Slovenian Seismological Network used to determine the location of the controlled detonation of an aerial bomb in the Bay of Rijeka

Table 1: List of seismological stations from Croatia and Slovenia used to locate the detonation of aerial bomb. Station type – Permanent (P), Temporary (T)

CODE	Latitude	Longitude	Elevation	Location name	Station type	Sensor	Recorder
BOJS	45,5° N	15,25° E	252 m	Bojanci	P	Nanometrics Trillium T360 [360 sec], Kinemetrics EpiSensor (ES-T) [2g]	Quanterra Q330HRS
CRES	45,83° N	15,46° E	431 m	Črešnjevec	P	Streckeisen STS-2 [120 sec], Kinemetrics EpiSensor (ES-T) [2g]	Quanterra Q330HRS
GBRS	45,53° N	14,81° E	610 m	Gornja Briga	P	Streckeisen STS-2.5 [120 sec], Guralp Fortis [2g]	Quanterra Q330HRS
KNDS	45,53° N	14,38° E	1035 m	Knežji dol	P	Streckeisen STS-2 [120 sec], Guralp CMG-5TC [2g]	Quanterra Q330HRS
CADS	46,23° N	13,74° E	751 m	Čadrg	P	Nanometrics Trillium 120QA [120 sec], Nanometrics Titan [2g]	Quanterra Q330HRS
CEY	45,74° N	14,42° E	579 m	Cerknica	P	Guralp CMG-3ESPC [120 sec], Guralp Fortis [2g]	Quanterra Q330HRS
CRNS	46,08° N	14,26° E	712 m	Črni Vrh	P	Nanometrics Trillium 120QA [120 sec], Nanometrics Titan [2g]	Quanterra Q330HRS
GBAS	45,93° N	14,44° E	525 m	Gornja Brezovica	P	Nanometrics Horizon 120 [360 sec], Nanometrics Titan [2g]	Quanterra Q330HRS
GORS	46,32° N	14° E	1048 m	Gorjuše	P	Streckeisen STS-2.5 [120 sec], Kinemetrics EpiSensor (ES-T) [2g]	Quanterra Q330HRS
GCIS	45,87° N	15,63° E	385 m	Gornji Cirnik	P	Streckeisen STS-2 [120 sec], Kinemetrics EpiSensor (ES-T) [2g]	Quanterra Q330HRS
GROS	46,46° N	15,5° E	930 m	Grobnik	P	Nanometrics Trillium 120QA [120 sec], Kinemetrics EpiSensor (ES-T) [2g]	Quanterra Q330HRS
JAVS	45,89° N	14,06° E	1100 m	Javornik	P	Streckeisen STS-2.5 [120 sec], Guralp CMG-5TC [2g]	Quanterra Q330HRS
SKDS	45,55° N	14,01° E	552 m	Skadanščina	P	Streckeisen STS-2.5 [120 sec], Nanometrics Titan [2g]	Quanterra Q330HRS
VISS	45,8° N	14,84° E	399 m	Višnje	P	Streckeisen STS-2.5 [120 sec], Guralp CMG-5TC [2g]	Quanterra Q330HRS
VNDS	46,1° N	14,7° E	531 m	Vrh pri Dolskem	P	Guralp CMG-3TC [120 sec], Kinemetrics EpiSensor (ES-T) [2g]	Quanterra Q330HRS
AKK04	44,97° N	14,75° E	73 m	Baška	T	Kinemetrics Etna2 (1g)	Kinemetrics Etna2
OZLJ	45,6° N	15,5° E	155 m	Ozalj	P	Guralp CMG-40T [30s - 50Hz]	Guralp DM24S3
SAVD	45,49° N	13,50° E	14 m	Savudrija	P	Guralp CMG-40TD [30s - 50Hz]	Guralp DM24S3
PA25	45,25° N	14,63° E	189 m	Križišće	T	Kinemetrics Etna2 (1g)	Etna2
PS27	45,07° N	14,67° E	63 m	Krk - Vrbnik	T	Kinemetrics MBB2	Quanterra Q8
PA27	45,07° N	14,67° E	63 m	Krk - Vrbnik	T	Kinemetrics Etna2 (1g)	Etna2
QBSK	44,97° N	14,75° E	73 m	Baška	T	Kinemetrics Etna2 (1g)	Etna2
RICI	43,5° N	17,1° E	431 m	Ričice	P	Guralp CMG-3ESPC [120s-50Hz]	DM24S3
PS06	45,73° N	15,47° E	408 m	Zelezno	T	Kinemetrics MBB2	Quanterra Q330HRS

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Methodology

Seismological data from the Croatian and Slovenian seismological network was processed and analysed for first arrivals and location of explosion on SANDI (Seismological Analysis and Display) software developed at Department of Geophysics, Faculty of Science, Zagreb. The waveform was filtered with a 3–8Hz, N=3 Butterworth band-pass filter to enhance body waves.

