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Industrial Remediation — Confinement Interventions: Installation of Sheet Piling in Compact and Rocky Formations

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Abstract: Implementation of containment or physical barrier interventions is a common measure in environmental engineering to ensure the safety of a contaminated site. This article aims to present a specific and tailored approach to technical solutions and constructability issues addressed at a former industrial site. As for the design, which was driven by specific site conditions, sheet piling and secant pile walls were chosen as containment technologies, whereas the confinement work was completed by the installation of the capping consisting of HDPE sheets, non-woven fabric (TNT), topped with gabions or reno mattresses. The adopted technical solutions required unique adjustments based on specific site constraints such as the high consistency of the subsoil, limited operational spaces and environmental impacts.

Key words: environmental engineering, geotechnical engineering, remediation-confinement, sheet piling

1. Introduction

AECOM Italia SpA was commissioned to design a confinement structure as part of a broader environmental project for the Operational Safety Measures (MiSO) of a former industrial site. The Site is located along a bank of a stream that recharges the aquifer contaminated by past industrial activities. The containment barrier was obtained by coupling different technologies such as sheet piles and secant piles. Given the site-specific geology — with the presence of lithoid blocks, compact formations, and a length of about 20 m — secant piles were adopted at the terminal sections of the alignment. The remediation project was completed by installing the waterproofing system on the site side riverbank (capping), comprising an HDPE sheet placed between two TNT sheets and covered by a gabion wall and Reno-type mattresses for an additional bank defense. The sheet pile wall primarily extends along the bank of a stream in lithologies, such as calcarenites and marls, that are generally unsuitable for that kind of technologies. Based on in-situ testing, the installation of sheet piles to a maximum depth of about 15 meters could have been achieved only with treatment of the ground. The barrier was completed with secant piles, diameter of 880 mm and maximum depth of 22 m, bored in the internal portion of the industrial site, both upstream and downstream of the groundwater flow, outside the streambed.

The described mixed solution, employing both sheet piling and secant piles, was driven by the numerous environmental, logistical and operational constraints. To apply the selected technologies and achieve the prescribed confinement, multiple construction methods and treatments were evaluated during design phase to enable the installation in compact and rocky horizons with limited space on-site for manoeuvring the machinery. Since the structure extends all along the mentioned stream, technologies using cement-based mixtures, such as plastic diaphragms walls, were not applicable due to site environmental constraints. Furthermore, the installation of mixing plants would have been

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particularly complex due to space limitations. In the terminal portion within the site, where hydraulic and operational constraints were no longer present, the barrier was completed through secant piles.

Fig. 1 Sheet piling installation area.

2. Material and Methods

The subsoil of the industrial site consists mainly of alluvial deposits made up of heterometric gravels and cobbles in a sandy-silty matrix, with occasional layers of finer silty-clayey deposits. These deposits have been identified at depths ranging from 9-10 meters below ground level on the eastern side of the site to approximately 25-30 meters b.g.l. on the western side. On the opposite bank of the industrial site, as the ground slopes down to the river, alluvial deposits can be found in alternation with heterogeneous colluvial debris.

The alluvial layer is found, with an erosional boundary, resting on top of the bedrock. The bedrock is composed of bioclastic limestones, which are moderately lithified and white in colour, interbedded with marly and calcareous-marly layers of greenish-gray colour.

The strata are generally characterized by a sub-horizontal bedding or a dip towards the SSE direction, with inclinations varying from a few degrees up to a maximum of 20°. These rock formations are characterized by numerous fractures and faults with various orientations, as suggested by the area's morphology, which features elongated ridges in a meridional direction.

Previous in-situ investigations revealed the presence of several sub-vertical faults and fractures, as well as highly tectonized and fractured rock horizons.

According to the geological framework described above, the alluvial aquifer rests either on an impermeable substrate in the northern part of the industrial site or, in the central and southern areas of the facility, on a substrate that may exhibit a variable degree of permeability depending on the degree of fracturing.

The permeable portions of the bedrock could lead to a secondary water circulation system. Unlike the main aquifer, fractures in the bedrock may serve as primary pathways for water entering the contaminated site.

The recharge of the aquifer within the permeable portions of the bedrock appears to be primarily driven by precipitation infiltration. In the fractured calcarenitic formation, seepage from surface watercourses or streams may provide a secondary recharge path.

The main aquifer identified within the alluvial unit is defined as a phreatic and unconfined aquifer. This aquifer exhibits a significant piezometric fluctuation, influenced by both seasonal cycles and meteorological events. Each phenomenon influences the water level with a seasonal fluctuation averaging 10-12 meters.

