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Research Article

Ground Penetrating Radar in Dam Monitoring: The Test Case of Acerenza (Southern Italy)

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Nowadays, dam safety management is gaining great importance since it affects in a crucial way the monitoring and improvement of risky reservoirs, but this topic is very challenging since the dam safety requires long-term and time-continuous monitoring. In this framework, the exploitation of conventional geotechnical investigation methods often requires invasive actions in the inner of the structure to be investigated (destructiveness) and only provides punctual information for small volumes. On the contrary, the application of noninvasive sensing techniques makes it possible to investigate higher volumes without affecting the structure. In this paper we describe the application of GPR for the monitoring and diagnostics of one of the largest dams in the Basilicata region (Southern Italy). The investigation aims at detecting and localizing underground sandstone banks that are potential ways of flow of water below the dam. The manageability and the noninvasiveness of GPR have resulted in particularly suitable for this kind of application because the versatility of this geophysical method allows to investigate large areas with a good spatial resolution giving the possibility to detect the presence of inhomogeneities in the subsoil below the dam.

1. Introduction

Maintenance and monitoring of the critical infrastructures play an important role for public safety and prevention and thus it is important to routinely monitor and control them [3]. In particular, the exploitation of noninvasive diagnostic techniques is crucial for the monitoring of the critical infrastructures since they do not affect the normal operating behaviour of the structure, which is one of the main requirements during the control inspections.

Here, we focus on the problem of the detection, characterization, and evaluation of the potential losses of water through a dam, which is an important aspect of civil, hydrology, and environmental engineering. In particular, this contribution deals with the exploitation of Ground Penetrating Radar (GPR) technique for monitoring and diagnostics of a dam.

In fact, among the possible issues that may affect dams, the presence of voids or fractured zones embedded in the structure or in its foundation soil represents one of the most significant problems to be tackled. Voids, lithological discontinuities, or induced discontinuities, for instance by reparation, are sometimes hard to be identified by visual inspection and can dangerously damage the structure itself by jeopardizing its stability.

Traditional inspection methods have, in particular, drawbacks; in fact, conventional geotechnical investigation methods applied on the structure often require invasive actions in the inner of the structure to be investigated (destructiveness) and only provide punctual information for small volumes.

In recent years, nondestructive investigations on building and civil infrastructures are increasingly improving [4–7], but, the literature on the applicability of GPR techniques to the problem of levees and dams is still very limited [3, 8]. Determining their state of health in a nondestructive and, possibly, fast way is a critical issue for a number of public bodies and institutions (e.g., civil protection agencies, river basin authorities, etc.).

GPR techniques offer the possibility of quickly investigating large portions of dam interior without the need of destructive actions. In particular, the paper deals with the surveys, which have been carried out at Acerenza dam, through its longitudinal tunnel inspection, in order to locate underground sandstone layers and banks, potential routes of flow of water below the dam.

These basins create a "complex water system" designed to provide drinking water, irrigation, and industrial use, not only for the Basilicata region, but also neighbouring regions, in particular Puglia and Calabria.

Therefore, the paper is organised as follows: Section 2 presents the hydrological scheme of the Basilicata region; Section 3 deals with the geological background at regional and local scales; Section 4 deals with the diagnostic requirements of the Acerenza dam in the framework of local geology and the GPR survey design. Then, GPR results are presented and discussed in Section 5; finally, in Section 6, conclusions are discussed.

2. Hydrological Setup

Basilicata is one of the few regions of Southern Italy that has a large number of water resources due to the presence of a close hydrographic network [9].

Its water system is based on five main rivers: the Bradano, the Basento, the Cavone, the Agri, and the Sinni. They develop from northwest to southeast, all flowing into the Jonian Sea (Figure 1), and their basins extend over 70% of the regional land. The rest of the region is concerned, to the north, with the basin of the river Ofanto, which flows into the Adriatic Sea, and, to the south and southeast, with the basins of the rivers Sele and Noce, both flowing into the Tyrrhenian Sea. Besides the rivers, there is an extensive network of small waterways and numerous springs.

Described hydrogeographic network is regulated and exploited by great hydraulic works such as dams, crosses, spring and groundwater collectors, supply networks and distribution systems, lifting and water drinkability plants. This infrastructure system was designed and implemented largely in the 50s and 60s, with the main objective to develop and enhance agriculture, then considered as the determining factor for the socioeconomic emancipation of regions Basilicata and Puglia.

In the 70s, the system was expanded and integrated through the construction of new works in order to satisfy the civil needs as well as to potentiate the industrial plants.

The system of dams, built on main rivers of Basilicata region and on their main tributaries, consists of 16 large- and medium-sized river basins, including:

the basins of San Giuliano, Acerenza, Genzano and Basentello on the Bradano;

Pertusillo and Marsico Nuovo basins on the Agri;

Monte Cutugno basin on the Sinni;

Rendina basin on the Ofanto;

Camastra basin on the Basento.

