geosciences

MDPI

Article

Marl Mining Activity and Negative Repercussions for Two Hillside Villages (Northern Italy)

Fabio Luino [1,*], Sabrina Bonetto [2], Barbara Bono [1], Cesare Comina [2], William W. Little [3], Sabina Porfido [4], Paolo Sassone [5] and Laura Turconi [1,*]

[1] CNR IRPI, Strada delle Cacce 73, 10135 Turin, Italy; barbara.bono@cnr.it
[2] Dipartimento Scienze della Terra, Via V. Caluso, 10125 Turin, Italy; sabrina.bonetto@unito.it (S.B.); cesare.comina@unito.it (C.C.)
[3] Department of Geology, Brigham Young University-Idaho, 525 South Center Street, Rexburg, ID 83460-0510, USA; william.little@wwlittle.com
[4] INGV-Osservatorio Vesuviano, Via Diocleziano, 80125 Napoli, Italy; sabina.porfido@cnr.it
[5] StudioSASSONE Engineering Geology, Str. Boccardo, Casalborgone, 10020 Turin, Italy; info@studiosassone.it
* Correspondence: fabio.luino@cnr.it (F.L.); laura.turconi@cnr.it (L.T.)

Abstract: Coniolo and Brusaschetto, are two small towns located in the Monferrato area of the Alessandria Province, northern Italy. These communities have similar histories related to development and subsequent abandonment of marl quarry activity that began more than a century ago and continued until recently. Quarrying occurred until soil conditions, water infiltration, and excessive depth made cost of extracting and7 lifting material prohibitive. Quarries consisted of tunnels located directly beneath the towns at about 150 m below ground surface. Collapse of the tunnels led to surface subsidence and destruction of overlying homes and much of the municipal infrastructure. In the early Twentieth Century, regulations pertaining to mine and quarry safety were typically deficient, entirely absent, or not followed. Extractive activities of non-energy mineral resources from quarries and mines were and continue to be widespread in Italy, which currently ranks fifth among what are now countries of the European Union (EU). Mining sites are present in all regions of Italy, particularly in the northern part of the country and along coasts, often in areas of geohydrogeological risk. Consequences of anthropogenic pressures that alter the natural environment, such as the physical size of aquifer drawdowns, are linked to issues for a number of extractive sites across the country. This report analyzes historical and technical documents, conducts a geomorphological analysis of hilly slopes surrounding these communities, and examines urban planning and geophysical surveys to determine the impact of subsurface quarrying activities on the overlying ground surface. The study highlights significant problems that are applicable to other localities globally. This research demonstrates: (a) the importance of geological considerations to development and abandonment of mining activity in inhabited areas; (b) the importance of establishing and following safety protocols; and (c) the manner in which economic interests can take precedence over the well-being and lives of those employed to extract resources.

Keywords: mining exploitation; mining hazards; ground subsidence; environmental mitigation; abandoned villages; Casale Monferrato; Piedmont

check for updates

Citation: Luino, F.; Bonetto, S.; Bono, B.; Comina, C.; Little, W.W.; Porfido, S.; Sassone, P.; Turconi, L. Marl Mining Activity and Negative Repercussions for Two Hillside Villages (Northern Italy). *Geosciences* **2024**, *14*, 181. https://doi.org/10.3390/geosciences14070181

Academic Editors: Johnbosco C. Egbueri, Chaitanya B. Pande, Quoc Bao Pham and Jesus Martinez-Frias

Received: 8 May 2024
Revised: 24 June 2024
Accepted: 26 June 2024
Published: 8 July 2024

1. Introduction

From prehistoric times, man has extracted stone and metal from the earth. The oldest recognized mine dates back 43,000 years, in the present-day Swaziland, and was used to extract hematite as an ochre-red pigment. From around the same period, flint mines in Hungary were established and used to manufacture tools and weapons [1]. For thousands of years, mining activities were of little environmental concern; however, with onset of the industrial revolution and the subsequent ever-increasing demand for earth materials, the past approximately two hundred years have seen mining become a major factor affecting morphological characteristics of our landscape, as well as the creation of potential hazards [2–5]. Among the more serious physical hazards associated with mining is ground subsidence, which can result from the collapse of underground mine workings. This phenomenon can limit land use, hinder reclamation efforts, damage infrastructure, lower property values, and pose a threat to life [6].

Mine-related subsidence has been a matter of global concern for millennia. For instance, geologic hazards of anthropogenic origin are found widely across the United Kingdom, which has a history of mining dating back more than 3000 years [7]. Many urban centers are located in regions where mine abandonment has left a legacy of old workings with continued underground access, much of which remains unmapped. The problem of ground subsidence associated with salt mining is well known in and around the city of Tuzla, Bosnia and Herzegovina [8]. From the start of drilling in 1950 to when measurements concluded in 2003, subsidence rates of up to 40 cm/year had been recorded for the most developed part of the area, with a total subsidence of 12 m over the entire period. As a result, much of the region experienced damage to buildings and other infrastructure, including a large portion of the historic city. A new mapping approach for urban planning in subsidence-prone settings was developed using the Darkov region of the northeastern Czech Republic, where coal is mined [9]. The new approach included three mapping criteria: isolated ground subsidence, land-use, and delimitation of slope deformation and was designed to be used by land planners, developers, investors, engineering geologists, and others to determine whether or not ground subsidence values are acceptable for a particular developmental purpose. Machowski [10] studied an area of about 9.6 km^2 in the Silesian Plateau of southern Poland. A century of records (1890–1990) documented that 82.9% of the area had been affected by mining-related subsidence, with a maximum vertical displacement of more than 30 m and an average rate of 30 cm per year. A consequence of the subsidence is that arable land was reduced to about one-fifth of the original area. Solarski [11] described the impact of several years of underground mineral extraction on changes in topographic elevation for the urban area of Bytom, Poland. Between 1883 and 2011, the amount of relief within the city increased from 90.0 m to 105.4 m, as subsiding basins up to 35 m deep developed. The anthropogenic subsidence rate in the city during this time averaged 43 mm/year.

In the United States, problems associated with subsidence and ground movement in the copper and iron mines of Michigan's Upper Peninsula are well known [12], as are those associated with subsidence resulting from the Athens mining system in Negaunee, Michigan [13], and with ground movement due to mining at the Brier Hill mine in Norway, Michigan [14]. Allen [15] addressed the environmental effects of ground subsidence related to underground coal mining throughout the United States, analyzing the relative importance of location, magnitude, areal extent, type of disturbance, and nature of damage in order to determine potential mitigation measures. He concluded that the most effective mitigation procedures would be development of subsidence control technology to minimize ground movement and the institution of insurance programs to compensate for surface damage, once it does happen.

Wood and Renfrey [16] published a paper concerning impacts of mining on urban development in Ipswich, South Queensland, AUS, a town that has expanded into areas where extensive underground coal mining had taken place for more than a century. Starting with a cadastral map, they overlaid mine plans and other data to identify specific hazards and developed a classification scheme that ascertained six categories of subsidence. The area was then assessed according to the degree of risk associated with surface deformation, and this was used to establish land-use restrictions and formulate requirements for new construction. Subsidence is most frequently associated with movements caused by removal of mineral deposits, whether in solid, liquid, or gaseous form, from the ground. Mining is one of the earliest identified human activities and has taken place on all continents. Bell et al. [17] listed some mining activities to illustrate the different types of subsidence that occur and the problems that result. The examples cited are gold mining in the Johannesburg area and rim-and-pillar coal mining in the Witbank coalfield in South Africa. These mineral deposits have often been worked for more than a century and, as a result, abandoned mines, especially shallow mines, are a major problem. Abandoned shallow mines can be a serious problem in areas under development or redevelopment. Bell et al. [18] drew attention to a number of unusual examples of subsidence, including one caused by gypsum mining in southern England, the collapse of slate mines and caverns in Germany, underground evaporite mining in Northern Ireland, and the extensive pumice mining on the flanks of the Galeras volcano in Colombia.

Cui et al. [19] (2014) described eight sudden surface collapses induced by shallow coal mining in Datong, China, which led to the destruction of 69,959 homes, 97 schools, and 13 hospitals, along with several hundred deaths and thousands of serious injuries. Because collapses are often unexpected, instantaneous, and impossible to predict, the authors studied statistical characteristics of sudden collapses using on-site surveys and theoretical analyses. Pan et al. [20] cite the case of the Meitanba Coal Mine in Hunan Province, China, which has been affected by severe collapse and sinkhole development since 1982, associated with mine dewatering. After closure of the coal mine in February 2015, the groundwater level increased significantly. Thirteen collapses occurred, induced by abrupt changes in air–water pressures in response to heavy rainfalls. Sahu and Lokhande [21], citing examples from India, point out that surface collapse is dangerous to life and property because of its tendency to occur without warning.

There is a wide range of environmental damage that can be caused by mining activities, such as deforestation, ecosystem destruction, loss of biodiversity, disruption of water supplies, production of hazardous waste, and damage to overlying infrastructure [22]. Mining can lead to significant changes in the landscape, including significant alteration of topographic relief [5], removal of prominent geomorphic features, and creation of new features. The nature and magnitude of potential hazards depends upon several factors, but the most important are type of mining operation and scale of mine workings. The primary focus of this study is subsidence due to collapse of underground mine structures. Bell [23] pointed out that urban development in coal mining areas always poses a potential risk of subsidence, which requires the mine owner to have a mitigation and remediation plan in place to minimize and compensate for damage. Some mining methods give rise to contemporary subsidence, while others may occur long after the mines have been abandoned. In the latter case, it can be impossible to predict effects or timing of subsidence [23].

Changes in surface gradient, the slope stress state, physical and mechanical properties of slope material, and water table levels can trigger surface deformation, such as landslides, and ground collapse [24–28]. Sinkholes, whether natural or artificial, can open to the ground surface abruptly and catastrophically, with diameters and depths varying from a few to hundreds of meters [29]. Natural sinkhole development is dependent entirely upon the geological and hydrogeological setting and most commonly forms in carbonate sedimentary rocks, producing an overlying karst topography [30]. Anthropogenic sinkholes, on the other hand, while still influenced by geologic and hydrologic conditions, are caused by direct human activity, mostly by collapse into tunnels, stopes, shafts, and other underground mine workings or as a result of an artificial lowering of the water table and subsequent subsurface erosion. The emergence of a surface collapse is influenced by depth of mining, density and height of underground workings, thickness and character of overburden, and exposure to vibrations induced by machinery, traffic, and explosions [31]. The vast majority of damaging collapse features are the result of human activities [30]. Chen [32] affirmed that manmade collapses globally make up 66.4 percent of total collapses; whereas, natural collapses form only 33.6 percent. Roof collapse can pose a significant risk to public safety in built-up areas [33]. The occurrence of mining subsidence in the environment can sometimes be catastrophic, destroying property and causing loss of life [23,34,35].

Environmental pressure indicators [36] indicate that for Italian regions exposed to significant natural hazards, there is a relevant presence of extractive activities, in particular for northern Italy (over 44%) and coastal municipalities (about 20%). Areas designated for protection or those at geohydrogeological risk for floods and landslides are often affected by extraction. Extractive activities in Italy for non-energy mineral resources from quarries and mines are linked to the great geological diversity found across the country. Mining sites are present in all regions, currently placing Italy fifth for non-energy mineral extraction among EU countries, after Germany, Romania, France, and Poland. Implications for the natural environment are expressed in terms of "pressures", i.e., all processes and phenomena attributable to anthropogenic activities that alter the state of environmental components, such as number of extraction sites, physical size of extraction, and physical characteristics of the territory [36]. Mining of minerals from quarries accounts for 92% of national mineral production (about 154 million tons); although, the trend has been declining over the past 10 years. Deep mining is often carried out without due investigation as to the impacts to the population living above the mining operation.

This work fills a knowledge gap pertaining to the history of Brusaschetto and Coniolo that is known only locally. The purpose of this paper is to produce a record regarding management of mines that could have influence at the international level to potentially avoid similar harm to other populations. Small communities, in particular, have historically been harmed by a lack of policies and regulations to protect against detrimental mining procedures. As part of the mitigation process, it is important that safeguards be emplaced and strengthened to protect inhabitants and their property from hazards associated with extraction of mineral products.