Nevertheless, the water level maintains a constant hydraulic gradient of about 1%.

The predominant groundwater flow direction is NNE-SSW.

The stream runs over alluvial deposits and colluvial debris being also fed by karstic springs, which are present along the riverbed in the northern part of the site, as well as by discharge waters from adjacent industrial sites.

Piezometers installed near the stream, along the length of the industrial site, show water levels that are 4-5 meters higher than those of piezometers located within the facility. Instrumentation installed in the industrial area exhibit rapid level fluctuations which are synchronized with the ones of stream. This confirms the presence of a discontinuity between the local hydrogeological system and the main valley hydrogeological system.

2.1 Stratigraphical Layout

The design stratigraphical layout of the industrial site can be summarized as follows:

- Alluvium consisting of sandy gravels with silt
- Fractured calcarenites (ranging from weakly to extremely fractured)
- Consistent silt
- Consistent clay/lithified marl.

Fig. 2 presents a stratigraphical section of the barrier alignment constructed within the streambed, where containment by sheet piling is shown in blue. As mentioned above, the in-situ geological investigations highlighted the consistent nature of the soils and rocks where the sheet pile wall is embedded. This was also confirmed by the results of the Standard Penetration Test (S.P.T.), which, in many cases, reached refusal. These results could not be attributed to a specific depth or geological unit but were distributed along the entire alignment of the sheet pile wall, particularly at greater depths.

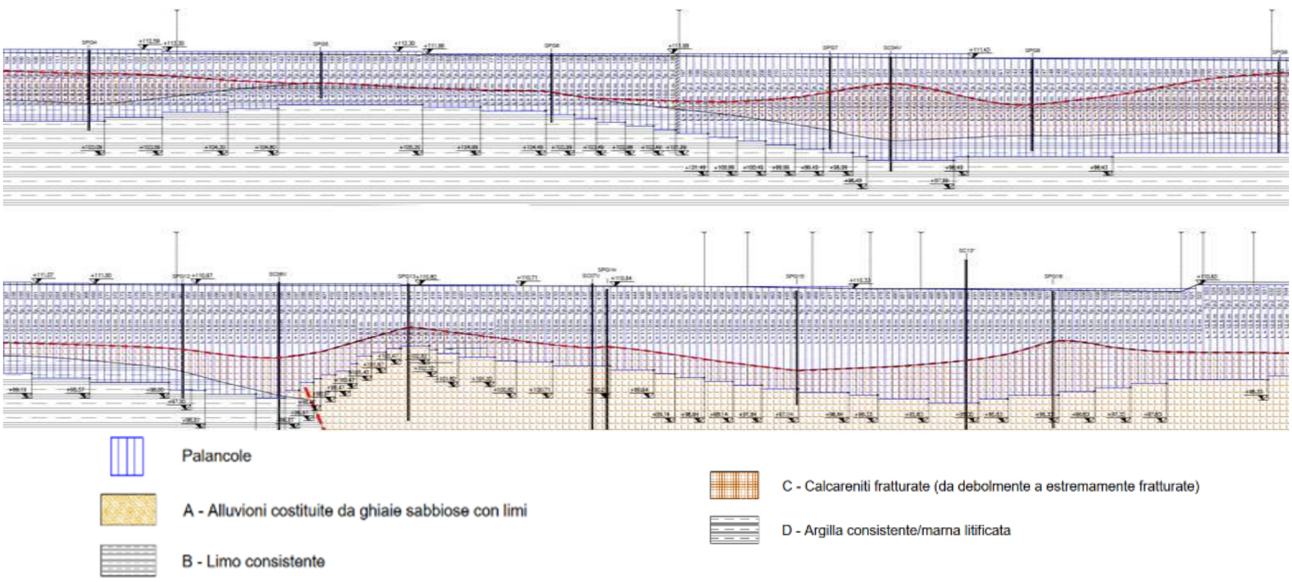

Fig. 2 Stratigraphy of the area — cross-section along the centerline of the sheet piling barrier.

3. Design Details

3.1 Sheet Piling

Sheet piling is typically installed by driving metal sheet piles into the ground.

For the designed barrier, metal profiles between 7 m and 19 m long were installed.

To instal sheet piles in a geologically unfavourable lithology, a specific solution was required to ease the driving of metal profiles into the ground.

Relief holes with variable diameters ranging from 300 to 600 mm were design as the most efficient answer to the problem.