Table 1: Primary system of water infrastructure in Basilicata region (modified from [9]).

Basilicata	257 MCM per year (million meters cubes per years)	40%
Puglia	373 MCM per year (million meters cubes per years)	58%
Calabria	10 MCM per year (million meters cubes per years)	2%

These basins create a complex water system that is intended to supply drinking water, irrigation, and industrial and hydroelectric power not only to Basilicata itself, but also to the neighbouring regions, especially to Puglia and Calabria (Table 1).

The system can supply about 5 million inhabitants, 100,000 hectares of cultivated land, and hundreds of industrial companies including one of the most important Italian steelworks such as the Ilva in Taranto, which has 14,000 employees.

In particular, the reservoir of Acerenza, with a capacity of 47 million cubic meters, is part of the water scheme Basento-Bradano, consisting of works of storage (reservoirs and cross) and works of adduction. It is intended for the irrigation of the land underlying the dam of commons Acerenza Oppido and Tolve.

3. Geological Background

The investigated area is located in the northern part of the Bradanic trough, which is a narrow Pliocene-Pleistocene sedimentary basin, with a NW-SE direction, placed between the southern Apennines and the Apulian foreland. This trough is filled by a thick Pliocene-to-Pleistocene sedimentary succession (up to 2-3 km) whose upper part of Late Pliocene(?)-Late Pleistocene in age, widely outcrops in Southern Italy because of the intense quaternary uplift occurred in the area [10].

The neotectonic uplift was driven by the arrival at the subduction hinge of the thick buoyant south adriatic continental lithosphere, which caused a lower penetration rate of the slab and a consequent buckling of the lithosphere [11]. It occurred first in the northern sectors of the trough and after in the southern most ones. Moreover, it was higher in the western edge than in the eastern one, producing then a regional tilting of the geological formations deposited in the Bradanic trough [12, 13] towards the Adriatic Sea.

The progressive uplift is testified by the regressive trend of the sediments deposited in this trough from early Pleistocene, which are represented by the geological formation shown in Figure 2. In particular, Figure 2 depicts, from top to bottom, *Marine-Terraced Deposits* (regressive deposits consisting of sands, conglomerates, and silts of Middle-Upper Pleistocene in age, outcropping in the southern parts), formations of *Sabbie di Monte Marano* and *Conglomerato di Irsina* (sands and conglomerates of Early-Middle Pleistocene in age outcropping in the northernmost and central sectors),

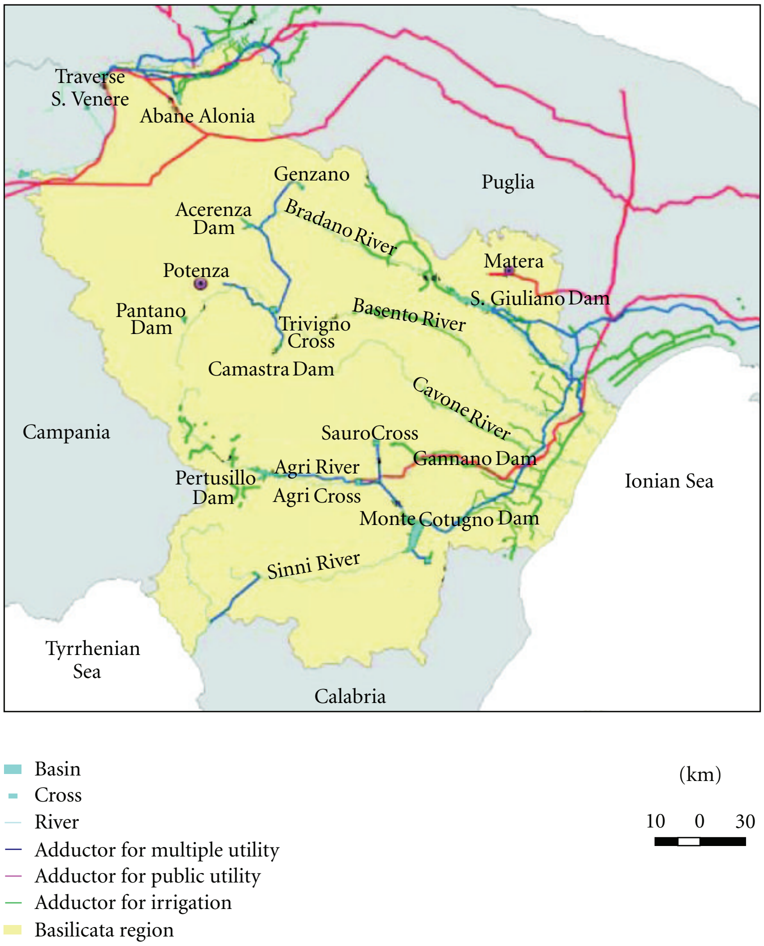


Figure 1: Primary system of water infrastructure in Basilicata region (modified from [9]).

