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Stability analysis for the rehabilitation of a wastewater treatment plant on cohesive soils in the Troina area (South-Italy)

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ABSTRACT: The study deals with a numerical analysis applied to the rehabilitation of the wastewater treatment plant in Troina town (Province of Enna, Sicily, Italy) which had been experiencing displacements of approximately 8 to 10 cm. A detailed geotechnical characterization of cohesive soils of the subsurface through in situ and laboratory tests has been performed to define a geotechnical model. Using PLAXIS 3D software, the case study was modelled, and the stability assessment was conducted to determine the displacements measurements and the factor of safety. Based on the results, geotechnical reinforcement solutions were designed using high-capacity micropiles to enhance structural stability and control potential displacement of the structure. The findings provide a useful approach for the rehabilitation of structures and offer practical guidelines for implementing reinforcement solutions in infrastructure projects on saturated cohesive soils.

KEYWORDS: Numerical stability analysis, displacements, cohesive soils, micropiles, geotechnical characterization.

1 INTRODUCTION

The wastewater treatment plant located in Contrada Schiddaci, near Troina (Enna, Sicily), as shown in the Figure 1, serves approximately 7,000 inhabitants. In 2018, the plant was reported to be experiencing horizontal displacements of about 8-10 cm in the sedimentation tank structure, primarily directed westward. This prompted an urgent need to investigate the underlying causes of the instability and propose a technically sound rehabilitation solution.

This report outlines the project for the renovation and upgrading of the treatment plant, focusing on the works necessary to restore the geotechnical stability of the treatment units. The study was carried out to identify the necessary interventions for renovating the existing structures and upgrading the plant for operation, in accordance with discharge limits imposed by Legislative Decree No. 152/06.

Figure 1. Territorial framework of the purification plant in Troina Contrada Schiddaci in the province of Enna (Sicily, Italy).

2 GEOTECHNICAL INVESTIGATION

2.1 *Site Investigation*

To analyze the phenomenon, it was necessary to carry out the following in-situ tests and geophysical surveys: a) three boreholes with depths up to 20 m with continuous coring, four undisturbed sample extractions, and two Standard Penetration Tests (SPT); b) one piezometer needed to measure how groundwater could be affecting the foundations of the structure; c) one MASW (Multichannel Analysis of Surface Waves) based on the recording and analysis of Rayleigh waves in a stratified half-space. From shear wave measurements and velocity profiles, a shear wave velocity (V_s) value of 380.53 m/s was obtained.

2.2 *Laboratory tests*

The four undisturbed samples were taken (two from Borehole 1 and two from Borehole 2) and tested at the University of Enna "Kore" laboratory. The following tests were performed:

- Sample identification and description.
- Atterberg limits.
- Granulometry (grain size analysis).
- Direct shear tests at 100, 200, and 300 kPa.
- Ring shear at 100, 200, and 300 kPa.

All laboratory procedures were carried out in accordance with international standards (UNI EN ISO 17892 series for soil identification and mechanical testing; ASTM D422 for grain size distribution; ASTM D1586 for SPT execution and corrections). In this study, the term fines refers to the soil fraction passing the 0.063 mm sieve, in accordance with UNI EN ISO 14688.

2.3 *Loads*

For the geotechnical analysis, it is necessary to calculate the loads or pressures to which the structure being analyzed is subjected. Therefore, from the load analysis of the existing state, the pressures to which the soil has been subjected for years (without any type of reinforcement) were calculated: the biological oxidation tank, the secondary sedimentation tank, the disinfection channel, the aerobic digestion unit, the scraper bridge, as well as the internal walls of the structure, obtaining a bottom pressure that acts throughout the foundation area of the tank.

Similarly, the water exerts lateral pressure on the walls of the tank, which was also taken into account in the analysis, as shown in Figure 2.

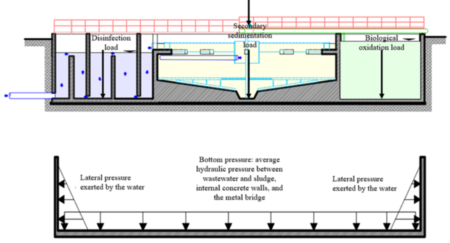

Figure 2. Pressures considered for calculating loads in the tank.

3 GEOTECHNICAL CHARACTERIZATION

3.1 *Stratigraphic sequence*

The results of the in-situ and laboratory tests were used to define the stratigraphic sequence and subsequently create stratigraphic profiles that allow for the subsequent definition of geotechnical properties, which serve as the basis for the geotechnical analyses.