The purpose of this technological approach is to facilitate the proper driving of the steel profiles. By adequately overlapping the excavated portions of the rocky formations to cover the entire profile of the sheet pile at depth, it is possible to create a preferential path through the disintegration of lithoid and/or rocky soils. Additionally, relief holes ease the installation of sheet piles through the initial alluvial layer, allowing access to the underlying substrates composed of marls and calcarenites.

For the project, two different layouts of relief holes were adopted:

- Diameter of 300 mm: the configuration is shown in Fig. 3 was used, creating five holes per sheet pile following the "Z" profile of the element.
- Diameter of 600 mm: where operational spaces were not limited, a bigger profile was drilled using a coated auger mounted on a machine with a double rotary head (Fig. 4).

Fig. 3 Relief holes: D300 mm – drilling phase.

Fig. 4 Relief holes: D600 mm — sheet pile installation.

Using a larger boring diameter reduces the number of holes needed per metal sheet (from five to three), while maintaining adequate overlap and minimizing the volume of spoil material produced by the drilling.

By employing this relief technique, it was also possible to achieve a reduction in terms of vibrational effects associated with driving the sheet pile wall into the ground.

3.2 Secant Piles

Secant piles were identified as the most suitable technology for completing the hydraulic containment barrier in the "Baffo Nord" and "Baffo Sud" areas, which are the terminal parts of the barrier located, outside the stream, respectively to the north and south of the site. The adopted layout consists of a secant pile wall made of bentonite mixture with a diameter of D880 mm.

This technology requires the use of a drilling machine (as shown in Fig. 5) equipped with an auger fitted with bits suitable for drilling rocky soils.

Fig. 5 Drilling machine for D880 mm secant piles.

By employing a powerful drilling machine, combined with a well-established construction technology for penetrating rocky lithotypes, as well as installing piles with considerable drilling diameters, a highly reliable containment barrier can be achieved by fulfilling design impermeability requirements.

The prescribed construction sequence is as follows:

1) Drilling of primary piles
2) Drilling of secondary piles.
3) Construction of piles using the designed mixture of water, cement, and bentonite tailored to the site-specific conditions. The unique blend of materials was defined after multiple laboratory trials and is composed of:

- Water
- Dispersant additive (type Dracrill 771)
- Bentonite (type Bentogel Y)
- Pozzolanic cement (type R42.5)

The mixture's composition will be given by the following weight variation ranges:

- Cement-to-water ratio: 0.25/0.30
- Bentonite-to-water ratio: 0.028/0.068
- Additives-to-water ratio: 0.0035/0.0045

The mixture volume will consist of an indicative additive weight of around 30% of the total (ranging from 1190 kg to 1230 kg per 1000 liters of mix), with the remaining 70% composed of water.

As the mixture dries after casting, its defined resistance ensures that secant piles drilling can be performed even after aging of the material.

The design permeability values for the mixture (about 10-8 m/s) allows the secant pile wall solution to function equivalently to the sheet piling alternative, effectively limiting groundwater flow between external systems and the site, as intended by the MISO project.

The mixture will be cast directly from the bottom of the hole during the upward phase to counteract possible wall collapses. This is achieved by supporting the bore thanks to the counter-pressure exerted by the mixture itself.

The resulting secant pile wall, as shown in Fig. 6 will have a verticality ratio of 0.5% and a minimum overlap of two adjacent piles of at least 40 cm.

3.3 Capping

The overall MISO project was completed by waterproofing the right bank of the river stream, which is adjacent to the industrial site, over a length of approximately 400 meters. The proposed sealing structure is composed of a capping layer, consisting of an HDPE membrane with a thickness of 1.5 mm, that is placed between two layers of non-woven geotextile (TNT) with weights of 400 g/m² and 1000 g/m², respectively.

The 400 g/m² geotextile is placed below the HDPE sheet and it is in direct contact with an already existing bank protection system (gabions and concrete lining installed by the owner of the site), while the 1000 g/m² geotextile is the protective layer above the HDPE sheet.

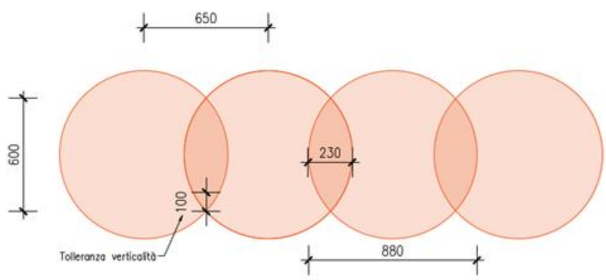

Fig. 6 Secant piles wall layout.

This external layer lies beneath the protective elements of the designed capping (gabions and Reno mattresses).