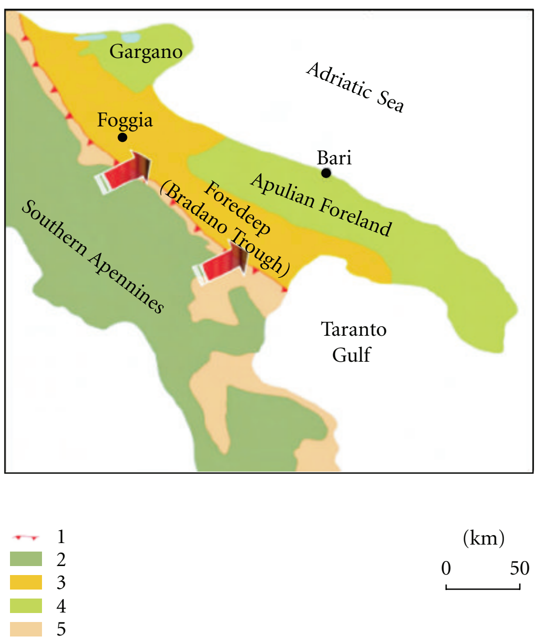


Figure 2: Schematic representation of the Southern Italy structural domains. Legend: (1) outcropping buried thrusts front; (2) chain domain; (3) foredeep deposits; (4) calcareous foreland domain; (5) outer thrust-belt front and piggy-back basins (modified from [1]).

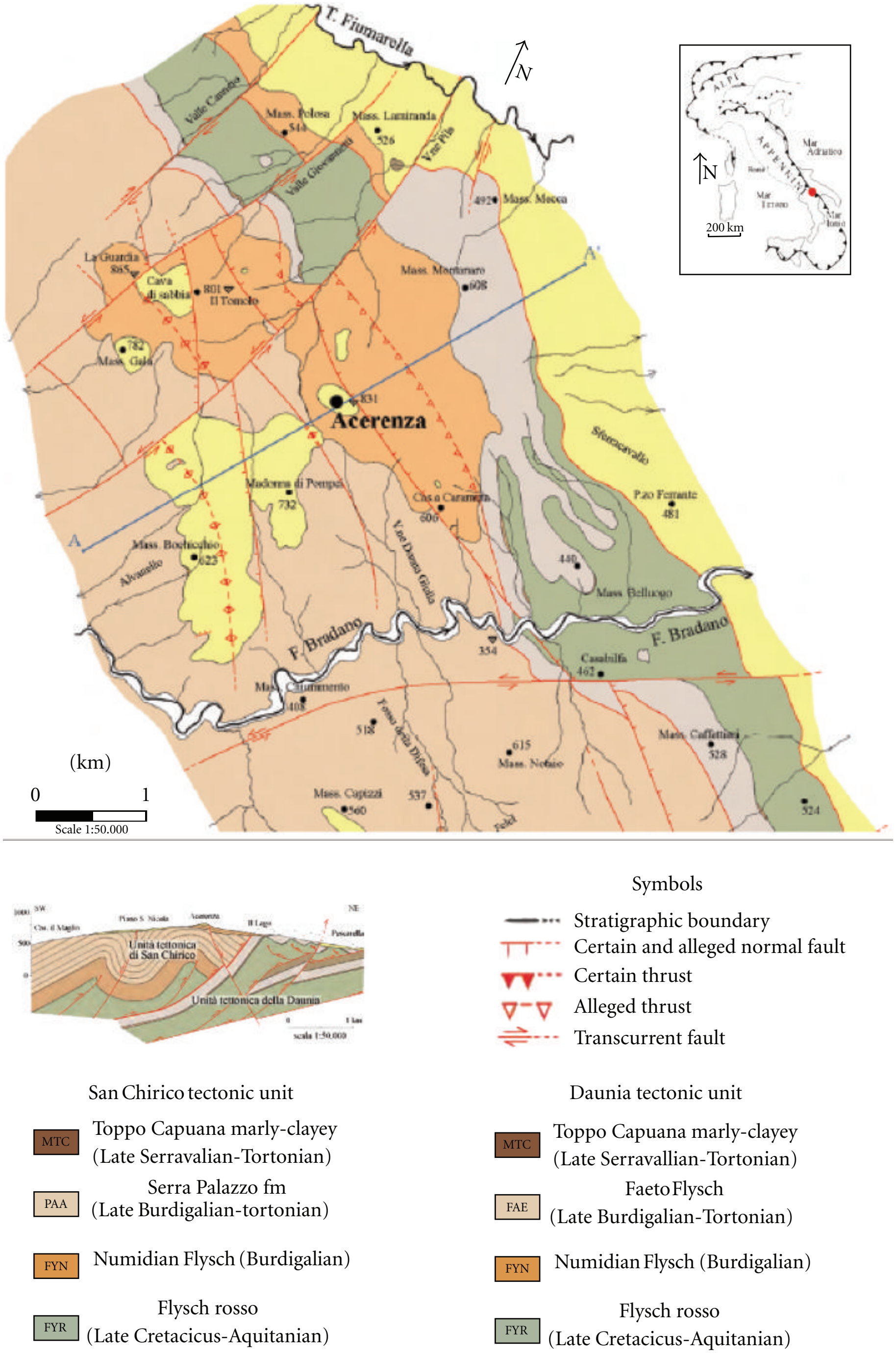


FIGURE 3: Geologic Map and section of the Lucanian Apennines between Acerenza and Oppido Lucano (Basilicata—Italy) (modified from [2]).

and *Argille subappenine* (silty-clayey successions of Late Pliocene-Middle Pleistocene in age, widely outcropping) [1].