Spectral analysis was employed by the Snuffler software. Spectrograms were computed using a short-time Fourier transform (STFT) and 100 seconds window length to ensure high frequency resolution. A Hanning was applied to each segment. No band-limiting filter was applied before spectrogram computation. The analysis was applied to all three components (BHZ,BHN, BHE) for phase comparison.

Results

The explosion occurred on March 19, 2023, at 12:14 UTC, at coordinates 45°14'32.6" N and 14°23'56.0" E, 8.3 km offshore from the nearest land.

Spectrogram analysis shows that the dominant frequency range at most stations is between 2 Hz and 5–6 Hz. The strongest components fall between 3 and 4.5 Hz, which is consistent with the frequency profile of underwater explosions, known for producing significant low-frequency energy (*Figure 6*).

The energy contribution above 6–7 Hz decreases rapidly, and the signal above 8 Hz nearly disappears, suggesting that higher frequencies are strongly attenuated due to distance and energy loss. However, at stations QBSK, AKK04, and PA25, dominant frequencies are observed between 20–80 Hz, with peaks around 40–60 Hz (*Figure 7*). Arrival times at these stations were later than others, around 12:26 UTC. The average log power spectral density (PSD) value was around 15, while stations VNDS, CRNS, KNDS, and SKDS recorded values up to 17.5. The explosion produced a very clear and broadband signal, indicating isotropic energy radiation, which is evident across all waveform components. The prolonged reduction in background noise following the event may indicate reverberations or long-lasting acoustic/seismic wave transmission through the subsurface.

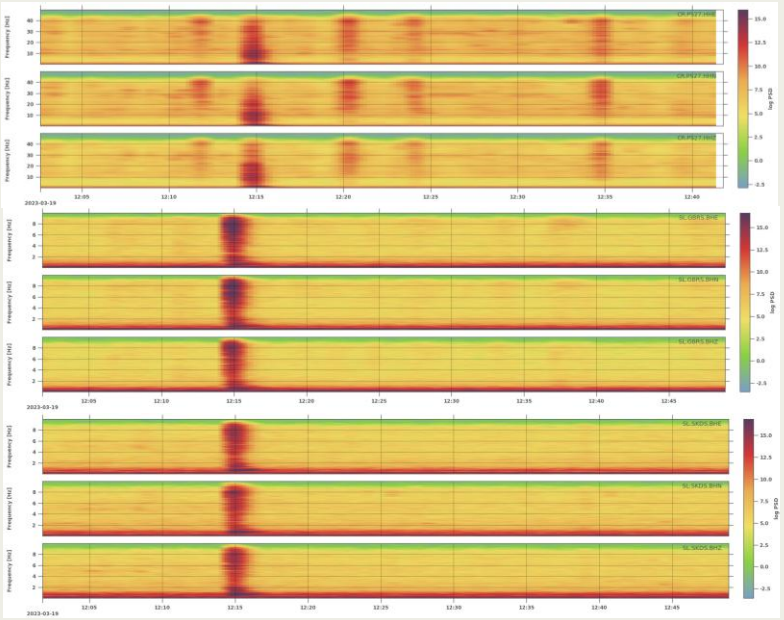

Figure 6: Spectrogram of the detonation showing a dominant frequency range between 2 Hz and 5–6 Hz, with peaks around 3 Hz and 4.5 Hz, recorded at stations PS27, GBRS, and SKDS

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Results (cont.)