The capping system and the portion of the sheet piling barrier, which runs parallel to the stream, are connected via a reinforced concrete (RC) capping beam. The beam has a width of 60 cm and a variable height ranging from 60 cm to 120 cm; sheet piling is embedded directly into the capping beam.

On the top face of this beam, a specially designed HDPE labyrinth joint is installed, featuring an anchoring part embedded within the concrete and an external visible part (Fig. 7). The HDPE layer is then welded to the mentioned joint, with a minimum thickness of about 20 mm, to connect the waterproofing stratum to the capping beam.

Fig. 7 Capping connection to beam (left), final layout of the riverbank protection system (right).

To protect the capping layers installed on the existing bank, metallic gabions or Reno mattresses are placed above the waterproofing system. Through this technology reprofiling of the slope is achieved with local geometries adapted to the configuration of the bank. Different solutions were adopted for the covering, protection and waterproofing depending on the original condition/slope of the bank. The different applied options are:

- Lines of gabions (1 m × 1 m × 2 m)
- Reno mattresses (23 cm thick)

Cyclopean blocks (used for bank protection where the HDPE sheet was not installed).

3.3.1 Soil-Structure Interaction Analyses

To support and validate the design of the bank stabilization and protection structure, multiple analyses were carried out to define the best technical solution and eventually optimize the proposed layout.

3.3.2 Global Stability Analysis

This type of verification of the slope aims to define the stability conditions of the capping protection system, under both static and seismic conditions, by considering potential failure or slipping mechanisms:

- At the soil-capping interface (with slip surfaces of “generic” shape).
- Within the filling material between the capping and the gabions/Reno mattresses (characterized by “circular” slip surfaces).

3.3.3 Local Equilibrium Analysis

Local equilibrium analysis is performed to define the stability conditions of the capping system by referring to potential failure mechanisms at the defined location:

- Sliding along the installation plane of the gabions.
- Overturning of the gabions (assuming a “rigid body” behavior).

3.3.4 Stress-Strain Analyses

Stress-Strain analyses are conducted to estimate:

- The magnitude of horizontal displacements.
- The bending moment and the shear stresses that sheet piling and the reinforced concrete beam are experiencing due to the earth pressure applied by the backfill material as per the

design layout (filling/leveling and gabion placement).

3.3.5 Structural checks of the RC Beam

The structural integrity of the reinforced concrete (RC) beam located at the top of the sheet piling must be checked versus the internal forces deriving from the stress-strain analyses mentioned above.

3.3.6 Analysis and Verification of Tensile Stresses in the capping

Finally, the compatibility between the tensile stresses in the capping and the mechanical/strength features of the material must be verified. Acting forces are driven by the self-weight of each of the installed protective covering elements.

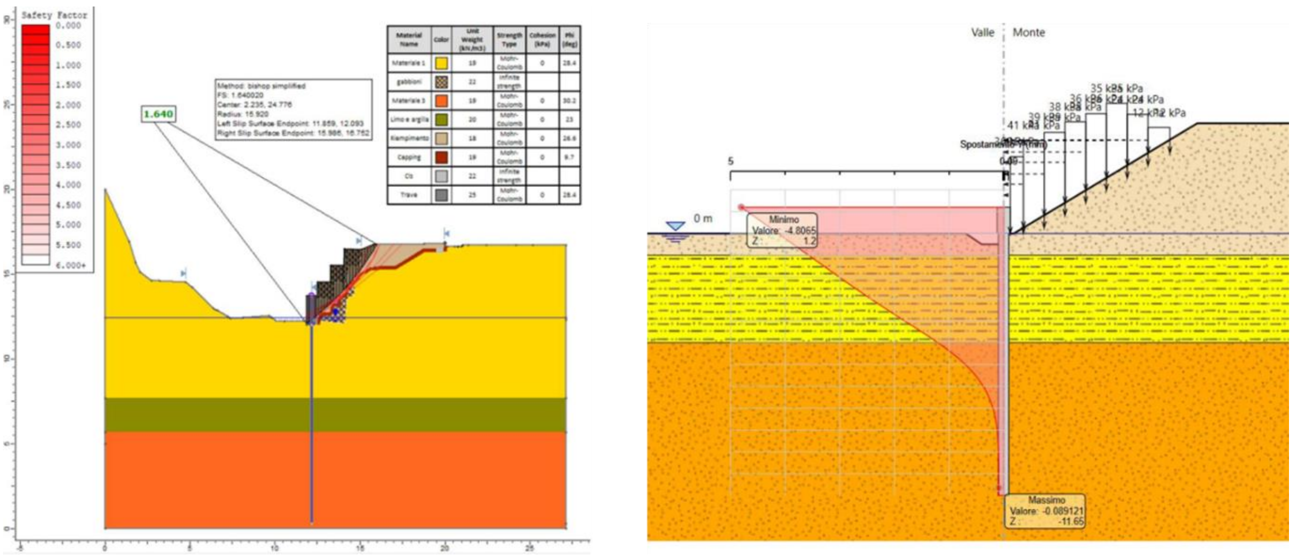

Fig. 8 Global stability analysis (left), overall horizontal displacement of the barrier (right).