The frontal sector of the Lucanian Apennines between Acerenza and Oppido Lucano localities (Potenza) in Basilicata (Southern Italy) is mainly characterized by two Cretaceous to Tortonian tectonostratigraphic units represented from west to east by San Chirico and Daunia tectonic units; these units are unconformably overlaid by Pliocene thrust-top basin deposits (Figure 3).

The San Chirico tectonic unit consists of the following formations: *Flysch Rosso* (Late Cretaceous-Aquitanian), *Flysch Numidico* (Burdigalian), *Serra Palazzo* (Late Burdigalian-Tortonian p.p.), and *Marne Argillose del Toppo Capuana* (Late Serravallian-Tortonian).

The Daunia tectonic unit consists of a sedimentary succession having the same previous lithostratigraphic units with the exception of the formation of *Flysch di Faeto* (Late Burdigalian-Tortonian p.p.) that replaces the formation of *Serra Palazzo* [2].

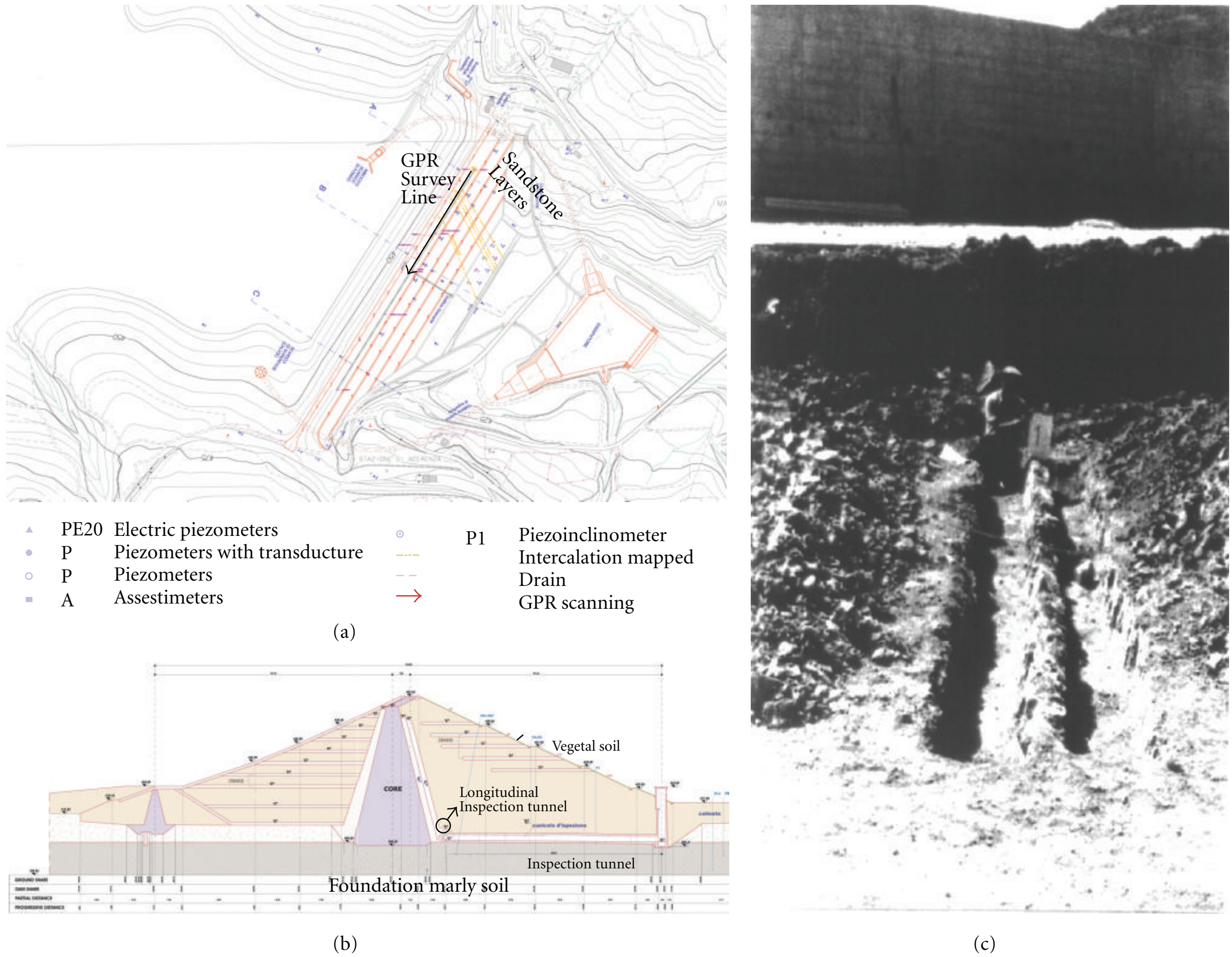


Figure 4: Map (a) and cross-section (b) of the zoned-earth Acerenza dam; (c) sandstone layers outcropping after the dam building excavations.