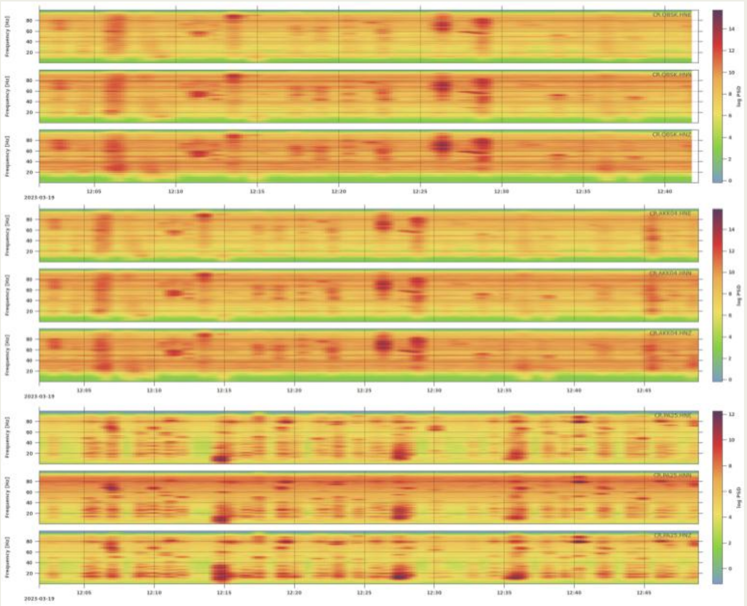

Figure 7: Spectrogram of the detonation showing dominant frequencies range between 20–80 Hz, with peaks around 40–60 Hz, recorded at stations QBSK, AKK04, and PA25

Seismograms reveal a sudden and high-amplitude arrival of primary P-waves, which is typical of explosions and contrasts with natural earthquakes that usually have a preparatory signal. All three components (HNZ, HNE, HNN) exhibit a rapid rise in amplitude, a fast decay, and weak trailing oscillations. The vertical component (HNZ) shows the highest amplitude, highlighting the strong compressional nature of the P-wave. This is consistent with underwater explosions, where energy is predominantly directed vertically. Horizontal components (HNN, HNE) also register the event but with lower amplitude, further confirming P-wave dominance and the absence of a well-defined S-wave, as S-waves do not propagate through water (*Figure 8, 9*).

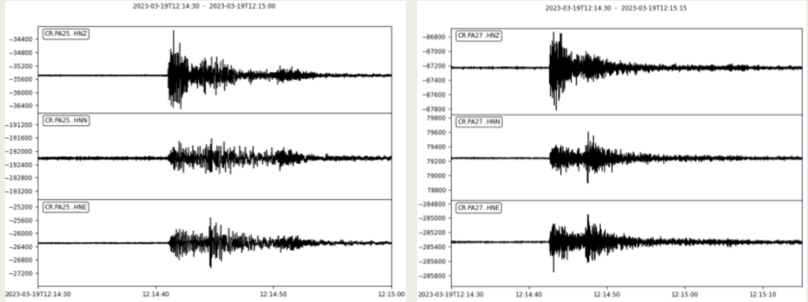

Figure 8: Seismograms from the detonation event recorded at Croatian seismological stations PA25 and PA27

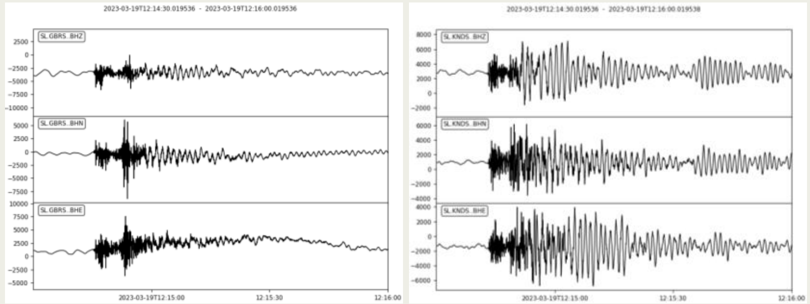

Figure 9: Seismograms from the detonation event recorded at Slovenian seismological stations GBRS and KNDS

Thanks to the availability of data from Slovenian seismic stations, it was possible to more accurately locate and characterize the explosion. The current number of seismic stations in Croatia is still insufficient for high-precision localization. However, the Croatian Seismological Survey is currently implementing the CROSSNET project under the National Recovery and Resilience Plan, aiming to install 95 new seismic stations across the country, significantly improving national seismic monitoring capabilities.

Unexploded ordnance and legacy explosive devices continue to pose a serious safety risk, highlighting the urgent need for systematic clearance efforts and international cooperation within political and humanitarian frameworks to ensure civilian security and regional stability.

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Introduction - citation

Benčić, L., Hina, & Novak, S. (2023b, March 19). VIDEO Ovo je trenutak u kojem je detonirana mina kod Rijeke: Snažna eksplozija čula se u cijelom gradu. Jutarnji List. https://www.jutarnji.hr/vijesti/hrvatska/video-ovo-je-trenutak-u-kojem-je-detonirana-mina-kod-rijeke-snazna-eksplozija-cula-se-u-cijelom-gradu-15316948

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Data and methodology - citation

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