2. General Setting

2.1. Geology

The area analyzed in this paper is located in the Piedmont Region of northwestern Italy, more precisely in a district called "Casalese", which takes its name from the city of Casale Monferrato. Cement exploited in the Casalese area is found within the Casale Monferrato Formation, which has been dated as lower to middle Eocene in age (Ypresian-Lutezian-Bartonian), ranging from approximately 56 to 38 ma based on planktonic foraminiferal assemblages [37] (Figure 1). Lithologically, the Casale Monferrato Formation is composed of repeating successions of yellowish or bluish, variably-cemented sandstone at the base that is sometimes present only as a thin lamination [38]. The sandstone is overlain by an interval dominated by gray-brown clay and less commonly black or greenish clay with interbeds of marly bluish-gray to white limestone in individual beds a few centimeters to over 6 m in thickness. In total, there are 23 marly beds with an aggregate thickness of up to 83 m [39]. The successions are capped by yellowish, bioturbated (*Chondrites*) limestones. In total, the formation ranges in thickness from 600 [40] to 1000 m [41]. Marl is a historical term that refers to a calcareous shale or shaley limestone, depending upon the relative abundance of clay to carbonate between 35% and 65% for each; therefore, it is a transitory rock type between shale and limestone. An important aspect for this study, is that the greater the content of calcium carbonate, the greater the resistance of the rock to removal through meteoric processes. Though not in common use today, term is used in this manuscript because of its historical usage in the literature used to compile this report. During the late Miocene (Messinian), ~7 to ~5 ma, the Casale Monferrato Formation was folded, fractured and faulted, producing mostly sub-horizontal beds that are now expressed in the hills of the Casale area.

The $CaCO_3$ content is highly variable within marl and limestone units and changes not only from bed to bed but also within the same bed, progressively decreasing in relative percent upward through the formation. Commercial use depends upon the carbonate concentration according to the following sequence [38]:

- Between 86 and 80%, only lime is produced;
- Between 80 and 78%, both lean lime and cement are produced;
- Between 78% and 73%, slow-setting Portland cement is produced;
- Between 73 and 67%, fast-setting natural Portland cement is produced;
- Below 67% there is no production of hydraulic binders.

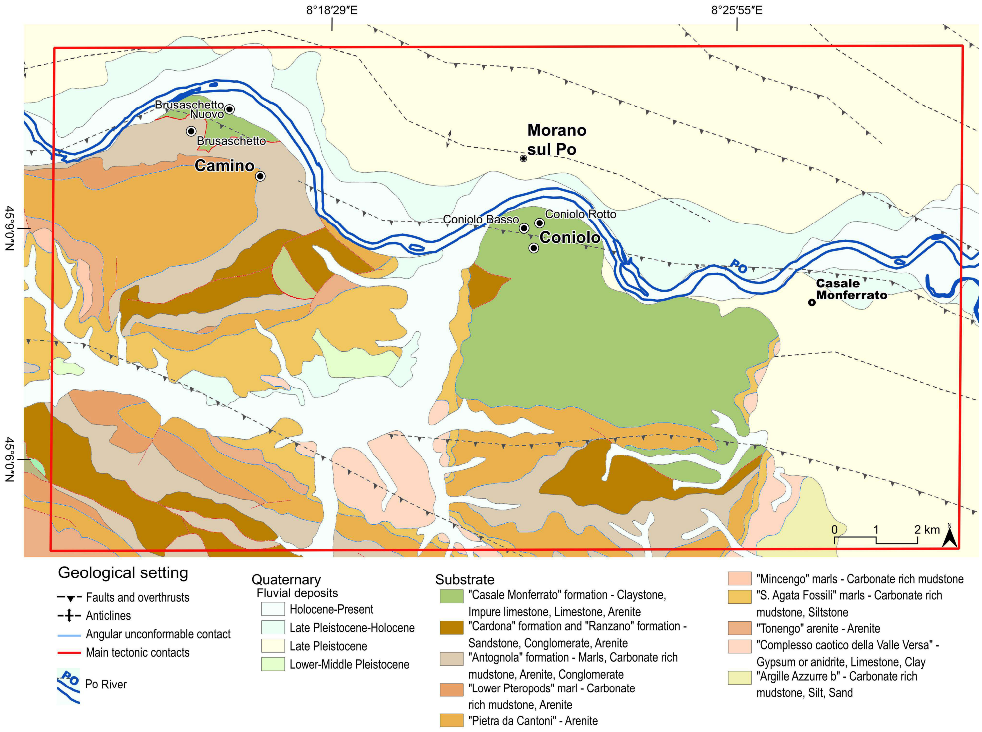


Figure 1. Bedrock geology of the study area [37], modified.

2.2. Historical Settings

Monferrato is a historical region of Piedmont in northwestern Italy that covers much of the provinces of Alessandria and Asti. The study area is located in the northernmost part of Monferrato, on the hydrographic right bank of the Po River and is divided by the Tanaro River, an important tributary of the Po River (Figure 2).

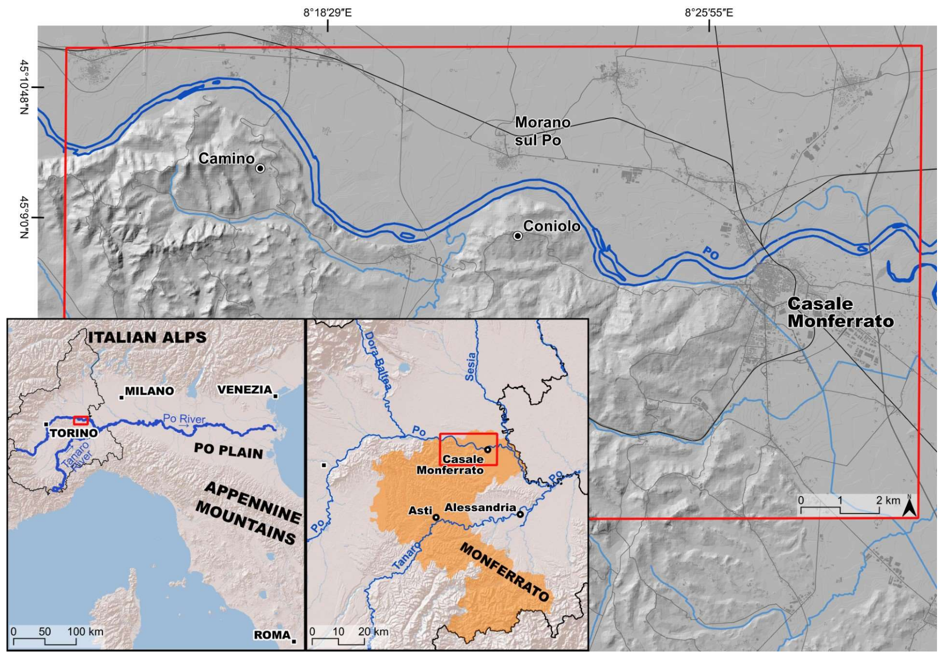


Figure 2. Index map showing the area immediately west of the city of Casale Monferrato, indicating locations for the villages of Camino and Coniolo.

This region is renowned for having been one of the richest territories in the history of the Italian mining industry, dating to the time of colonization following the Roman conquest (2nd century B.C.) [41]. There are four mining-related Roman archaeological sites. The main one is located at the fourth mile on the road westward from Casale Monferrato, along the right bank of the Po River. It is very close to limestone outcrops along the bank of the river and bears traces of brick and lime firing from a settlement that must have been extensive [38]. From this locality, slaves extracted limestone and underlying refractory clays that were used as a lining for furnaces. With the decline of the Roman Empire, the vitality of this territory declined, and for a few centuries the institutions, organizations, and techniques used to create the famous "Pozzolana" cement fell into obscurity [42].

James Parker, an Englishman in the late 1700s, while baking marl extracted from the Thames River clays, made and patented the first cement as we understand it today. It was the first real hydraulic cement, which, when combined with water, undergoes chemical reactions that generate and lead to solidification. The only drawback was that it solidified too quickly. However, it was discovered that firing it at high temperatures and adding gypsum to the finely ground clinker resulted in a slower-setting cement. This led to the Portland cement that is now in common use [43]. This discovery was important for Italy, in particular the Monferrato area. Thanks to the need for cement, marl became economically important, and Monferrato had the highest quality marl in terms of lime content found in nature. In the Monferrato Formation, clays often include beds of sandstone and shaley limestone, including well-known gray and brown clays.

Cement exploitation from the late 1800s provided employment for thousands of people. Due to the need for laborers in the marl mines, hundreds of peasant families became miners. The minimum age required to work in the mines was 9 years old, and many children found employment with the quarrying companies [41]. Coniolo village, at that time, had around 1000 inhabitants, while Brusaschetto had about 250. Thanks to this industrial expansion, the town of Casale Monferrato became identified as the national capital of lime and cement production. The quality and the extent of the underground seams and outcrops led to the emergence of numerous mining localities. Two of these are the municipalities of Camino and Coniolo. Many adits were created, opening toward the Po River on the north and directed horizontally from north to south into the hillside. Once a bed of marl was identified, it was followed as long as soil conditions, water seepage, depth, and thus uplift costs, allowed. Adits and tunnels were up to a kilometer long and continued to depths of 150 m below the ground surface [41]. Because the surrounding material was prone to caving, workings had to be stabilized with planks and locust poles. Another concern was the infamous firedamp, a mixture of air and methane that could explode, as in fact chronicles report happened, killing several miners. At this time in history, the environment and even people's lives were given little consideration. Environmental and safety regulations were few or entirely absent.

2.3. Mining Activities and Aftereffects

Physical characteristics of the deposits influenced methods of mining. The oldest method was an "open air" or "room" quarry, locally called "scuerta" (uncovered). This method involved tunneling into a "vein" or "bench" of limestone or marl, starting where the bench intersected a hillside. The bench would often be identified by a "Pietra Cagna" (hard limestone) at its base. Loose sediment (eluvium) would be removed to expose the calcareous bedrock, and a tunnel, typically 5 to 6 m high, would be excavated following the slope of the bench (Figure 3). A protective slab 60 to 100 cm thick would be left as a roof and shored by locust poles 25 to 35 cm in diameter. When a length of 5 to 6 m was reached, poles would be removed to allow roof collapse, unless excavation continued, in which case shoring was maintained and the room system ("a baracche") was expanded by advancing an additional 15 m into the vein.

In the late nineteenth century, open air methods were gradually replaced by deeper excavations, using the method of tunnel advancing and retreat logging. This method allowed for greater production and less loss of ore, while the above mechanization of transport allowed for the continuity of work throughout the year.

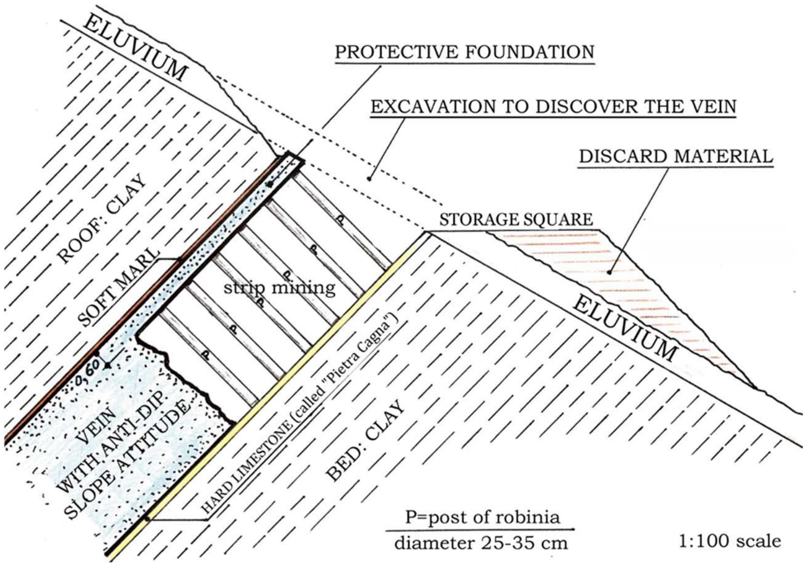


Figure 3. Open-air excavation scheme [41], modified.

Excavations of limestone and marly deposits had been defined legally as quarries from ancient operations until implementation of Italian Law 1443 on 25 July 1927, which reclassified them as mines.

After a successful start to mining that saw many companies operating successfully at increasing depths of the mine, early Twentieth Century inhabitants of Coniolo and Brusaschetto, found themselves dealing with dramatic and unstoppable after effects [44]. Due to primitive underground excavation techniques, a lack of environmental regulation, and subsequent blasting to form large cavities, mining-induced ground subsidence beneath the towns became widespread and highly damaging. In Coniolo, eighty-four houses were damaged or destroyed, as were many other centuries-old buildings [45] (Figure 4). Eventually, the inhabitants of Coniolo, now called Coniolo Rotto (Broken Coniolo), having realized there was nothing they could do to save their settlement, were forced to evacuate and move to an adjacent hill, where part of the settlement was already located. An old church was enlarged and became the center for construction of new dwellings.

Figure 4. Coniolo hamlet in a photograph taken at the end of the 19th century. The village was abandoned, then completely demolished in 1907. Today, only few ruins of it are visible, called "Coniolo Rotto" (Broken Coniolo), hidden in a thick forest [46].

