POSTHOLE BROADBAND SENSORS FOR THE UPGRADE OF THE SEISMIC NETWORK IN SICILY WITHIN THE GRINT (ITALIAN RESEARCH INFRASTRUCTURE FOR GEOSCIENCES) PROJECT

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Introduction. GRINT Italian Research Infrastructure for Geosciences" is a project in the framework of the "Programma Operativo Nazionale" (PON) of the Italian Ministry for the University and Research. This plan envisages both the upgrade of monitoring systems in the already existing nodes, and the integration of new nodes. The main objective is to build a multiparametric network which integrates the main seismic network, with the monitoring of other geophysical signals, aimed at recognizing the phases of an earthquake: from the preparatory processes, to the trigger and arrest. Such upgrade will provide also the improvement of a series of seismological products: waveforms, seismological studies, bulletins for the seismic surveillance.

Sicily (Italy) is one among the target areas of the GRINT project. Here, the plan for the modernization started some years ago (D'Alessandro *et al.*, 2021) and the existing multi-parametric monitoring infrastructure will benefit of GRINT project. The activity is mainly of technological nature. It consists of the technical enhancement and upgrade of existing systems, an upgrade of seismic stations with installation of sensors covering the entire bandwidth of the seismic signal, both velocimeters and accelerometers. New nodes will be integrated in the existing network. The new seismic sensors are posthole broad-band velocimeters. They are installed in apposite perforations or wells that intercept the bedrock. Such solution reduces the level of seismic noise whose sources are almost always superficial (i.e. anthropogenic sources, wind, atmospheric pressure, vegetation) and makes as stable as possible parameters such as temperature, pressure and humidity. Together with sensors, power-supply systems, data loggers, real-time data transfer systems will be updated to optimize the performances, reduce the costs and the maintenance, and ensure the full operational services also during possible crisis. In addition, radon sensors will be installed in some seismic stations of the network.

In detail, this contribution introduces the experiences gained by the group Osservatorio Nazionale Terremoti (ONT, INGV) which operates in Sicily, and concerns the installation of post-hole broad-band sensors. This activity at such extended scale (35 sensors to be installed) can be considered as a pioneering one in Italy. We introduce the adopted procedures and the technical challenges faced for the optimal and effective deployment of the borehole sensors.

Post-hole sensors: installation and signal characterization. Sicily (Italy) is one among the target areas of the GRINT project. Here, the plan for the modernization started some years ago (D'Alessandro *et al.*, 2021) and the existing multi-parametric network will benefit of GRINT project. The installation of broadband posthole sensors thanks to GRINT project will allow the acquisition of high quality data directly usable for all the aims of the earthquake network.

The main reason for installing a seismometer in a well is to search for an environment in which the seismic-environmental noise is lower than the surface and consequently the signal-to-noise ratio (SNR) is maximized. The reduction of noise for well installations is strictly dependent on the frequency and is also variable on the different components. At frequencies of a few Hz, reductions of the order of 20 dB are observed already at a depth of a few tens of meters and reductions of up to 40 dB at a few hundred meters. For frequencies higher than 10

Hz, noise attenuations of even 40 dB are observed at depths of a few tens of meters (Greig *et al.,* 2014; Withers *et al.,* 1996; Hutt *et al.,* 2017)

Among the sensors used for installation in wells, the “borehole” and “posthole” seismometers are generally distinguished. While the former are designed for deep drilling (hundreds and thousands of meters) and are equipped with lateral anchoring systems to the well casing, the latter are designed for installation at the bottom of shallow drillings (<50 m), even without coating (Hayman, 2014).