4. Diagnostic Requirements and Survey Design

The Acerenza dam is a zoned-earth embankment dam built on the Bradano river (Figures 1(a) and 1(b)). During its building works (1973–1986), several subvertical sandstone banks and layers belonging to the Serra Palazzo formation directed 60°–70° N in the north-eastern sector of the foundation soil were detected (Figure 1(c)).

Such layers were suspected to be permeable and possible cause of erosion of the dam foundation soil and core. In fact, they were described by the technicians involved in excavation work as strongly fractured and saturated.

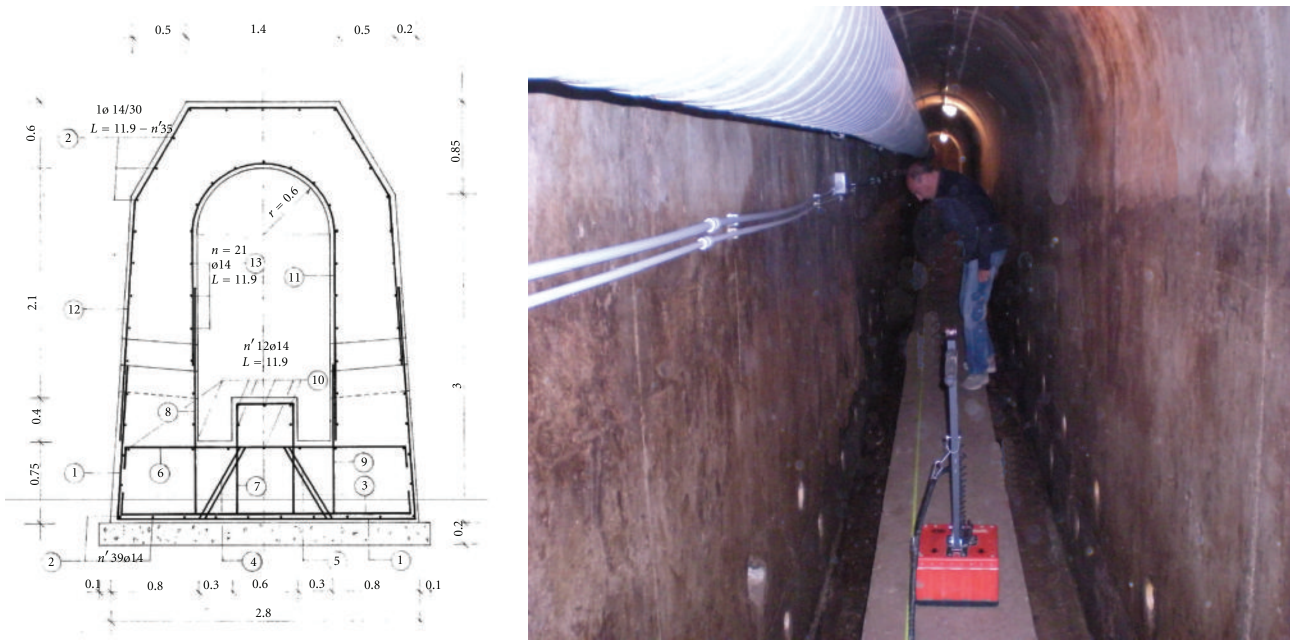
Therefore, specific works were designed and carried out in order to waterproof the head of discovered layers, while a series of coring was performed in order to detect other possible arenaceous intercalations. Finally, a piezometric network was installed downstream of the dam in order to detect possible losses.

Such works revealed some inaccuracies in the localization of the permeable layers. Despite of the above said difficulties, the building of the dam continued, but the Italian Dams Office has imposed a strong limitation on the amount of water that the dam can hold, by limiting the fill quote to 432 m above the level sea from the initial level established at 454.50 m. In order to restore the capacity of the dam to its initial volume, an hydraulic monitoring of the foundation soil was required. In the subsequent years, some piezometers were installed in the foundation soil through the inspection tunnel both in the marly and in the sandstone layers, but without the certainty of placing a piezometer in each permeable layer.

This strong limitation persists untill now, since the presence and the exact position of all possible permeable layers in the dam foundation soil are not perfectly known.