4. Testing of the Containment Barrier

Given the specific features of the designed structure presents and the site-specific peculiarities that, in certain aspects, deviate from the usual practices, a tailored approach to testing was needed. For this reason, specific measurement methods were adopted during testing to verify parameters indicative of the correct installation of the sheet piles.

4.1 Driving Speed Test

A fundamental test to verify the correct installation of a sheet piles wall is the assessment of the driving speed. A testing strategy was defined consisting in measuring driving speed for one element every six installed metal sheets or, alternatively, one per day of driving.

The sheet piles subjected to the test were marked every 1 meter before installation into the ground to facilitate the survey of driving times.

To allow for easier measurements, a reference point was taken for each sheet pile (e.g., the ground level or another fixed marking point near the sheet), and the driving time was recorded every 1 meter. The output values of the described test were then compared with values found in the literature for similar soils. By identifying similarities or discrepancies between the values, it was possible to verify the quality of the installation process. If the measured descent time was excessively slow (greater than 30-40 seconds per meter), the driving process was stopped for a few minutes to allow the joint to cool down; after a defined time frame, installation was resumed until the design depth was achieved.

Achieving an optimal driving speed, not only indicates a correct installation process of the sheet piles but also ensures proper fluidization of the sealing joint (Akila® in this case) applied to the interlocks of each steel profile.

4.2 Verticality Tests

Since sheet piles naturally tend to tilt in the direction of driving due to the varying friction behaviour of the soil with depth, an additional planned test was to measure each day the verticality ratio of the last metal sheet installed. To ensure consistent results, the test was conducted when the selected element protruded about 2 meters from the ground. As per project's specifications, to avoid excessive friction during driving, a maximum tolerance of +/- 5% was deemed acceptable in the planimetric direction of the sheet pile alignment.

In cases where the measured verticality exceeded 5%, a special trapezoidal profile with the same was used to restore proper verticality; special segments were tested so to ensure performance characteristics as a normal sheet pile. In addition to the in-plane verticality check, an out-of-plane verification was also performed using a removable probe inserted into a guide tube welded to the sheet pile before the installation. The probe consisted of a cylindrical body, equipped with two inclinometers placed along two mutually orthogonal directions, and two carriages, each fitted with two rolling wheels.

After the sheet pile was driven in place, the out-of-plane inclination of the profile was measured.

4.3 Connection Tests

The continuity of the sheet pile wall is a basic topic to be tested because it ensures the watertightness of the barrier. Impermeability is ensured by the connection between adjacent sheet piles, and it is achieved through the geometric interlocking of the terminal interlocks of each individual profile. In this case, this characteristic was verified through a connection test (referred to as the "anti-disconnection test") was put in place. This specific approach was designed to check the correct driving procedure and provide objective confirmation of the occurred sliding between the two connected interlocks.

The test, specifically designed for the site-specific conditions, consisted in the installation of a first sheet pile equipped with several steel cable guides; through those guides, a steel cable was inserted. At the end of the cable, a mechanical anchor with an eyelet was attached; the anchor was and positioned at the terminal section of the interlock. When the interlock of the adjacent sheet pile reached the base of the equipped sheet pile during driving, it was expected to contact the mechanical anchor. As driving continued, the mechanical anchor was expected to be pulled down, causing the steel cable to move downward. This movement was measured at the top of the sheet pile by the displacement of a marker previously applied marker.

The displacement of the mentioned marker at the top of the sheet pile is the needed evidence of the actual connection of the two interlocks.

5. Conclusion

By drilling relief holes of various diameters and employing different excavation techniques, the confinement barrier was successfully installed using steel sheet piles in compact, rocky stratigraphic layers. By coupling sheet piling with secant piles, the project met all defined specifications and was tested by the client to ensure compliance with design requirements for watertightness and streambed bank protection.

The unique site constraints, combined with the unfavourable geological conditions for driving sheet piles, required a tailored application of an alternative and unconventional approach to testing. In particular, the connection test required a dedicated solution to confirm the successful connection between two successive elements.

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