The posthole sensor is the model Trillium Compact PH from Nanometrics. It is a compact (3.2 kg, 97x160 mm) sensor with bandwidth up to 120 s. When connected with Nanometrics Centaur digital recorder, a graphical interface allows to set the sensors and also to access the digital level integrated within the sensor. The installations have been carried out either in already existing wells and specifically drilled perforation. Of course, in both cases, some characteristics should be preliminarily evaluated. Devoted geophysical investigation (seismic tomography, MASW, ambient noise characterization) have been carried out to fully characterize the sites. Before the installation, the well is inspected by means of a borehole camera to verify the integrity of the casing and of the bottom (Fig. 1).

Fig. 1 - Installation operation at various sites. a: visual inspection by means of a borehole camera; b: the lowering of the sensor inside a drilled perforation; c: details of the pulley aligned on the top of a pre-existing well; d: final set-up of the earthquake monitoring site: note the posthole sensor placed at surface next to the well and the accelerometer for its later replacement; e: lab testing for the anchoring system.

The metered cable of the camera also helps to estimate the depth of the well and therefore to design the waterproof extension supply cable and the stainless steel retaining cable. Then, the well is filled some tenths of meters of sands to constitute a bed for the sensor. The sensor, along with its cable, is lowered within the hole by means of the retaining cable (diameter 3 mm). The two cables are tightened together with plastic ties at distance of about 1.5 m during the descent. The descent is controlled with a hand winch screwed into a portable wooden tripod and a pulley which is aligned to the top of the hole (Fig. 1). A digital dynamometer provides the indication of the load under the pulley, so that the operators are able to detect exactly the touchdown of the sensor and arrest its lowering. After a final camera check, another layer of sands is then released in the well to cover the sensor. Now the sensor can be connected to the data logger and powered to check the digital leveling system. By means of gentle maneuvers on the retaining cable, together with a bit of luck, the sensor is leveled at its best. Anyway, the tilt tolerance of the downhole sensor is ±2.5°. In some cases, the conditions of a pre-existing wells may suggest to locate the posthole sensor along the casing, rather than the bottom. To face these situation, an electro-mechanical positioning system is under development. It is based on two curved metal plates mounted on an electrical powered jack, which also serves as base for the sensor (Fig. 1e). The system has been designed to be with the center of mass aligned with the upper anchoring, to ensure a levelling within the tolerance limits.

An identical post-hole sensor is then located at surface: it will serve as a reference for the orientation of the down-well sensor. This sensor will be later replaced (weeks to month) with an accelerometer, then, the site in its final configuration is integrated within the rest of the earthquake monitoring network The horizontal axes of sensors are normally oriented along the north and the east directions using a magnetic compass, but this operation is not possible for posthole installation. It is of fundamental importance to determine the orientation before to integrate its data within the network. There are many studies establishing the orientation of a borehole instrument using different methods, such as receiver functions, body-wave polarization studies, surface-wave polarization studies, ambient seismic noise, and seismic noise from ocean waves (see Lin *et al.*, 2022 for an overview). In the present study, we use an approach based on the cross-power spectra of the seismic noise between the two sensors. The cross-power spectra is determined between horizontal components of the surface reference sensor and the posthole sensor. The horizontal components of the posthole sensor are rotated by applying a rotation matrix. The rotation was exacted in steps of 1°; the cross power spectrum is then calculated at angular step in the whole range of available frequencies (120s - 50 Hz). For the purposes of estimating the correct horizontal orientation of the sensor in the well, only low frequencies (<1 Hz) are considered. Fig. 2 shows the average value of the cross power spectrum in the 120s - 1 Hz range, as a function of the rotation angle. The maximum value of the average cross power spectrum identifies the best estimate of the rotation angle. The closer the maximum value is to unity, the more robust is the estimate of the rotation angle. The estimations of the angular correction are quite reliable (Fig. 2) and in the case of FAVA site it has been further refined using the signal of a teleseism.