Therefore, GPR investigation was requested with the aim of achieving a detailed mapping of permeable layers. In particular, a GPR profile 180 m long has been carried out in the northeastern part of the inspection tunnel by using a 400 MHz central frequency antenna in combination with a GSSI SIR 3000 control unit (Figures 4(a) and 5(a)).

The narrow catwalk allowed to perform just a 2D profile without odometer (Figure 5(b)). Then, the survey line has



(a) (b)

Figure 5: Detail of the longitudinal inspection tunnel: (a) cross-section and (b) picture.

been split in several adjoining profiles 20 m long, in order to limit possible marker mispositioning.

During the survey, the position of the existing piezometer along the GPR profile, revealing the position of yet identified sandstone layers, has been annotated in order to check their radar response.

5. Data Processing and Discussion

All radargrams, having a range of 65 ns, have been processed according to the following steps:

(i) trace removal for removing initial and final traces of the radargram gathered when the antenna is standing,

(ii) marker interpolation for equalizing the number of traces between markers imputed each meter during the acquisition,

(iii) dewow, necessary to remove low frequency system-dependent noise,

(iv) fk-filter, an advanced bandpass filter acting in a frequency-wavenumber domain,

(v) migration, for improving section resolution and provide more realistic images.

The velocity analysis, carried out by using the hyperbola method, provided an average velocity of 0.1 m/ns.

Figure 6 shows all processed radargrams with the projection of sandstone layers detected during the dam building works (grey arrows and lowercase letters), novel sandstone layer detected on the basis of the GPR interpretation (black arrows with capital letters), and the positions of the piezometers (bold grey arrows and "Pn" symbol).

Reflectors related to the reinforced concrete structure of the catwalk and inspection tunnel are present in all radargrams. They are highlighted just in the radargram no. 1 of Figure 5. In particular, between 0.0 m and 0.4 m of depth, several reflectors can be related to the structure of the catwalk. Between 0.4 m and 0.8 m, other reflectors can be related to the reinforced concrete structure of the tunnel. Finally, between 0.8 m and 1.0 m reflectors can be related to a thin reinforced concrete plate. Then, geological structures are visible below 1 m depth.

By comparing the sandstone layer positions projected below the inspection tunnel with those derived from the radargram interpretation, it is possible to note that not always they coincide. Moreover, piezometers encountered on the antenna path are perfectly recognizable in the radargrams, and their positions, previously annotated, are perfectly overlapping with their anomaly. Table 2 reports the comparison between the positions of the sandstone layer derived from the projection of direct data with those derived from the radargram interpretation. The table reports the piezometer positions too.

At first glance, GPR allows to detect more sandstone layers than the previous studies detecting just seven zones interested by arenaceous inclusions, mainly concentrated between 20 m and 40 m. Instead, the GPR survey allowed to detect around twenty sandstone layers present along all the antenna path. In particular, between 0 m 20 m three layers have been detected by the GPR against no layers previously known. No piezometers have been installed in this area.