As this drama unfolded, Italy entered World War I, and many men had to leave their families and would not return; nonetheless, at the end of the war, reconstruction resumed vigorously. Using bricks, roof tiles, doors, and floors salvaged from the collapsed centuries-old buildings in Coniolo, construction of houses to replace those that had been lost was restarted. These houses appeared new, but the use of ancient materials revived the ancient soul of the village. However, the industrial economy of the postwar period needed cement, and the beautiful hills were still full of it, so the inhabitants went back to digging, and it appeared as though history would repeat itself. Following the mid-1920s, new tunnels were dug directly beneath the recently rebuilt village [41]. This time, however, the people of Coniolo, drawing on their past experience, banded together and opposed the project, demanding government intervention. By so doing, they succeeded in obtaining a suitable perimeter for the village, saving it from a second destruction. It was not until 1956, with decades of incomprehensible delay, that the hamlets of Coniolo and Camino were included on the list of villages eligible for benefits of transfer or consolidation under Italian Law No. 445 of 9 July 1908 et seq., but this decree was either never or only partially executed.

Brusaschetto suffered a similar fate. The village, established in the 1890s, suffered surface collapses due to underground mining. In the early Twentieth Century, it was decided to abandon the hamlet because houses were badly damaged (Figure 5). In some cases, quarry operations caused damage to houses even at a very considerable distance [37] from the processing area. In 1931, a protection zone was demarcated northeast of the settlement, beyond which companies could not push tunnel excavation and exploitation. Explosive blasts were still clearly felt by the population above ground. In 1955, a governmental commission proposed relocation of Brusaschetto to a quieter area. In 1956, a decree was issued by the President of the Italian Republic to include Brusaschetto among villages to be relocated at the expense of the Italian state. Semi-detached houses were built as row houses that did not remotely possess the features of these farmer's previous homes. Moreover, the new location of Brusaschetto Nuovo (New Brusaschetto) was an unfortunate choice, because it was situated in an area historically flooded by the Po River. Population decline occurred slowly, as shown by census numbers, from 80 inhabitants in 1971 to 54 in 1991. The latest phase of the decline occurred in response to Po River floods that hit the area in November 1994 and October 2000, resulting in final abandonment of the remaining small buildings, their demolition, and transformation of Brusaschetto into a ghost town [43].

(**a**) (**b**)

Figure 5. *Cont.*

(c) (d)

Figure 5. Damage in Brusaschetto: (**a**,**b**) images taken in the mid-1950s showing two seriously damaged buildings in the village (CNR IRPI Archive); (**c**,**d**) photos taken in 1990: a house and the church show large cracks in external walls [46].

3. Materials and Methods

3.1. Historical Research of Past Instability Sites

Data were identified, collected, and analyzed as follows: (i) selection of data repositories (libraries, public and private archives, etc.); (ii) identification of data-containing documents (manuscripts, maps, aerial photos, published and unpublished technical reports and manuscripts, newspaper articles, etc.); and (iii) data processing and analysis. Historical data (Tables A1 and A2) were obtained from four primary sources:

- Official government agency archives (the Ministry of Public Works, the Ministry of Agriculture and Forestry, State Archives, the Hydrographical Po Office, the Superior Council of Public Works) that contain unpublished reports, maps, and other materials pertaining to the timing and dynamics of past instabilities; newspaper and periodical archives that include national and local newspaper articles;
- Municipal archives of the two villages examined (Figure 6). These were the most useful sources of historical information. The documents classified under "Public Works" contain information about past instability events, casualties, and the amount of damage. From the thousands of documents examined, dates and sites of instabilities were collected and listed in Appendix A (Tables A1 and A2) [41,45–48];
- Municipal libraries, which hold papers, technical reports, and historical books regarding the Camino and Coniolo municipalities (Figures 7–9).

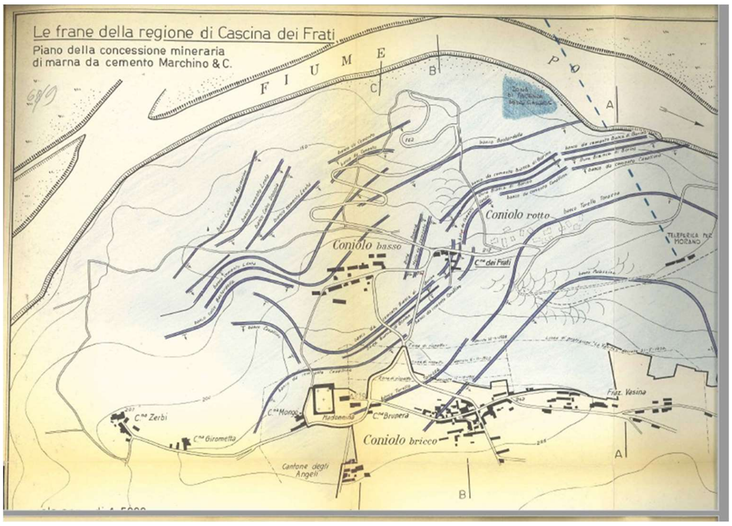


Figure 6. Example of a historical document found in the archive of Coniolo Monferrato [41]: detailed map of the "Plan of the cement marl mining concession" for the Marchino Company.

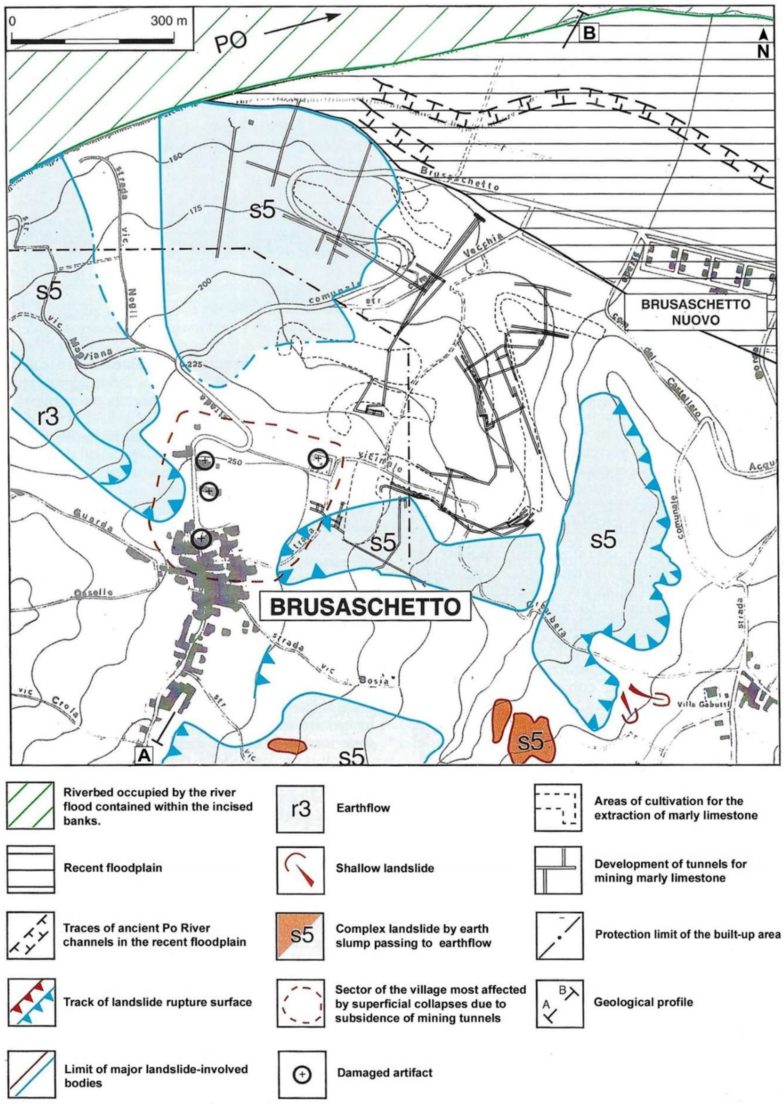


Figure 7. Geomorphological map with indications of damage and human activity in the Brusaschetto area [46].

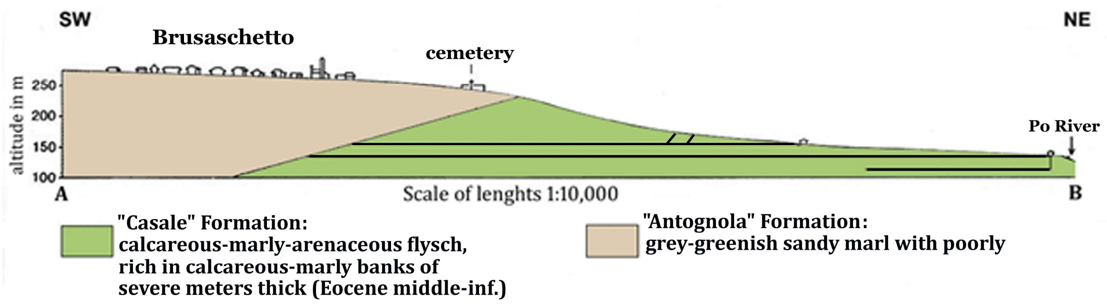


Figure 8. SW-NE geological profile of the bedrock in the Brusaschetto area. Highlighted with horizontal black lines are tunnels used until the 1950s for the exploitation of limestone–marly veins. See Figure 7 for the profile trace [46].

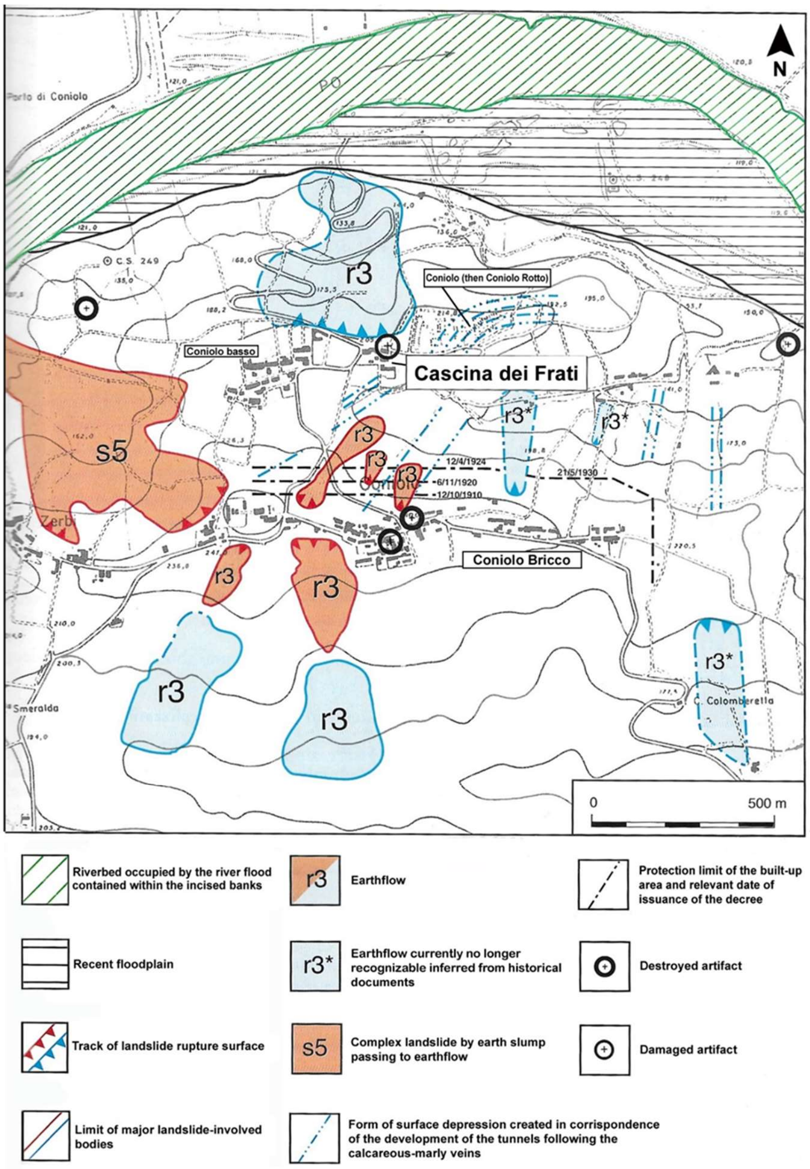


Figure 9. Geomorphological map with indications of damage and human activity in the Coniolo–Cascina dei Frati area [46].

3.2. Geomorphological Analysis

A geomorphological study was conducted in two closely related stages. First, the evolution of hill slopes for the last seventy years was reconstructed through an in-depth photo analysis using multi-temporal aerial images. Second, a soil survey was conducted, along with an interpretive analysis of aerial photographs to produce a geomorphological map that identified areas of surface runoff, standing water, and subsidence in relation to the mining structures. A photointerpretative analysis of Brusaschetto shows the presence of two distinct areas of subsidence on the slope from Brusaschetto to the Po River. These areas most likely developed along with the expansion of "a baracche" cultivation, which occurs less than 40 m below ground surface. These were holes that followed the inclination of the limestone bank. These cavities, which were lined with poplar or acacia poles, measured 8 to 12 cm in width, and the slope measured 20–25 m in length. Tunnels were dug side by side, leaving a limestone cavity wall between them. The reliability of historical data and aerial photograph interpretations were verified by field surveys performed along the hillslopes where Brusaschetto and Cascina dei Frati-Coniolo are located. The historical documents were assessed and photographed and their state of conservation and function were noted. Areas involved in ground movements were identified from historical documents. Maps and the technical comments in technical reports were evaluated.