Table 1 shows the results of laboratory tests with the variation of: fines content (FC), natural water content (ω), plastic index (PI), liquid limit (LL) and standard penetration (N_{60}), of each geotechnical unit from 2 to 4 (silty clays).

Based on the results of the laboratory and in-situ tests, the following stratigraphic sequence was derived, identifying four main geotechnical units, shown in Figure 3 and described below:

1. Unit 1: A surface fill layer, typically ranging in thickness from 1.8 to 2.0 m. It consists of brown sand.
2. Unit 2: It is located immediately beneath Unit 1, extending to approximately -6.0 meters below ground level. One section is composed of silty clay with sandy intercalations, olive-green in color, locally organic, interspersed with centimetric and millimetric inclusions of argillite; and another section contains, interspersed with sections of fine sand, ranging from slightly firm to firm with a flaky texture and very dark gray in color. Alterations and organic matter are present.
3. Unit 3: It is located beneath Unit 2 and extends from -11.0 m. It consists of clayey silt with occasional gravel and sand and olive-gray in color. Slight weathering and organic matter are present.
4. Unit 4: It lies beneath Unit 3 and consists of silty clay interspersed with fine-grained sand lenses measuring millimeters in size, with a scaly texture, ranging from firm to soft and dark olive gray in color. Intercalations and millimetric and centimetric lenses of gypsum inclusions are present.

Table 1. Laboratory test results: fines content, natural water content, plastic index, liquid limit and stroke number.

Geotechnical Unit	FC (%)	ω (%)	LL (%)	PI (%)	N_{60}
Unit 2	47-74	17-19	32-39	9-11	13
Unit 3	63	16	36.25	13.68	-
Unit 4	78.15	13	39	13.97	29

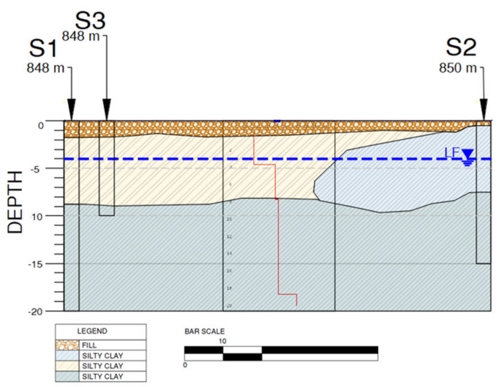

Figure 3. Stratigraphic profile of the study point

4 NUMERICAL MODELING

The information obtained was used to prepare the stability analyses, for this purpose, PLAXIS 3D software was used. It is suitable for selecting soil/rock constitutive models in numerical analyses and for assessing the effects on structures to simulate the interaction between structure and soil under the influence of landslides and settlement.

In this study, the Mohr-Coulomb (MC) constitutive model was adopted to simulate soil behavior in the PLAXIS 3D analysis, this model offers several practical advantages. Table 2 summarizes the geotechnical parameters adopted in the numerical model as: unit weight (γ), Young's modulus (E), and Poisson's ratio (ν), cohesion (c); which are typically available from standard laboratory and field tests. It is especially suitable for preliminary design phases and global stability assessments, where a first-order approximation of soil behavior is sufficient to evaluate potential failure mechanisms and deformation patterns.

Table 2. Geotechnical parameters adopted in PLAXIS 3D (Mohr-Coulomb model).

Geotechnical Unit	γ (kN/m^3)	E'_{ref} (kN/m^2)	ν′	c'_{ref} (kPa)
Unit 2 (CL)	20	4875	0.35	75
Unit 3 (CL_1)	19	5200	0.40	80
Unit 4 (CL_2)	21	11050	0.45	170

However, the model presents several limitations. It assumes perfectly elastic–plastic behavior and does not account for the non-linear stiffness degradation or stress-strain dependency observed in real soils. Additionally, it is not appropriate for simulating time-dependent processes, such as creep or primary and secondary consolidation, which are especially relevant in saturated cohesive soils. Because of these simplifications, the model tends to underestimate settlements and cannot simulate strain-softening or hardening behaviors, which may be critical in some foundation or slope stability problems.

In this case, stability analysis was chosen, which will determine the displacements and factor of safety in the existing state (which would correspond to the current state) and in the design state, after entering the proposed solution into the software. The numerical analysis was carried out through staged construction, including: (i) generation of initial stresses, (ii) application of structural loads corresponding to the existing condition, (iii) calculation of displacements, (iv) introduction of micropile elements, and (v) safety analysis using the strength reduction method.