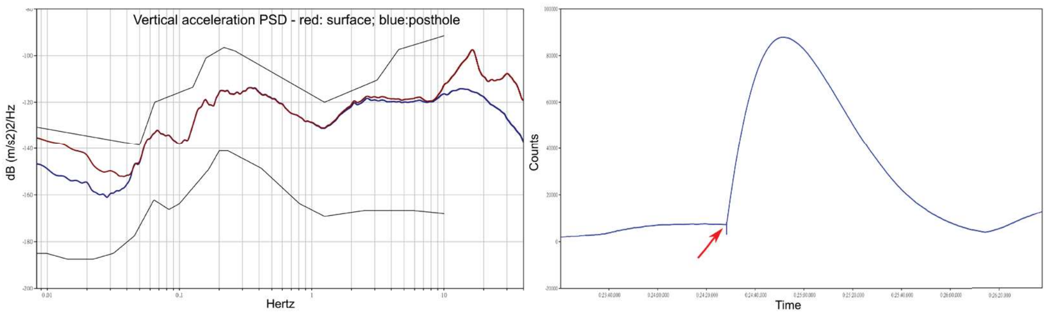

Fig. 2 - Estimation of the angular deviation of the pairs of horizontal components of the two sensors (i.e. surface and down-well). The vertical dashed lines correspond to the maximum values of the coherence and indicate the angular correction (21° for LIBRI and 349° for FAVA).

The analyses of the early signals show some anomalous waveforms which have been interpreted as the results of micro cracks consequent to the stabilization of the sandy bed which surrounds the sensor. The occurrence of such oscillations decreases with time and they disappear after some weeks. The reduction of the background noise has been evaluated comparing the power spectral densities of the surface and posthole sensors (Fig. 3). Below 3 s, and down to 120 s, the reduction of the power is more than 10 dB. This reduction at very low frequencies is essentially linked to a better thermal stability of the sensor, therefore to a reduction of the instrumental self-noise. The power is reduced also above 2 Hz, and even more clearly above 10 Hz. At high frequencies, the noise reduction is essentially linked to the physical attenuation of the wavefield. In the band between 0.3 Hz and 2 Hz the power is almost identical.

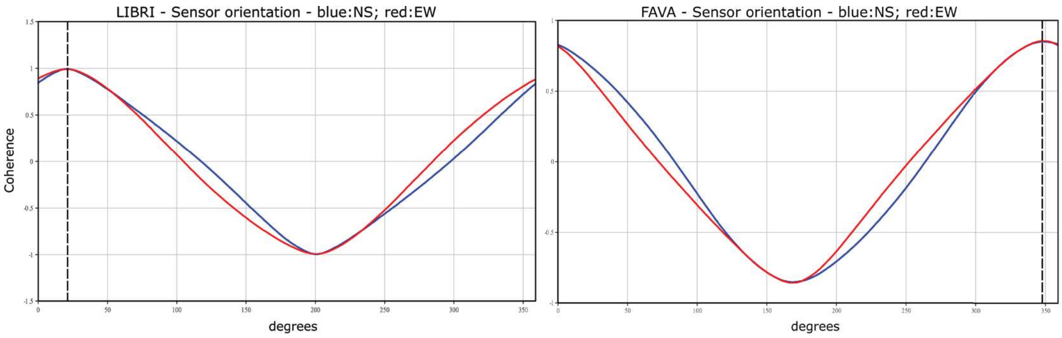

Fig. 3 - Left: a comparison between the acceleration power spectral densities (24 hours signal) for the vertical components at FAVA site (62.5 m deep); red line: surface sensor; blue line: posthole sensor. Right: a micro-crack (red arrow) triggers a low-frequency asymmetric oscillation at LIBRI site (27 m deep).

Conclusion. The upgrade of the earthquake monitoring network in Sicily thanks to the GRINT project represents a main advancement that makes the infrastructure more efficient, reliable, and sustainable for the next decade. In particular, the integration of the posthole seismometers will provide better quality data which will enhance a variety of high-quality seismological studies and will better support the Istituto Nazionale di Geofisica e Vulcanologia in the seismic surveillance of this region characterized by the highest seismic hazard of the whole Italy.

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