3.3. Urban Planning Analysis

In the first stage, cadastral (scale 1:2000–5000) and regional technical (scale 1:10,000) maps were analyzed to document existing or planned land use. A comparison of past and present urban conditions was made. In the municipal archive, a layout of Coniolo at a scale of 1:500 was found (Figure 10), taken from sketches of cadastral surveys from 1890 [47]. It shows rural and urban buildings that collapsed between 1905 and 1922. In 1990, the Research Institute for Hydrogeological Protection of the Italian National Research Council (CNR) conducted a technical inspection by walking all streets of Brusaschetto and Cascina dei Frati, marking on a map and photographing houses that still showed damage. In Brusaschetto they also visited the church and cemetery, where many graves were found to be uneven and sloping. The inspections made it possible to verify significant differences between the disastrous situation in the early decades of the 20th century and today and to note the state of houses many years after the events that caused their damage.

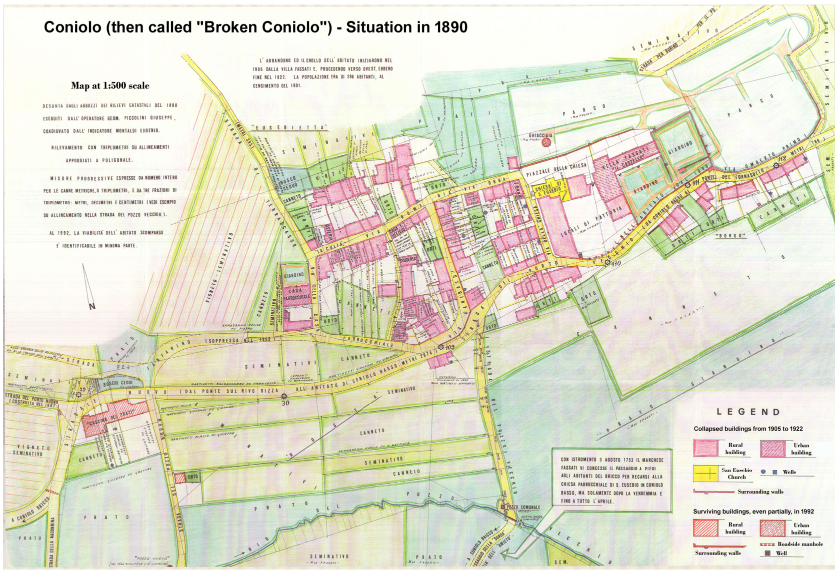


Figure 10. Coniolo, then called Coniolo Rotto (Broken Coniolo). Reproduction of a valuable color (pastel) map taken from the 1890 cadastral surveys, updated in 1922. It highlights collapsed buildings for the period 1905 to 1922 and surviving buildings (even partially) in 1992 [41].

3.4. Geognostic Investigation and Geophysical Survey

Since the geological and geomorphological settings of the two sites examined are very similar, we chose to focus on the Brusaschetto locality as representative of both. Site investigations were aimed at identifying anomalies in the subsurface that are potentially attributable to mining tunnels and to identify potential relationships to ground disturbances and damaged structures on the surface.

Investigations performed over the past two decades (Figure 11) include:

i. Geological examination of four continuous boreholes (Figure 12) drilled to depths between 50 and 60 m below ground level and related standard penetration tests (SPT) performed in advance at every 3 m of borehole depth.

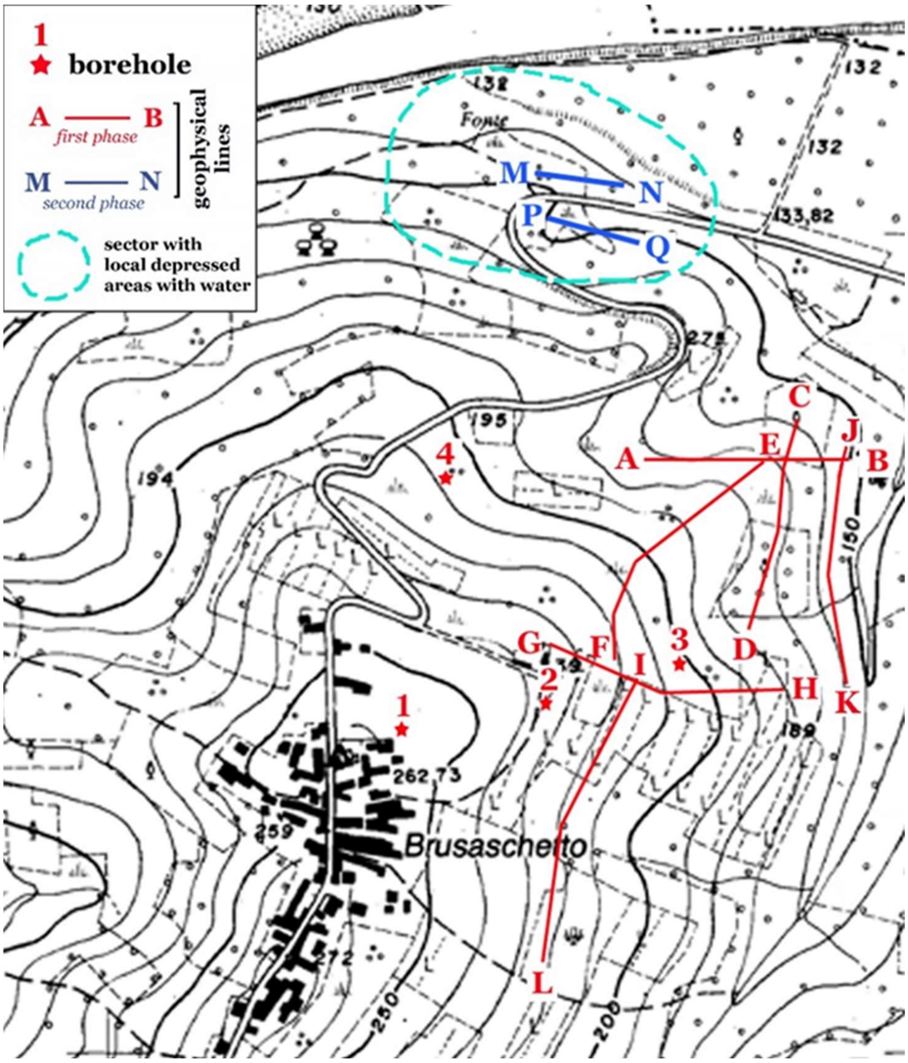


Figure 11. Map of geognostic investigations for the Brusaschetto site. Four boreholes and eight electrical tomographies (red lines in 2006, blue lines in 2009) are evidenced. The sky-blue dotted line defines a sector with a high concentration of locally depressed areas up to several meters in diameter or elongated along a preferred direction that are partially or completely filled with water.

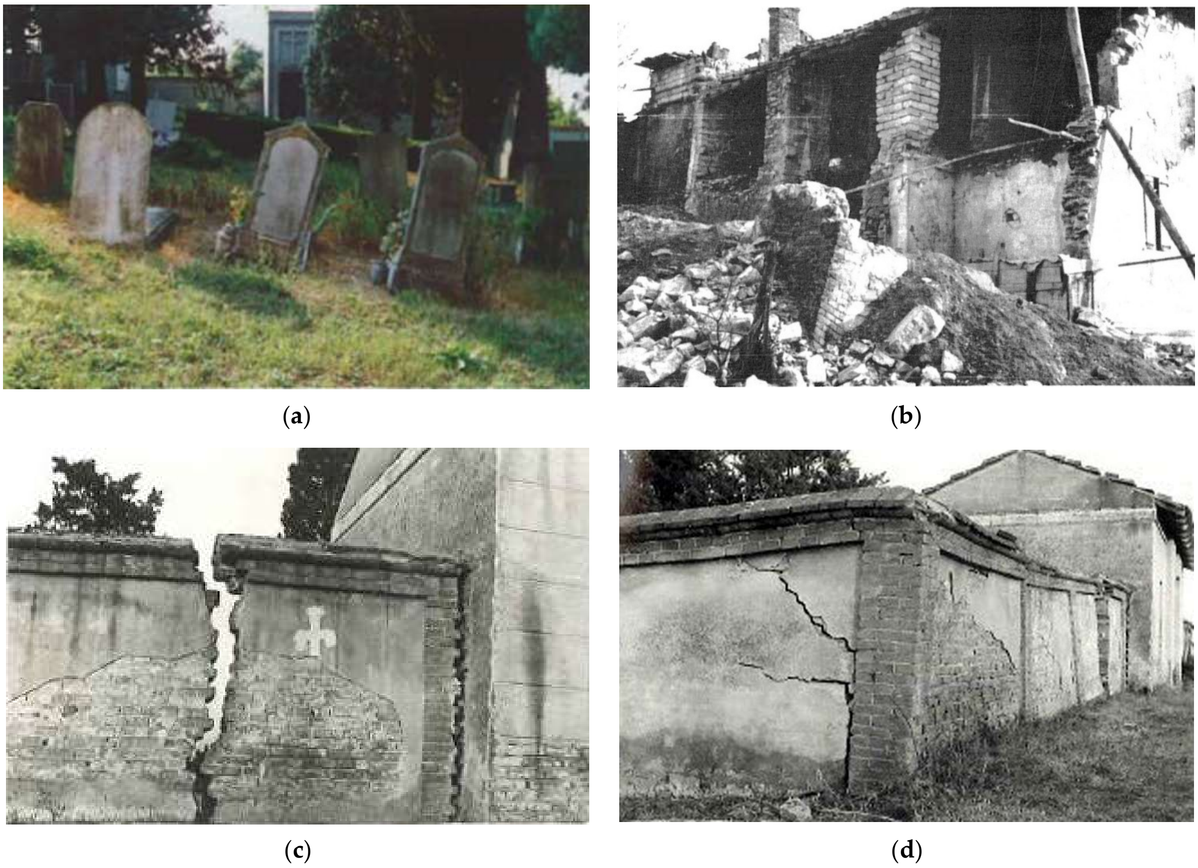


Figure 12. (**a**) Brusaschetto cemetery. Numerous headstones appear slanted due to gradual subsidence (photo by F. Luino); (**b**) Brusaschetto farmhouse in 1955. Sinking of the underlying mine galleries caused periodic differential subsidence of the lying plane and subsequent collapse of the structure (CNR IRPI Archive); (**c**,**d**) Brusaschetto: wide fractures in the cemetery boundary walls (CNR IRPI Archive).

ii. Geophysical review (first phase) consisting of six electrical resistivity tomographic (ERT) surveys performed with 48 electrodes at spacings between 6 and 7 m. These surveys were carried out with both Wenner and Dipole–Dipole configurations in order to combine depth and lateral resolution. An effective investigation depth of around 30 to 40 m was obtained. The aim of these surveys was to conduct a first screening of potential resistivity anomalies related to the presence of cavities. Dipole–Dipole data resulted in noisy and difficult-to-interpret data.

iii. ERT surveys (second phase) using only the Wenner–Schlumberger electrode configuration and 72 electrodes at 1.5 m spacing to increase resolution in identification of anomalies with respect to previous surveys. Sections were located south of the village of Brusaschetto and south of the area affected by the first phase of geophysical investigations. In particular, new sections (M-N and P-Q) were derived at the foot of the concentric slope that descends from Brusaschetto toward the Po River, following the state road that connected the villages of Brusaschetto Nuovo and Brusaschetto. The choice of location for the second-phase geophysical surveys was chosen because of evidence of potentially dangerous subsidence that affected the municipal road connecting Brusaschetto to Camino. The monitoring survey of landslides in Piemonte [48] also revealed instability in relation to possible subsidence in the same area.

4. Results

4.1. Multidisciplinary Investigation Result

This multidisciplinary methodology of incorporating historical, land surveys, and urban planning data produced interesting results, which can be divided into a few key points. Since the two villages of Brusaschetto (Municipality of Camino) and Cascina dei Frati (tMunicipality of Coniolo) are only 8.8 km apart as the crow flies and are both located on the right bank of the Po River, they will be examined together, pointing out minor differences. Main results are reported schematically in Table 1.

Table 1. Multidisciplinary investigation results.