4.1 *Analysis without renovation works*

4.1.1 *Detected displacements*

The analysis in the current condition yielded horizontal displacements exceeding 1.7 m, as can be seen in Figure 4, predominantly in the westward direction, which correlates with the direction of movement observed in the field. These displacements can be attributed primarily to long-term undrained shear deformation of the saturated cohesive soil layers, particularly Units 3 and 4.

The displacements likely developed gradually as a result of progressive loading from the structure over time, without prior geotechnical reinforcement or drainage control. Given the saturated and low-permeability nature of the soil, consolidation settlements also contributed to the movement, particularly under the static load of the sedimentation tank.

Therefore, the failure mechanism is interpreted as a combination of creep-induced lateral translation and global instability, typical of plastic clay formations under long-term loading.

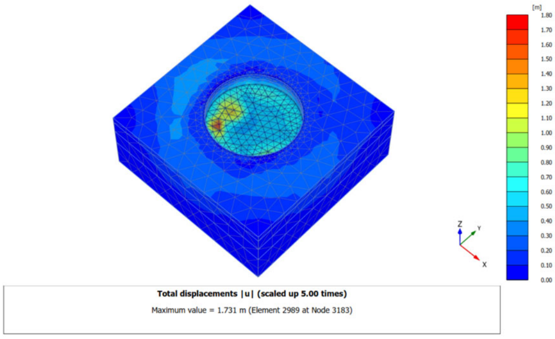

Figure 4. Result of the displacements found in the analysis carried out in PLAXIS 3D.

4.2 *Failure mitigation*

To resolve the landslide and the displacement of the basin, it was decided to use micropiles. Micropiles are deep foundation elements with high compressive load-bearing capacity that transfer loads to the ground at depth.

To perform the analysis, it is therefore necessary to select the dimensions of the micropiles. It was indicated that for the machine used in-situ, it is most effective to use micropiles with a diameter of 600 mm, with a length up to the most resistant layer of approximately 12 m.

4.2.1 *Micropile load capacity*

The geotechnical bearing capacity of the micropile was calculated by considering both resistance mechanisms provided by the soil: lateral friction and toe resistance.

Various methodologies have been proposed for estimating pile bearing capacity for both lateral friction and toe resistance, Figure 5 presents the results from each method.

Unit base resistance was estimated using Nq factors following Meyerhof (1976), Decourt (1995), and the Canadian Foundation Manual and API recommendations, with conservative values under limiting stress conditions. Shaft resistance was calculated using the β-method for granular and cohesive soils, the α-method for cohesive soils (USACE; Randolph & Murphy, 1985), and the λ-method by Flaate and Selnes (1977).

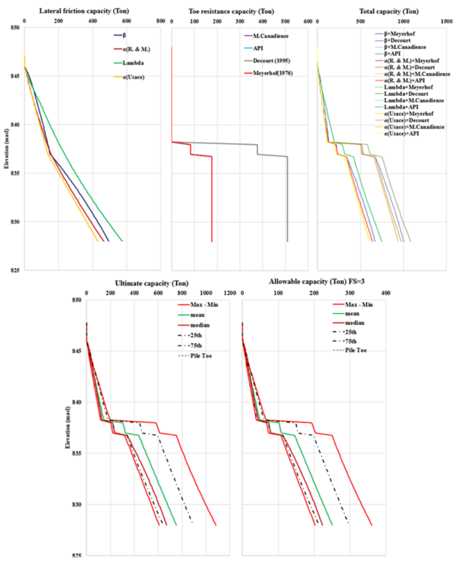

Figure 5. Calculation of the bearing capacity of the micropiles: 1) lateral friction, 2) toe resistance, 3) total capacity for micropiles. And the statistical analysis was conducted on 16 possible ultimate capacities, resulting in maximum, minimum, average, and 25th and 75th percentile values of: 4) the ultimate bearing capacity and 5) allowable bearing capacity.

4.3 *Rehabilitation of the wastewater treatment plant*

After analyzing the lateral friction, toe resistance, and ultimate bearing capacities of the micropiles to be used with the present soil type, this data was entered into the program; in this case, it was entered with a 45-degree inclination (Figure 6).