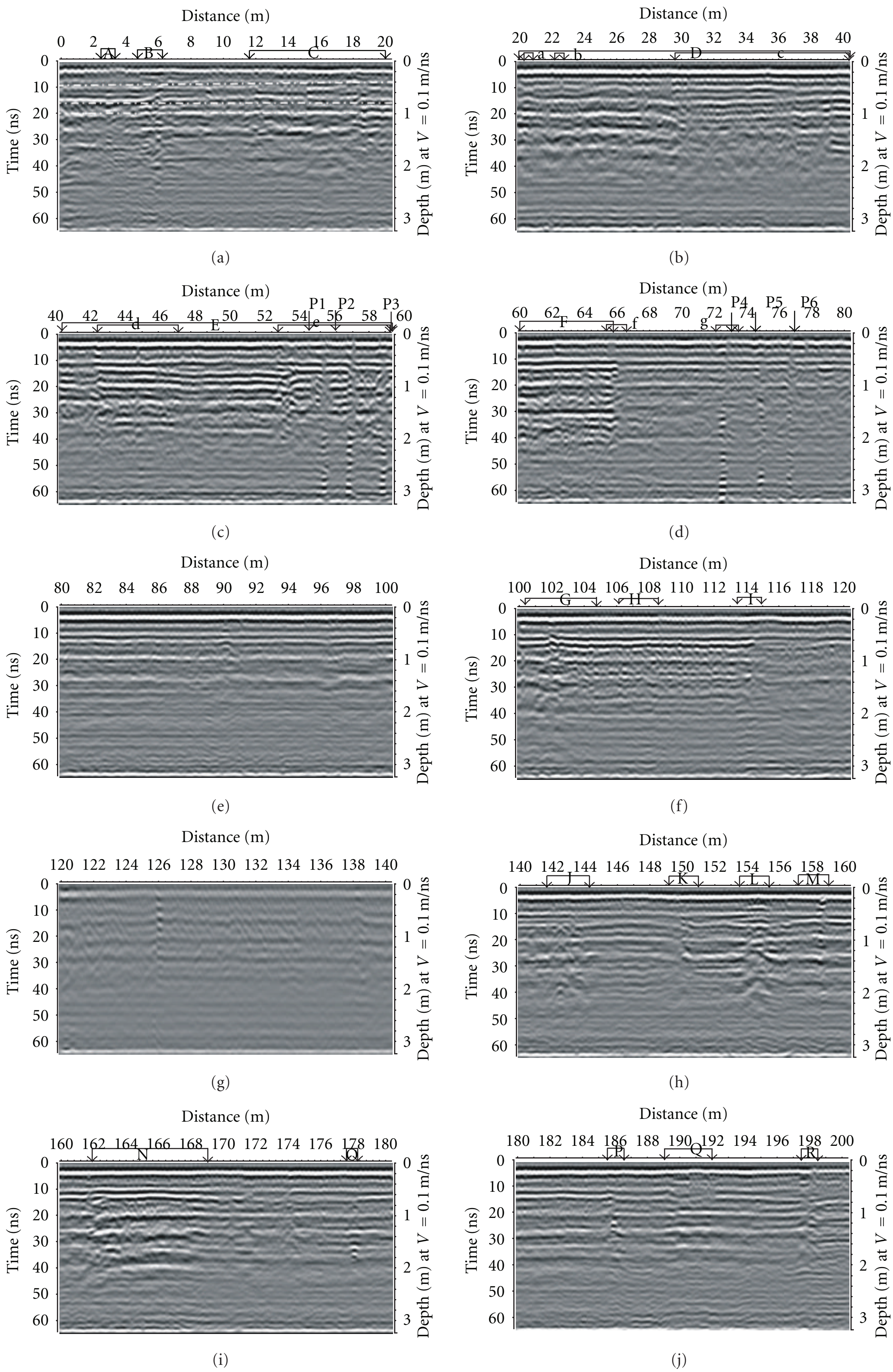
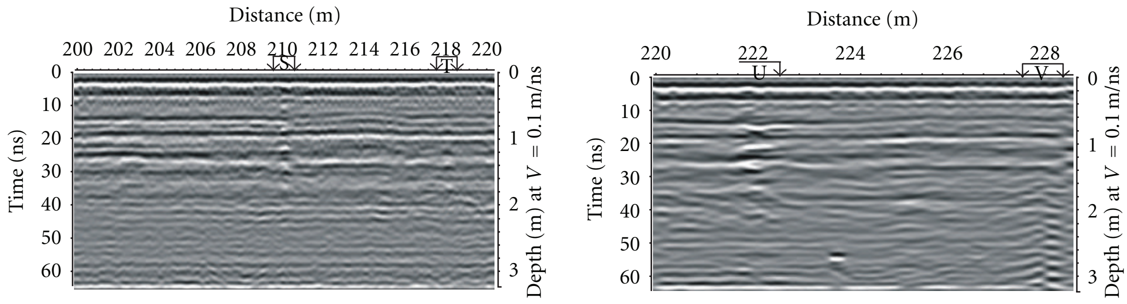


Figure 6: Continued.



(k) (l)

Figure 6: Processed radargrams covering the northeastern part of the inspection tunnel.

Table 2: Positions of the sandstone layers derived from the dam building excavations and from the GPR survey compared with position of the piezometers.

Sandstone layers projected positions	Start (m)	End (m)	Sandstone layer positions derived from GPR	Start (m)	End (m)	Piezometer	Position (m)
			A	2.4	2.6		
			B	4.4	6.1		
			C	11.5	20.0		
a	20.3	20.8					
b	22.1	22.3	D	20.0	40.0		
c	29.5	40.0					
d	42.1	47.0				P1	55.90
			E	40.0	60.0	P2	57.80
e	53.0	60.0				P3	59.65
f	65.2	66.4	F	60	65.6		
g	72.0	73.6				P4	72.35
						P5	74.55
						P6	76.30
			G	100.4	104.7		
			H	106.0	108.4		
			I	113.2	114.7		
			J	141.7	144.3		
			K	149.1	160.8		
			L	153.3	155.2		
			M	156.5	158.7		
			N	161.9	168.9		
			O	177.3	178.0		
			P	185.5	186.5		
			Q	189.0	191.8		
			R	197.2	198.2		
			S	209.5	210.4		
			T	217.2	218.3		
			U	221.7	222.5		
			V	227.5	228.3		

The zone between 20 m and 65 m has been interpreted as potentially rich in sandstone layer in agreement with previous studies. However, spatial resolution available in the band frequency used does not allow to distinguish each layer. However, piezometers P1, P2, and P3 installed in this area certainly indicate sandstone layers.

In the following part of the radargram some differences can be noted. In fact, previous studies report just the layer (g) where the piezometer P4 has been installed. Moreover, GPR survey confirmed that piezometers P5 and P6 have been installed outside any sandstone layer, in the marly soil. Finally, GPR survey gives its main contribution further on 100 m to the end of the antenna path where twelve zones hosting sandstone layers can be inferred by the radargram interpretation.