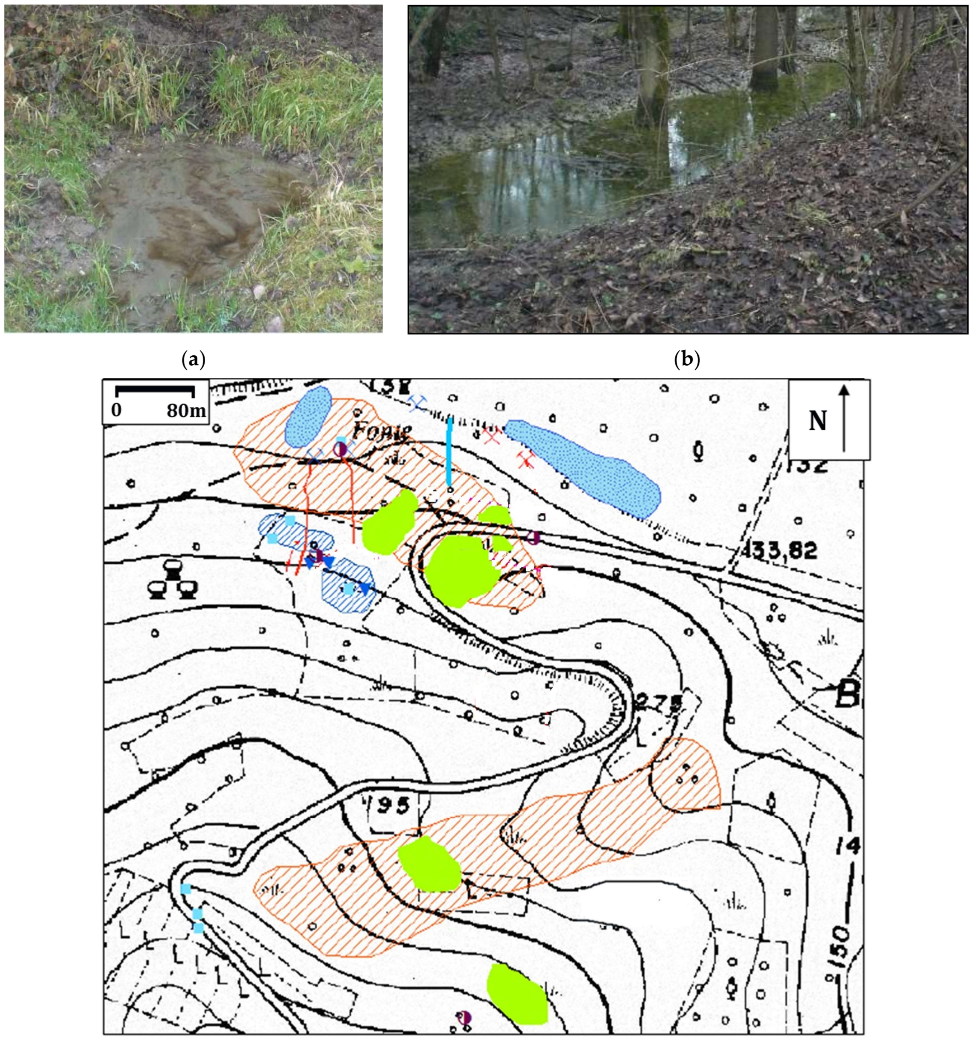
Analysis	Description of Results
Local morphological features	Brusaschetto (Camino), is located on a ridgetop in the hilly region between the cities of Turin and Casale Monferrato, with an average elevation of 260 m. Locally, the ridgetop forms a circular hill that slopes downward about 100 m to the right bank of the Po River. The slope consists of concentric levels that include depressions and counterslopes. The village of Cascina dei Frati (Coniolo) is also located within the hilly region between Turin and Casale Monferrato, at a slightly lower elevation of 205 m, and is about 700 m from the right bank of the Po River. The surface has a slight slope toward the river, with numerous depressions associated with marl mining.
Dominant processes	Ground subsidence associated with the collapse of mine galleries. Landslides due to rotational sliding and saturation of surficial materials.
Dimensional parameters	The area affected by ground subsidence for Brusaschetto is about 40 ha and for Cascina dei Frati almost 100 ha.
Kinematic parameters	Gradual subsidence and sudden collapse both increase in frequency and severity with time, in particular following heavy rainfall events.
Predisposing causes	(1) Underground mine workings passed directly beneath villages, using the "long-pillar" method, in which roofs separating overlapping galleries were blasted, creating cavities as high as a 12 m. (2) Poor lithological and structural characteristics of the bedrock.
Determining causes	(1) Ground subsidence due to collapse of underground mine workings. (2) Slumping landslides associated with large rainfall events and melting snowpack.
Damage occurred	(1) Brusaschetto village: a. Total collapse of a house. b. Differential subsidence of the foundations of about forty buildings. c. Damage to perimeter walls. d. Damage to the school building and church, due to failure of the foundation and the right fence wall. The bell tower of the church rotated toward the east. e. Damages to walls and numerous tombs of the cemetery (Figure 12). (2) Village of Coniolo: a. Irreparable damage to more than 80 urban and rural buildings at the turn of the century. b. Abandoned and subsequently demolished. c. Inhabitants recovered part of the bricks to rebuild in Coniolo Basso, Cascina dei Frati, and Coniolo Bricco. d. A few years later, houses in Cascina dei Frati also began to suffer damage.
Mitigation	(1) In 1956, construction began on 23 new houses in "Brusaschetto Nuovo". They were completed and made usable in 1958, along with the waterworks, roads, a school, sewer, and electric lighting systems. The houses, however, were not suitable for those who owned barns and animals. (2) In Cascina dei Frati, it was not possible to carry out relocation in the immediate vicinity because of the widespread extent of damage involving the entire hillside. Thus, reconstruction was opted for in the municipality of Morano sul Po, on the opposite bank of the Po River 2 km away; however, since there was no bridge nearby, inhabitants would have had to travel 14 km to their new homes. They refused to abandon their homes, which were reinforced with tie rods and partially renovated.
Mapping analysis	All data collected and processed were compared with historical information obtained from bibliographies and consultations of mining maps of the Turin Mining District. In this regard, both the adits and tunnels of the mine sites were located.

4.2. Geological Investigation and Geophysical Survey

4.2.1. Field Survey and Aerial Photo Analysis

The study area is characterized by slopes with low gradients marked by widespread depressions of different sizes. Many of these are best observed on aerial photos, due to their expanse and elongated shapes. Smaller circular depressions are observable by field survey. Lime and clay superficial deposits, vegetation, and anthropogenic features obscure much of the morphological evidence.

Sub-circular depressed areas generally have concave-downward profiles with sub-vertical walls. They vary in diameter from a few meters to hundreds of meters and are typically one to a few meters deep. Morphologically, these features resemble natural sinkholes and are commonly partially filled with standing water. Ponding also occurs at the base of slopes, where water seeps to the surface (Figure 13a). Five mine entrances have been identified, three of which are characterized by copious water inflows. Starting from these entrances, the presence of elongated depressed areas (Figure 13b) was observed in a north–south direction, presumably associated with tracks of old mine tunnels; although, there are currently no maps attesting to their existence and correct location.



(**a**) (**b**) (**c**)

Figure 13. Morphologically depressed areas with clear water retention. On the left (**a**) sub-circular depression with an approximate diameter of 3 m, while the one on the right (**b**) is an elongated depression measuring 9 × 2.5 m (photo S. Bonetto); (**c**) main morphological evidence and distribution of depressed areas (red: extensively depressed areas observed by aerial photos; blue: locally depressed areas observed directly in the field and filled by ponded water; green: dry depressed areas).

4.2.2. Geological Investigations

The drilling campaign, consisting of four boreholes up to 60 m deep, evidenced the presence of the marly–calcareous bedrock at about 5 m from the surface. Stratigraphies show the presence of alternating layers of clayey–marls and calcareous–marls a few meters thick. Most of them show high consistency, but locally, strata of inconsistent and loose material up to 2 m thick have been observed, as confirmed by low geotechnical features obtained by SPT. In particular, samples were taken at different depths (14, 33, and 54 m in the S2 borehole; 5, 9, 14, and 41 m in the S3 borehole), from which granulometric analysis showed loose to weakly compacted clayey-siltstone and sandy-clayey siltstone. Stratigraphic descriptions are similar for all boreholes, except for the inconsistent presence of chaotic silty clay containing calcareous and marly intraclasts and decimeter-scale wood fragments, which is prevalent at depths up to 40 m in both the S1 and S2 boreholes.

4.2.3. Geophysical Surveys

Phase one: Six resistivity sections were analyzed, primarily showing low resistivity values (around 10 Ω·m), related to the presence of shallow clayey siltstone with only local isolated values greater than 70 Ω·m. This last type of anomaly could represent the route of tunnels used for the extraction of the deposit and reflect subsequent collapse of the tunnels. Indeed, in the presence of collapsed tunnels or other voids, resistivity values usually increase due to the presence of air-filled voids. Conversely, low resistivity anomalies can be related to the presence of tunnels filled with water and/or highly altered clayey material.

Phalse 2: Resistivity sections obtained from inversions using Res2DInv software are reported in Figure 14 for the P-Q section and Figure 15 for the M-N section. Both sections were oriented perpendicular to the direction of possible tunnels, as identified from historical mining maps and the location of observed entrances. The depicted resistivity values related to the P-Q section (Figure 14) are generally low, less than 10 Ω·m; however, at least four anomalies are recognizable, three of which are conductive (N° 1, 2 and 3) and one resistive (N° 4), the latter at a depth of about 18 m. The conductive anomaly N° 1 has an elongate shape and reaches a depth of 8 m; however, being located at the borders of the line, it is considered unrepresentative. The conductive anomaly N° 2 is almost cylindrical in shape, located at a depth of 3 to 8 m and has resistivity values around 5 Ω·m. Anomaly N° 3 has resistivity values similar to anomaly N° 2, is located at a depth between 5 m and 15 m, and is characterized by an elongate shape. Resistive anomaly N° 4 has slightly higher resistivity values compared to the anomalies described above.

Generally, low resistivity values were also observed along the M-N section (Figure 15). Here, at least four main anomalies can be seen, some of which are conductive (anomalies N° 1, 2, 3) and one resistive (anomaly N° 4). The conductive anomalies are sub-cylindrical in shape and shallow, affecting only the first five meters of depth, with resistivity values of about 5 Ω·m. Anomaly N° 4, which is hemispherical, has resistivity values of about 9 Ω·m and is located at a depth between 7 and 15 m (Figure 15).

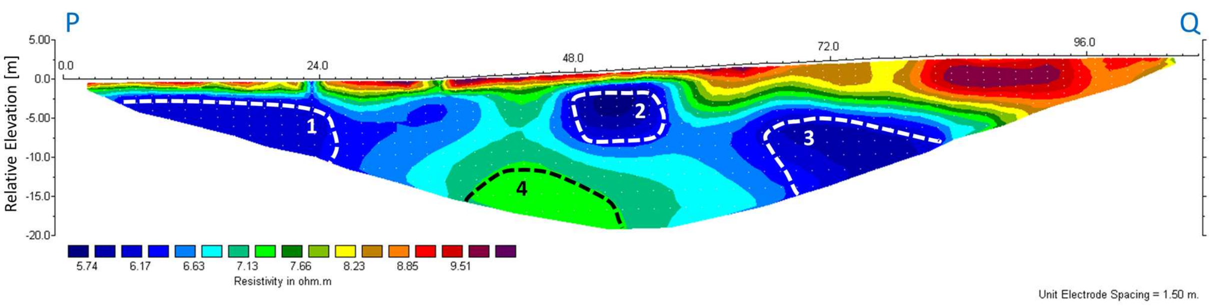


Figure 14. Electrical resistivity tomography (ERT). Line N° 1. Numbers indicate the local anomalies observed.

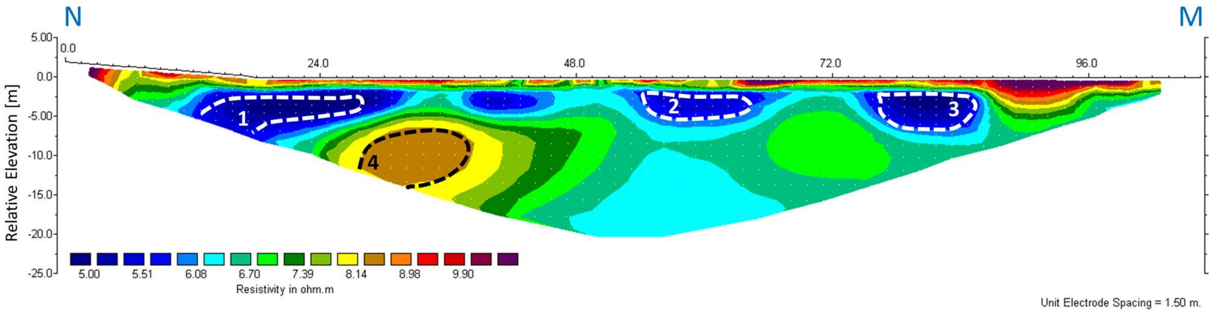


Figure 15. Electrical resistivity tomography (ERT), line N° 2. Numbers indicate the local anomalies observed.

Given the generally low resistivity values evidenced along the two investigated sections, interpreting them in terms of the possible presence of cavities, voids, or altered material is not straightforward. However, from the combined interpretation of the two sections, it can be hypothesized that there is linear continuity of a zone with higher resistivity that connects anomaly N° 4 between the two sections, potentially associated with the presence of higher percentages of limestone compared to clay. Low resistivity anomalies around this zone can, therefore, be related to depressed materials and/or collapsed cavities that contain a higher percentage of water or have a high clay content.

5. Discussion

It seemed fitting, more than a century later, to address this story of marl quarrying in an area of the central Piedmont. At the earlier time, in the absence of social networks, the reach of information was limited, and the story of Brusaschetto and Coniolo was little known, as it involved only two small towns. However, from a social point of view, the story certainly has something fascinating about it, namely the eternal battle between the rich and the poor.

An interesting aspect, perhaps somewhat overlooked, concerns the economy that revolved around this mining activity. Prior to mining, the area in question was poor, with a purely agricultural vocation, but after the start of the industrial period, the cultivation of the limestone deposits gradually achieved economic importance equal to that of the cultivation of the fields, both for manual labor and for related activities. Trade was exercised through the purchase and sale of commodities, as well as that of land and buildings with limestone beds underneath, but only the commodities brought high profits, as the race to exploit the limestone beds drove up their prices from 1882 to 1927, i.e., until the cement marl quarries were classified as "mines of state domain" by Law 1443 of 29 July 1927 [33]. Almost all landowners around the mines profited by granting companies the right to extract limestone from beneath their land, which included commodity price, duration of extraction, and levelling of the fields to allow again allow agriculture upon contract termination. At the end of the agreed term, landowners renewed the contracts, requiring further compensation for continued excavation. Many landowners granted rights of way for tracks, roads, cableways, tunnels, and water, demanding very high fees, both in the presence and absence of damage, as in the case of tunnel crossings. Fees were paid either on a one-off basis or in the form of tolls, commensurate with the quantity of lime passing through.

While mining activity has been an important source of income, there have been many reported damages in built-up areas linked to such activity. In order to verify the possible relationship between infrastructure damage mining activity, several investigations have been carried out using a multidisciplinary approach. Multidisciplinary methodology has been extensively tested across much of northern Italy (Lombardy, Liguria, Emilia Romagna) with excellent results for a wide range of geohydrologic situations, such as landslides, floods, and torrential debris flows. Such an approach requires the integration of analyses, tests, and data, and the development of multiple models for validation.

The history of these two small villages is unique and interesting. Initially, there was a question of how to approach the study of villages that had mostly disappeared from the national scene due to a lack of records. The approach of using historical documents was very productive, as it allowed the collection of published and unpublished material that enabled the compilation of an accurate and reliable chronicle more than 100 years later. The greatest difficulty involved finding original documents, which are often piled up in dusty and barely usable archives. Once useful documents were found, it was easy to sort them and create a chronology, despite the difficulties in understanding a "niche" topic, such as cement marl excavation.

The combined historical and geomorphological study was of fundamental importance for better understanding the evolutionary dynamics of the studied area. The presence of anomalous depressions was observed directly in the field and by photointerpretation, combined with borehole and geophysical surveys, then related to historical cartographic data (Figure 16). The distribution of mine entrances is obviously due to the relationship between ore body geometries and topography. Most entrances were located at topographically lower elevations to facilitate exploitation of calcareous–marly strata directly to the surface. If direct horizontal access was not feasible, vertical shafts up to 40 m depth were constructed to reach exploitable levels.

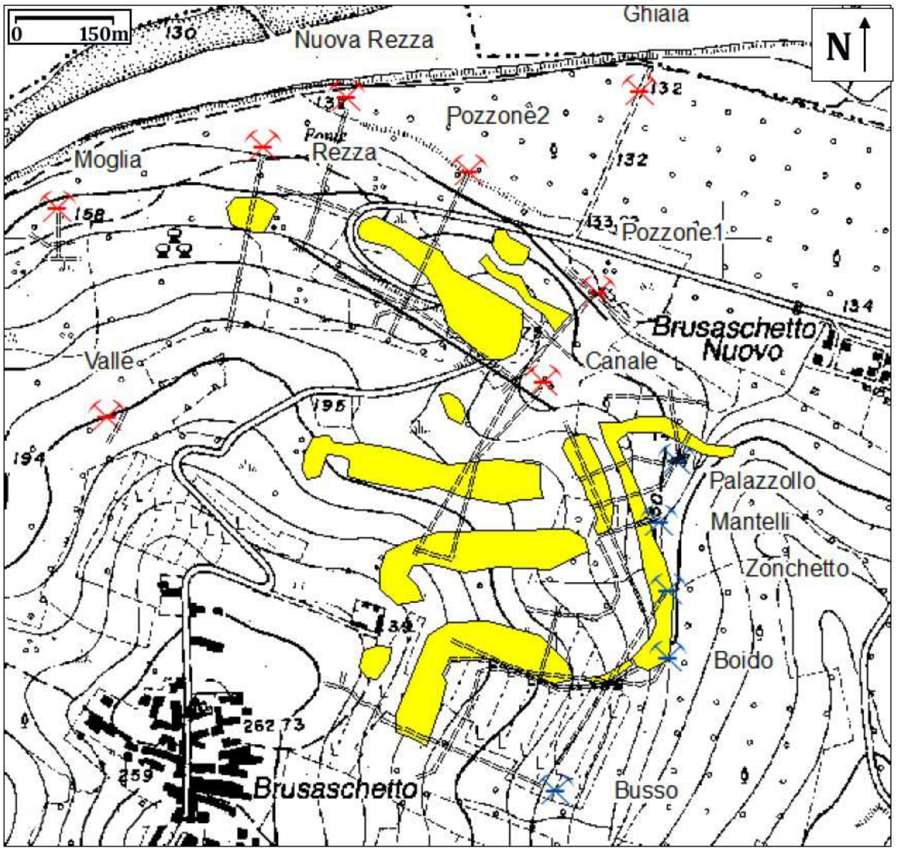


Figure 16. The distribution of tunnels (dashed parallel lines) and main entrances (red and blue mining symbols) for marl mines according to the Mining District. The yellow color represents cultivated areas called "a baracche".

Morphological evidence of subsidence (Figure 13c) corresponds well to the distribution of tunnels in Figure 16, supporting the hypothesis of a relationship between mining activity and surficial ground disturbance. Mining was carried out through tunneling with progressively retreating walls. These tunnels are in some cases now marked by isolated and occurrences of unconsolidated silty clay and sandy-clayey silt that contains chaotic calcareous–marly blocks and wood fragments. Although geophysical surveys only exposed shallower depths compared to drilling, anomalies show intervals of lower resistivity consistent with both the unconsolidated material and calcareous–marly strata observed in the boreholes. The unconsolidated and chaotic material was encountered intermittently in drilling to depths of about 40 m and is corroborated by resistivity anomalies to depths of at least 20 m.

Underground excavations had extended beneath the entire extent of the villages while they were still inhabited, causing contemporaneous surface movements and damage to buildings and other infrastructure. Additionally, subsurface explosions were heard and probably felt on the surface, likely generating great fear in many of the inhabitants. Citizens were aware their homes and personal safety were seriously threatened. In the area of Camino and Coniolo, two beds of remarkable calcareous–marly ore body were found.

The excavation and mining technique of blasting and retreat induced deliberate collapsing of mine workings, which undoubtedly impacted geohydrological conditions and exacerbated natural slope instabilities, which were already naturally predisposed to landslides from the clayey composition. It is not possible to distinguish specifically between individual ground movements related to natural processes and those triggered by subsurface collapsing of tunnels and other cavities. However, the close association between surface deformation and tunnel location show a clear relationship between the two. The effect was certainly felt by inhabitants on the crest of the hill, where the settlements of Brusachetto and Coniolo were both severely damaged. Coniolo suffered the greatest damage and was abandoned by between 1904 and 1906, after which, it was renamed Coniolo Rotto. Photographs of cracks in walls, floors, and ceilings taken over the years show that even after repairing some of the damaged buildings, movement continued and new cracks appeared. The frequency decreased decade after decade, but the hazard has not entirely dissipated.

6. Conclusions

The study area has been affected by a subsidence phenomenon induced by past underground mining activities, leading to severe damage to dwellings and other infrastructure and ultimate abandonment of entire communities. Reasons for abandonment of villages in Italy, as elsewhere in the world, are varied, but ground instability can certainly be a contributing factor. This subject arouses interest and curiosity, since anthropological cases are frequently considered to be rare and peculiar. In every age and in every culture, territories have been gradually inhabited, abandoned, and re-inhabited, according to a cycle that is both natural and unnaturally accelerated by political decisions. However, it seems clear, looking at the local history, that individual events have rarely been the exclusive cause of abandonment. Communities have often faced and overcome disaster, finding within themselves and their heritage stimuli and solutions for recovery. Problems arise, however, when the event is compounded by human action, including harmful intervention or even simple inaction. These are political actions that can lead to eventual abandonment both directly and indirectly, when they do not reconnect with historical links and are not structured according to the needs and identity of the people and their communities.

In mining areas, subsidence is commonly associated with vertical and/or horizontal movement of material from the subsurface that leads to weakening of the remaining overlying material. The studied areas of this report show clear examples of the potential impact of subsurface mining on overlying and nearby communities. Results of a multidisciplinary approach (historical data collection, morphological evidence, aerial imagine analysis, drilling campaigns, geophysical tests) show a clear relationship between mining tunnels beneath the surface and ground subsidence at the surface. Tunnels identified on historical maps may not be complete, and their real extent, therefore, might not be represented. The saying: "what happens underground stays hidden!" applies. This can create difficulties during the design phase of structures and infrastructures, presenting significant unidentified risks due to the threat of ground collapse.

The study of Brusaschetto and Coniolo has its foundation in events of an anthropological nature, and the phenomenon should, therefore, be interpreted from the perspective of a succession of events closely connected to economic, social, and cultural factors. The phenomenon was evaluated both quantitatively and qualitatively. The end result revealed very poor management by the companies that quarried cement marl by reaching all the way under the villages and creating considerable disruptions that led to the total abandonment of Coniolo and the partial abandonment of Brusaschetto. Even the relocation to Brusaschetto Nuovo, being built in the flood zone of the Po River, turned out to be a huge mistake. The inhabitants did not accept the mandate to relocate and refused to do so for good and logical reasons. The new village thus remained uninhabited for many years and was eventually torn down. Villages, once uninhabited, lose their fundamental reason for being, namely that of a place fit for the performance of human activities, become emptied of their main meaning, and are deprived of the functional value for which they were designed.

Local governments and the State have played an important but not always positive role. They could have provided much more for the affected citizens. The history of these two small towns once again underscores the importance of the role of institutions that are "strong with the weak and weak with the strong", and secondly, the fact that, as often happens, institutions have to take on important responsibilities, which are always unwelcome.

In conclusion, we can say that where abandoned mines and caverns are suspected, appropriate geological investigations are recommended to precisely locate and, if necessary, stabilize the ground in the vicinity of the abandoned mines in order to reduce the likelihood of subsidence, damage to land and infrastructure, and loss of life.

Author Contributions: Conceptualization, F.L., S.P. and P.S.; methodology, F.L., S.B., C.C. and L.T.; software, B.B.; validation, F.L., S.B., S.P., P.S. and L.T.; formal analysis, F.L., S.B. and P.S.; investigation, F.L., S.B. and P.S.; resources, F.L., S.B., C.C. and P.S.; data curation, F.L., S.B., B.B., C.C., W.W.L., S.P., P.S. and L.T.; writing—original draft preparation, F.L., S.B., W.W.L., S.P., P.S. and L.T.; writing—review and editing, F.L., S.B., B.B., C.C., W.W.L., S.P., P.S. and L.T.; visualization, F.L., S.P. and P.S.; supervision, F.L., S.B., S.P. and L.T.; project administration, F.L. and L.T.; funding acquisition, F.L., S.P. and L.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are openly available.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Summary of documents collected and sites indicated in relation to instabilities (Tables A1 and A2).

Table A1. Main historical data referring to the chronological reconstruction of the geomorphological instability for Brusaschetto–Camino. A date (first column) indicates the event one wants to report, while the second date refers to the document that witnesses or describes the event that occurred.