6. Conclusions

In this paper, we described a 2D GPR survey carried out at Acerenza dam in attempt to detect all possible fractured sandstone layers under the embankment, potential way of water loss, and consequent damage for the structure.

The GPR techniques, carried out in the northerneast part of the inspection tunnel, revealed very useful in the handled case, since it allowed to confirm the presence of previously known sandstone layers and to detect further ones. In fact, along a big section of the surveyed inspection tunnel several unknown sandstone layers have been detected. Moreover, by comparing sandstone layer positions with piezometers ones, it is possible to select more suitable holes for hydraulic tests and plan further corings. This experience demonstrates that the GPR can be a useful tool for dams' nonintrusive diagnostic encouraging its use for other typologies of defects affecting the dams such as: waterproof layer fractures and detachment and concentrated water infiltration zones. Main encountered limitation is that not always the spatial resolution has been adequate to resolve each sandstone layer, so that just large sections potentially hosting searched layer have been detected. A possible solution in order to overcome this limitation could be the use of novel data processing approach such as tomographic approaches.

Acknowledgment

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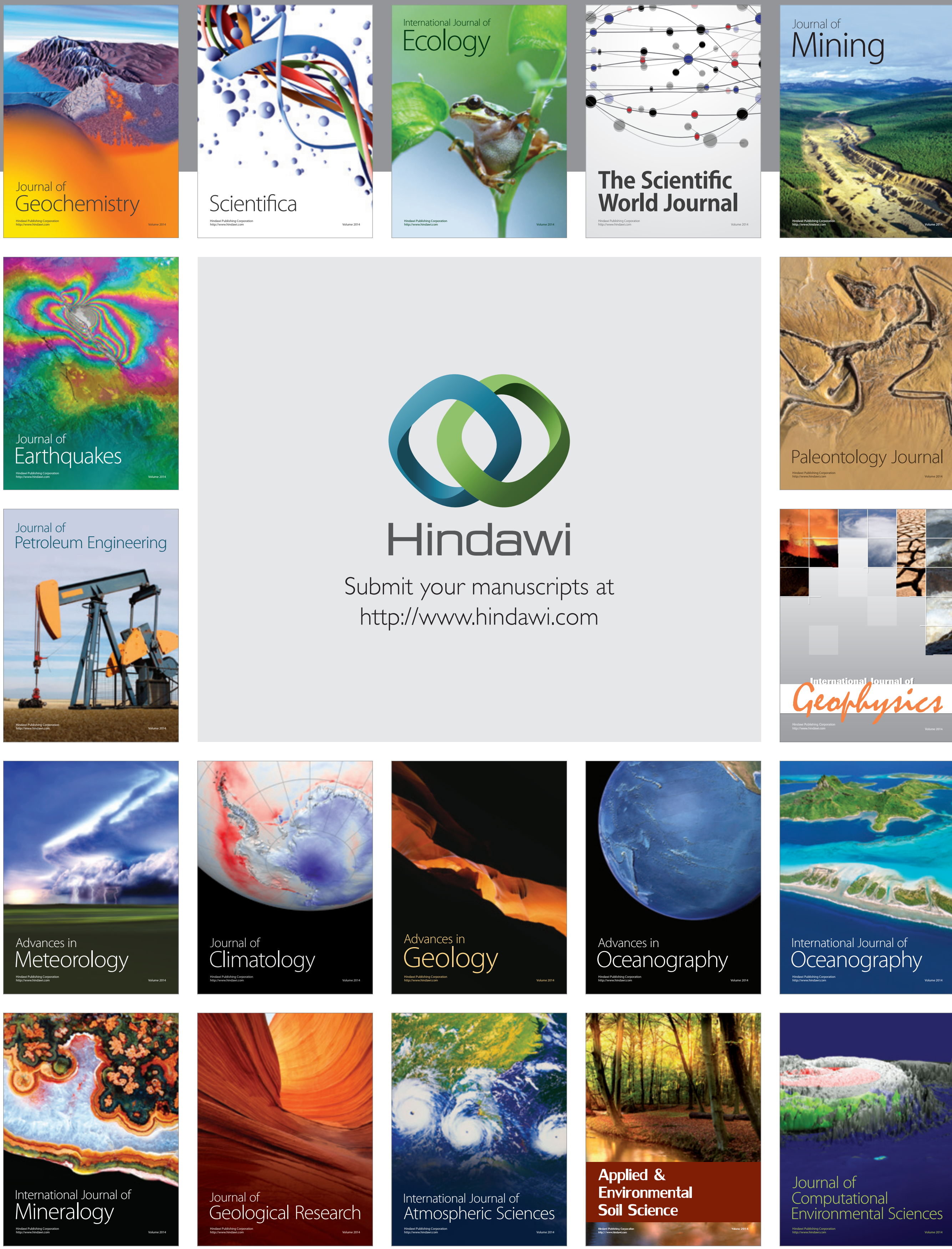
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