Date	Original Source, Date of the Document, Description	Source
1891	Civil Engineer of Alessandria, 1955/2/15: Beginning in 1891, excavations were made to extract cement marl, open a pit and construct horizontal shafts and tunnels at up to 40 m depth.	[46]
1903	Italian Geological Survey, General Directorate of Mines, 1955/04/30: Initial abandonment and demolition due to building damage and injuries associated with a long-standing landslide.	[46]
1927/7/29	Italian Geological Survey, 1955/04/30: Mining Law No. 1443 enacted. Marl was classified as a state-owned mineral substance subject to regulation.	[46]

Table A1. *Cont.*

Date	Original Source, Date of the Document, Description	Source
1930	Italian Geological Survey, General Directorate of Mines, 1955/April/30: First reports of slope instability. Movements were partly attributed to possible leaks from a newly completed aqueduct.	[46]
1931/8/26	Civil Engineer of Alessandria, 1955/02/15: By Prefectural Decree, a protection zone was established NE of the Brusaschetto built-up area, beyond which it was forbidden to excavate tunnels or extract marl. Mine blasts in the "permitted area" were clearly perceived on the surface, as vibrations were transmitted along the subvertical bedding.	[46]
1955/02/05	Italian Geological Survey, General Directorate of Mines, 1955/04/30: Subsidence and partial slippage along the foundation plane of houses in the northern part of the settlement were observed (Figure 7). About 40 houses, the church, and the cemetery were deemed unsafe. The commission proposed relocation of the northern sector that was most disrupted and mitigation measures were proposed to prevent additional landslide damage.	[46]
1955/04/30	Italian Geological Survey, General Directorate of Mines, 1955/04/30: Brusaschetto, particularly the northern part is unstable and prone to landslide. Advised relocation of the most affected areas and mitigation for the rest.	[46]
1956/03/27	Civil Engineer of Alessandria, 1958/03/11: The Superior Council of Public Works voted to relocate the part of Brusaschetto village affected by landslide movement.	[46]
1956/05/16	Civil Engineer of Alessandria, 1958/03/11: Issuance of a "Presidential Decree for partial inclusion of the township among those to be transferred to the care and expense of the State. Subsequently, work began to relocate the damaged area to a flat area called Brusaschetto Nuovo.	[46]
1956/12/11	"La Vita Casalese" Newspaper, 1972/06/22: Eviction decree regarding the parish church issued.	[46]
1957/06	Civil Engineer of Alessandria, 1958/03/11: Accentuation of landslide movements following prolonged rainfall.	[46]
1958/03	Civil Engineer of Alessandria, 1958/03: Infrastructure of Brusaschetto Nuovo (waterworks, roads, sewer, and electric lighting system, school) for the 23 new rural-type houses completed.	[46]
1958–59	Italian Geological Survey, 1965/06/24: Inhabitants of damaged houses did not comply with the invitation to move to the newly constructed buildings, as the new area was repeatedly reached by flood waters of the Po. They unanimously chose to remain in their old houses, repaired a little at a time, in order to continue their agricultural and artisanal activities. They requested a new survey to determine whether or not their settlement should indeed be relocated, as land subsidence and injuries to buildings had diminished considerably.	[46]
1959/09/22	Archive of Camino Municipality, 1959/09/22: An inspection by the Civil Engineering Office in Alessandria resulted in an order to vacate 23 homes and 5 other buildings threatened by collapse.	[47]
1959/11/03	"Il Monferrato" newspaper, 1959/11/06: Rainfall over several days further aggravated stability conditions, causing considerable alarm among the population. New cracks appeared on walls and others widened considerably, breaking the glass glued (strain gauges) to the walls.	[46]
1965/06/24	Italian Geological Survey, 1965/06/24: At the request of the Ministry of Public Works D.G. Special Services, a technical inspection was carried out. Modest landslides with detachment surfaces and local depressions were found in ground that was heavily waterlogged; however, the commission determined not to implement relocation due to lack of recent noteworthy landslide events and the desire of the inhabitants to not leave the village.	[46]
1977/10/10	"Il Monferrato" newspaper, 1977/10/11: Heavy rainfall led to flooding of many hectares along the Po River at Brusaschetto Nuovo.	[46]

Table A1. *Cont.*

Date	Original Source, Date of the Document, Description	Source
1993	Scientific publication by CNR IRPI of Turin and the Geological Service of the Piedmont Region, Date Compilation of geological, historical data and cartographic data (Figures 8 and 9).	[46]
2006	Archive of Camino Municipality, 2006: The settlement of Brusaschetto Nuovo was demolished after a long period of abandonment. A geological study commissioned to identify the causes of the surface collapse.	[47]

Table A2. Main historical data referred to chronological reconstruction of the instability processes for Cascina dei Frati-Coniolo.

Date	Original Source, Date of the Document, News	Source
1874	"La Stampa" Newspaper, 1932/04/23 "In the castle and church of Coniolo (which would later be called Coniolo Rotto), reinforcement of cracked walls using iron keys and spurs attests to the seriousness of subsidence, which also occurred before mining development. In the village of Coniolo Bricco (see Figure 2), an ordinance was implemented in 1874 by a monsignor, forbidding use of firecrackers in the vicinity of the church, for fear of damaging the walls and the vault, which had already been cracked.	[46]
1901/01/01	Private letter written by a witness, Mr. Martinotti R., 1993: Concession between private parties to extract the limestone in the lands north of Coniolo, later called Coniolo Rotto (Broken Coniolo). They began feverish excavation of tunnels.	[45]
1903/08	Private letter written by the witness Mr. Martinotti R., 1993: Marquis Fassati, fearing damage, had prohibited Mr. Bertone from excavating near his own buildings; however, Mr. Bertone continued undaunted, reaching under the homes of other owners. He was sued, and judgment was awarded to the injured parties, including compensation extending to future damage.	[45]
1904/05/18	Private letter written by the witness Mr. Martinotti R., 1993: Issuance of the Prefect's decree prohibiting the advancement of tunnels toward the township; however, advancement continued until October 1904 and in some tunnels until spring 1905.	[45]
1905/03	Private letter written by the witness Mr. Martinotti R., 1993: Cracks appeared in several buildings. Small glass rectangles were placed against perimeter walls to signal movement. The glass broke almost immediately, widening existing cracks. Maximum instability occurred in the northeastern part of Coniolo, where buildings were leaning toward the north. The 14.5 m high church bell tower reached an inclination of 30 cm from vertical. Wells that had masonry lining were broken, with the castle well (25 m deep) being broken into three separate sections.	[45]
1905/04	Private letter written by the witness Mr. Martinotti R., 1993: Mr. Bertone maintained his tunnels were unrelated to these disastrous events, filing an appeal with the Ministry, in which he requested an inspection by a mine inspector, who gave an unfavorable opinion.	[45]
1905/05/16	"L'Avvenire" Newspaper, 1905/05/23: The Prefect of the Alessandria Province, following an inspection and related technical report by the Inspector of the Royal Corps of Mines, decreed that no lime or stone quarrying work should be undertaken or continued within a designated area.	[46]
1905/05/21	"L'Avvenire" Newspaper, 1905/05/26: Part of the Coniolo parish church collapsed around 3 a.m, as did the mezzanine floor in one of the most damaged houses in Coniolo Rotto. The owner of the house fell through the rubble but was fortunately unharmed.	[46]
1905/05/28	"L'Avvenire" Newspaper, 1905/05/30: The chronicler of the time, after making a visit to Coniolo Rotto wrote: "There are walls with cracks into which a man's arm enters; there is even splitting of the ground on the square of the collapsing church, of a width of several tens of centimeters; violent breaking of the keys securing the arches. The so-called glass-sentinel, which applied in numerous cracks are already all broken, a clear sign that the movement of the soil continues unceasingly."	[46]

Table A2. *Cont.*

Date	Original Source, Date of the Document, News	Source
1905/06/10	"La Stampa" Newspaper, 1932/04/23: "On that tragic spring day in 1905, without any rumble having been heard, wide cracks had suddenly opened in the houses, while underneath and around them the ground shifted at a slow and progressive pace, opening into wide fissures that put everything in danger. The castle and the church were the most damaged buildings: they were immediately demolished, while later the other buildings were also razed to the ground." The 300 or so inhabitants migrated in crowds to a new village at West (Coniolo Basso), built in a plain area, outside the area of the excavations. However, it was not long before additional movement affected the new village, though outside the area of excavation.	[46]
1905–1922	Private archive of Mr. Martinotti R., 1993: This time frame experienced a gradual collapse and abandonment of Coniolo.	[45]
1907–1920	Private archive of Mr. Martinotti R., 1993: This period endured the most intense subsidence for Coniolo Rotto and the area to the southeast of that settlement.	[45]
1910	Civil Engineer of Alessandria, 1929/07/01: It was not until 1910 that the Royal Office of Mines in Turin received the first claims for damage to the houses in Coniolo Bricco. The conditions of the homes were well documented and related to the progress of the excavation beneath the village. On this basis, the Prefectural Authority adopted a measure to establish a 50 m wide buffer zone between the village and the area to the north. This delineation clearly shows that previous workings had approached to much less than 50 m from the line of houses.	[46]
1910–1920	Civil Engineer of Alessandria, 1929/07/10: In the decade 1910–1920, cracks in the walls of the buildings in Coniolo Bricco became more pronounced, and quarrymen were accused of carrying out excavations beyond the buffer zone. Most of the houses in Coniolo Bricco were found to be damaged, and the settlement was considered "irreparably threatened with ruin with progressive severity."	[46]
1920/11/06	Civil Engineer of Alessandria, 1929/07/10: A prefectural decree was issued, expanding the buffer zone north of the houses in Coniolo Bricco to 100 m.	[46]
1922/04/12	Civil Engineer of Alessandria, 1924/03/04: Complaints from residents about underground mine blasts. Seven "glass-sentinel" were placed on some houses in Coniolo Bricco during an inspection by Civil Engineers. These small glass pieces broke in June 1923.	[46]
1924/02/29	Civil Engineer of Alessandria, 1924/03/04: Gauges placed in 1922 had opened by 3–4 mm, with additional cracks to those documented in 1923.	[46]
1924/03/04	Civil Engineer of Alessandria, 1924/03/04: A horizontal fracture with displacement of about 10 cm to the north was noted at a depth of 7 m in a well at Coniolo Bricco. Gradual filling of voids at the foot of the hillside related to tunnel excavation was considered a potential precursor for the sliding of the upper hillslope upon which houses were built. Efforts were being made to shore vaults, floors, and masonry.	[46]
1924/04/12	Civil Engineer of Alessandria, 1929/07/10: A new decree increased the buffer width to 150 m with no depth limit.	[46]
1927/01/23	Famiglia Grande Newspaper, 1993/06: The inhabitants of Coniolo associated themselves into the Consortium for the Defense of Coniolo Bricco, and with the assistance of technicians and lawyers, obtained compensation for damaged houses and submitted an appeal to the government against an application by the Italian Cement Union to obtain the expropriation rights for public utility of the entire area, including the demolition and relocation of the village.	[46]
1927/07/29	Italian Geological Survey, Directorate General of Mines, 1955/04/30: Mining Law No. 1443 came into effect, limiting landowners' rights to exploit cement marl, by reclassifying it as a state-owned mineral substance, subject to concessions.	[46]
1929/97/01	Civil Engineer of Alessandria, 1929/07/01: The Civil Engineers of Alessandria determined that the destruction of the houses in Coniolo Bricco was linked to past and not current excavations for marl extraction, given the considerable distance and depth at which current workings were taking place.	[46]

Table A2. *Cont.*

Date	Original Source, Date of the Document, News	Source
1930/05/21	Italian Geological Survey, 1955/04/30: The buffer was extended to east of Coniolo Bricco.	[46]
1940	Private archive of Mr. Martinotti R., 1993: Heavy rainfall caused three earthflow landslides on the slope between Coniolo Bricco and Cascina dei Frati.	[45]
1949–1953	Coniolo Monferrato Municipality, 1953/11/20: North–south-oriented cracks initially reported in 1949 had widened through an otherwise imperceptible eastward sliding of the ground.	[41]
1951–1952	Coniolo Monferrato Municipality, 1953/05/15: Serious damage was reported for almost every house in the Cascina dei Frati village.	[41]
1951–1952	Coniolo Monferrato Municipality, 1953/05/15: The Office of Mines determined that the buffer distance of 100 m was insufficient.	[45]
1955/02/15	Civil Engineer of Alessandria, 1955/02/15: The seven houses in Cascina dei Frati are all damaged, several with cracks up to 6 cm wide. The buildings rest on soil that slopes gently to the east, toward the cement marl mines, the operation of which enhanced landslide potential. Concrete beams placed at ground level also broke. The likelihood of long-term continued movement makes mitigation difficult.	[46]
1956/02/13	Coniolo Monferrato Municipality, 1956/02/13: The mayor of Coniolo issued eviction orders, requesting the mining company to contribute to the compensation for damaged buildings.	[41]
1956/02/23	Coniolo Monferrato Municipality, 1956/02/23: The mining company did not hold itself responsible for damage to the houses and, therefore, did not give any compensation to the inhabitants.	[41]
1958/04/04	Civil Engineer of Alessandria, 1958/04/04: The Civil Engineer requested the mayor to implement an evacuation order.	[43]
1958/04/10	Coniolo Monferrato Municipality, 1958/04/10: The mayor notified homeowners of an order to clear their houses and to prohibit transit in the vicinity of the hamlet. He also urged the Civil Engineer's Office and the Prefecture to assign to the inhabitants houses built in the nearby village of Morano sul Po.	[41]
1959/11/30	Coniolo Monferrato Municipality, 1959/11/30: The Prefect of Alessandria informed the Mayor of Coniolo Monferrato that the buildings in the built-up area of Cascina dei Frati are in imminent danger of collapse.	[41]
1960/01/29	Coniolo Monferrato Municipality, 1960/01/29: First four families relocated from Cascina dei Frati village.	[41]
1962/02	Coniolo Monferrato Municipality, 1962/02: Though the stability of houses in Cascina dei Frati village was increasingly compromised, the residents opposed the move to Morano sul Po, both because of logistics and because the new homes were not granted but would have to be purchased.	[41]
1962/04/04	Coniolo Monferrato Municipality, 1962/04/04: The Prefect informed the mayor that the assignees of the new houses in Morano sul Po, having not occupied the houses by the deadline, were to be considered renunciates and, therefore, the houses would be reassigned to other people, including other municipalities.	[41]
1974/06	Regione Piemonte, Assessorato Viabilità e Trasporti, Settore Opere Pubbliche e Difesa Assetto Idrogeologico, 1974/10/18: A regional commission noted that the buildings in Cascina dei Frati were less severely damaged than those in Coniolo Rotto, which had already been demolished. Almost none of the restored buildings showed reopened fractures. This was attributed to the suspension of excavation about 15 days before and the subsequent settling of unstable slopes. A few new fractures that had appeared in roadways and in the outer walls were thought to be due to the late settling of soil and not to the development of new collapse structures.	[46]
1991	Regione Piemonte, Settore Prevenzione del Rischio Geologico, Meteorologico e Sismico, 1991: The Mayor of the Municipality of Coniolo filed a petition seeking a review of the transfer lien on Cascina dei Frati.	[46]

Table A2. *Cont.*

Date	Original Source, Date of the Document, News	Source
1993/05/18	Regione Piemonte, Settore Prevenzione del Rischio Geologico, Meteorologico e Sismico, 1993/05/18: It was deemed that the constraint of transfer would remain unchanged.	[46]
1993	Scientific publication by CNR IRPI of Turin and the Geological Service of the Piedmont Region on Italian Law 445 of 1908: Provided for relocation or consolidation of unstable settlements in Piedmont for reasons related to floods or landslides. The authors compiled data sheets with geological and historical data and detailed cartography (Figure 9).	[46]

References

1. Sethi, R. Introduction to the Conference "Le Attività Minerarie Nella Storia". Politecnico di Torino. 2018. Available online: www.diati.polito.it/miniere2018 (accessed on 11 October 2023).
2. De Vries, J. The Industrial Revolution and the Industrious Revolution. *J. Econ. Hist.* **1994**, *54*, 249–270. Available online: http://www.jstor.org/stable/2123912 (accessed on 3 January 2024). [CrossRef]
3. Mokyr, J.; Strotz, R.H. The second industrial revolution, 1870–1914. In *Storia dell'economia Mondiale*; Editori Laterza: Bari, Italy, 1998; pp. 1–18.
4. Dean, T. The towns of Italy in the later Middle Ages. In *The Towns of Italy in the Later Middle Ages*; Manchester University Press: Manchester, UK, 2013.
5. Dulias, R. Introduction. In *The Impact of Mining on the Landscape*; Environmental Science and Engineering; Springer: Cham, Switzerland, 2016. [CrossRef]
6. Styles, P.; Toon, S.; Branston, M.; England, R.; Thomas, E.; Mcgrath, R. High resolution microgravity investigations for the detection and characterisation of subsidence associated with abandoned, coal, chalk and salt mines. In Proceedings of the Conference: Post-Mining 2005, Nancy, France, 16–18 November 2005; 12p.
7. Culshaw, M.G.; McCann, D.M.; Donnelly, L.J. Impacts of abandoned mine workings on aspects of urban development. *Mining Techn.* **2000**, *109*, 132–139. [CrossRef]
8. Mancini, F.; Stecchi, F.; Zanni, M.; Gabbianelli, G. Monitoring ground subsidence induced by salt mining in the city of Tuzla (Bosnia and Herzegovina). *Environ. Geol.* **2009**, *58*, 381–389. [CrossRef]
9. Marschalko, M.; Yilmaz, I.; Kubečka, K.; Bouchal, T.; Bednarik, M. Utilization of ground subsidence caused by underground mining to produce a map of possible land-use areas for urban planning purposes. *Arab. J. Geosc.* **2015**, *8*, 579–588. [CrossRef]
10. Machowski, R.; Rzetala, M.A.; Rzetala, M.; Solarski, M. Geomorphological and Hydrological Effects of Subsidence and Landuse Change in Industrial and Urban Areas. *Land Degr. Develop.* **2016**, *27*, 1740–1752. [CrossRef]
11. Solarski, M.; Machowski, R.; Rzetala, M.; Rzetala, M.A. Hypsometric changes in urban areas resulting from multiple years of mining activity. *Sci. Rep.* **2022**, *12*, 2982. [CrossRef] [PubMed]
12. Crane, W.R. *Subsidence and Ground Movement in the Copper and Iron Mines of the Upper Peninsula, Michigan*; U.S. Department of Commerce-Bureau of Mines: Washington, DC, USA, 1929. Available online: https://digital.library.unt.edu/ark:/67531/metadc38772/ (accessed on 3 November 2023).
13. Allen, C.W. Subsidence resulting from the Athens system of mining at Negaunee, Michigan. *Proc. Am. Inst. Min. Met. Eng.* **1934**, *109*, 195–202.
14. Rice, G.S. Ground movement from mining in Brier Hill Mine, Norway, Michigan. *Proc. Am. Inst. Min. Met. Eng.* **1934**, *109*, 118–152.
15. Allen, A.A. Basic Questions Concerning Coal Mine Subsidence in the United States. *Environ. Eng. Geosc.* **1978**, *xv*, 147–161. [CrossRef]
16. Wood, C.; Renfrey, G.J. The Influence of Mining Subsidence on Urban Development of Ipswich, Queensland. *Int. Soc. for Soil Mech. Geotech. Eng.* **1975**, 4–9.
17. Bell, F.; Stacey, T.; Genske, D. Mining subsidence and its effect on the environment: Some differing examples. *Environ. Geol.* **2000**, *40*, 135–152. [CrossRef]
18. Bell, F.G.; Donnelly, L.J.; Genske, D.D.; Ojeda, J. Unusual cases of mining subsidence from Great Britain, Germany and Colombia. *Environ. Geol.* **2005**, *47*, 620–631. [CrossRef]
19. Cui, X.; Gao, Y.; Yuan, D. Sudden surface collapse disasters caused by shallow partial mining in Datong coalfield, China. *Nat. Hazards* **2014**, *74*, 911–929. [CrossRef]
20. Pan, Z.; Jiang, X.; Lei, M.; Guan, Z.; Wu, Y.; Gao, Y. Mechanism of sinkhole formation during groundwater-level recovery in karst mining area, Dachengqiao, Hunan province, China. *Environ. Earth Sci.* **2018**, *77*, 799. [CrossRef]
21. Sahu, P.; Lokhande, R.D. An Investigation of Sinkhole Subsidence and its Preventive Measures in Underground Coal Mining. Global Challenges, Policy Framework & Sustainable Development for Mining of Mineral and Fossil Energy Resources (GCPF2015). *Procedia Earth Planet. Sci.* **2015**, *11*, 63–75.

22. ISPRA. Indicatori Ambientali 2018. Available online: https://indicatoriambientali.isprambiente.it/sys_ind/76 (accessed on 21 May 2023).
23. Bell, F.G. The influence of subsidence due to present day coal mining on surface development. *Geol. Soc. Eng. Geol. Spec. Publ.* **1987**, *4*, 355–367. [CrossRef]
24. Suing, W. On the mechanism and process of slope deformation in an open mine. *Rock Mech.* **1981**, *13*, 145–156.
25. Malgot, J.; Baliak, F.; Čabalová, D. Influence of slope movements on the exploitation of mineral resources. In *Proceedings Progressive Trends in Engineering Geology Investigations, Bratislava*; 1986; pp. 169–178.
26. Rozsypal, A. Problems of prognosis of slope deformation of open pit mines. In Proceedings of the 5th International symposium on landslides, Laussane, Switzerland, 10–15 July 1988; Volume 5, pp. 1233–1236.
27. Marschalko, M.; Hofrichterova, L.; Lahuta, H. Utilization of geophysical method of multielectrode resistivity measurements on a slope deformation in the mining district. In Proceedings of the 8th International Multidisciplinary Scientific GeoConference Survey, Geology, Ecology and Management SGEM, Sofia, Bulgaria, 16–20 June 2008; Volume 1, pp. 315–324.
28. Marschalko, M.; Fuka, M.; Treslin, L. Measurements by the method of precise inclinometry on locality affected by mining activity. *Arch. Min. Sci.* **2008**, *53*, 397–414.
29. Gutierrez, F. Sinkhole Hazards 2016. Oxford Research Encyclopedia of Natural Hazard Science. Available online: https://oxfordre.com/naturalhazardscience/view/10.1093/acrefore/9780199389407.001.0001/ (accessed on 10 February 2024).
30. Gutiérrez, F.; Cooper, A.H.; Johnson, K.S. Identification, prediction, and mitigation of sinkhole hazards in evaporite karst areas. *Environ. Geol.* **2013**, *70*, 1463–1478. [CrossRef]
31. Malinowska, A.; Matonóg, A. Sinkhole hazard mapping with the use of spatial analysis and analytical hierarchy process in the light of mining-geological factors. *Acta Geodyn. Geomater.* **2017**, *14*, 159–172.
32. Chen, J. Karst collapse in cities and mining areas, China. *Environ. Geol. Water Sci.* **1988**, *12*, 29–35. [CrossRef]
33. Brinkmann, T.; Scholles, C.; Wind, J.; Wolff, T.; Dengel, A.; Clemens, W. Processing of coal mine gas with low methane concentrations for use in high-temperature fuel cells. *Desalination* **2008**, *224*, 7–11. [CrossRef]
34. Xua, J.; Heb, J.; Zhang, L. Collapse prediction of karst sinkhole via distributed Brillouin optical fiber sensor. *Measurement* **2017**, *10*, 68–71. [CrossRef]
35. Strzałkowski, P. Sinkhole formation hazard assessment. *Environ. Earth Sci.* **2019**, *78*, 9–17. [CrossRef]
36. ISTAT. Available online: https://www.istat.it/ (accessed on 5 March 2024).
37. ARPA Piemonte. Available online: https://webgis.arpa.piemonte.it/geodissesto/eventi/eventi.php (accessed on 25 February 2024).
38. Miniere d'Italia. Available online: https://sites.google.com/view/miniere-italia/regioni/piemonte/marna-da-cemento (accessed on 12 September 2023).
39. Lovari, D. *Giacimenti Calcareo-Marnosi Delle Colline di Casale Monferrato ed Alcuni Cenni Sulla Loro Utilizzazione per la Produzione della Calce Idraulica e del Cemento*; Ministero di Agricoltura, Industria e Commercio, Ispettorato delle Miniere: Roma, Italy, 1912; pp. 5–50.
40. Montrasio, A.; Premoli Silva, I.; Ragni, U. Osservazioni geologico-stratigrafiche sulla regione compresa fra Casale Monferrato, Vignale, Alfiano Natta e Gabiano. *Boll. Soc. Geol. It.* **1968**, *87*, 581–609.
41. Comune di Coniolo. *La Storia Mineraria di Coniolo*; Tipografia La Nuova Operaia: Coniolo, Italy, 2004; 156p.
42. Jackson, M.; Deocampo, D.; Marra, F.; Scheetz, B. Mid-Pleistocene pozzolanic volcanic ash in ancient Roman concretes. *Geoarchaeology* **2009**, *25*, 36–74. [CrossRef]
43. Gino, E. *Le Complesse Relazioni Fra L'uomo e L'ambiente Stretto Fra Esigenze di Sfruttamento e Salvaguardia*; Piemonte Parchi: Torino, Italy, 2011; 33p.
44. Frixa, A. Marne del Monferrato Casalese: Significato Geologico. In *Convegno "Marne del Monferrato Casalese-Pietra da Cantoni e Marna da Cemento fra Passato e Presente"*; Ist. Leardi: Casale Monferrato, Italy, 2011.
45. Martinotti, R. Private letter. In *Atlante dei Centri Abitati Instabili Piemontesi*; Luino, F., Ramasco, M., Susella, G., Eds.; Regione Piemonte: Torino, Italy, 1994; 246p.
46. Luino, F.; Ramasco, M.; Susella, G. *Atlante dei Centri Abitati instabili Piemontesi*; GNDCI CNR; Regione Piemonte: Torino, Italy, 1994; 246p.
47. Comune di Camino. Historical documents found in the historical archives of the Municipality of Camino (Alessandria Province, Piemonte, Italy). CNR IRPI Archive.
48. SIFRAP Project. Sistema Informativo Frane in Piemonte. Available online: https://geoportale.arpa.piemonte.it/app/public/ (accessed on 11 August 2022).