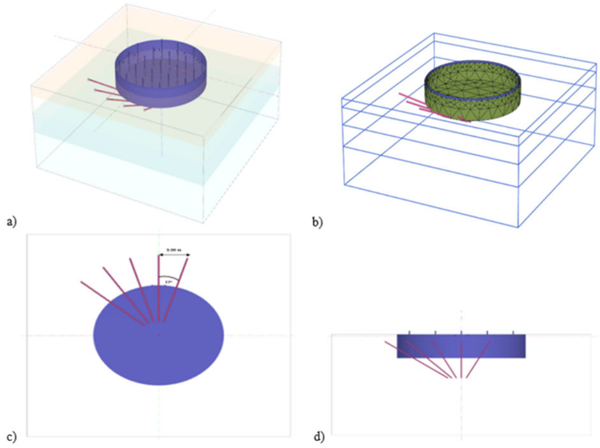

Figure 6. Micropile positioning configuration a) 3D stratigraphy, b) 3D mesh, c) plan, d) profile views.

4.3.1 *Detected displacements with the micropile solution*

Following the analyses, admissible values for structural performance were obtained, as illustrated in Figure 7.

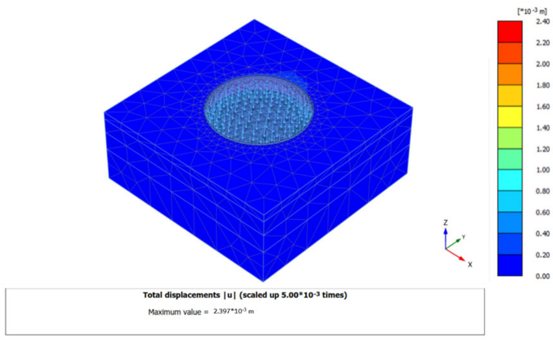

Figure 7. Displacement results from the PLAXIS 3D.

The implementation of inclined micropiles led to a significant improvement in the load distribution and overall soil-structure interaction. By transferring structural loads to deeper, stiffer layers (particularly Unit 4) the micropiles effectively bypassed the soft, compressible intermediate strata, thereby reducing consolidation and shear strains. This vertical load transfer mechanism, commonly known as “load shedding” refers to the ability of deep foundations to redirect stresses away from weaker soils and into more competent layers, improving system performance (Poulos & Davis, 1980; Randolph & Wroth, 1979).

The 45° inclination of the micropiles further enhanced lateral stability by mobilizing passive resistance along the direction of movement, countering the westward displacement of the sedimentation tank. The combined effect of depth, inclination, and group arrangement led to a substantial reduction in horizontal displacements, from over 1.7 m in the unreinforced condition to less than 2 cm in the reinforced configuration. Moreover, the increased shear resistance at the soil-structure interface contributed to a more robust global stability of the system.

4.3.2 *Calculation of the factor of safety (FS)*

It is useful to evaluate a global factor of safety for the problem. The reduction of strength parameters is controlled by the total multiplier ΣM_{sf}. This parameter is incrementally increased in a step-by-step procedure until failure occurs. The factor of safety is then defined as the value of ΣM_{sf} at failure, provided that a more or less constant value is obtained across a number of consecutive load steps.

The most effective way to evaluate the factor of safety is by plotting a curve where the ΣM_{sf} parameter is graphed against the displacements of a specific node. Although the displacements themselves are not critical, they indicate whether a failure mechanism has developed.

For this case study, the resulting factor of safety value was greater than 3 (Figure 8).

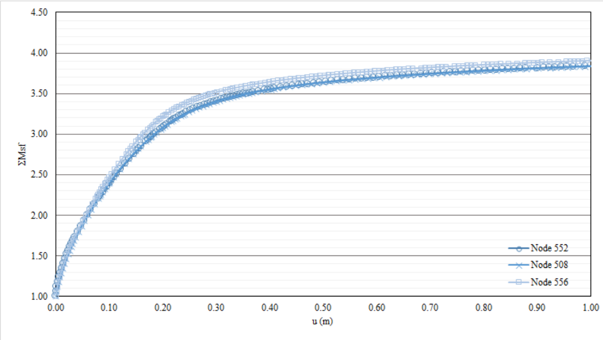

Figure 8. Evaluation of the factor of safety obtained in the nodes located at the foot of the tank.

5 CONCLUSIONS

The rehabilitation of the Troina wastewater treatment plant highlighted the critical role of geotechnical investigation and numerical analysis. The integrated approach of in-situ and laboratory testing, combined with 3D modelling, enabled a detailed understanding of subsurface conditions and failure mechanisms.

Where the soils were classified as slightly plastic to moderately plastic clays and silts, with low to medium compressibility. Based on these parameters, the soil profile was stratified into four geotechnical units for numerical modelling.

The fine element model accounted for: a) actual geometry and weight of the structure; b) subsoil stratigraphy and properties; c) initial stress state from in-situ conditions; d) water table at 4.0 m depth. Initial analysis confirmed displacements in the west direction, reaching over 1.7 m under the assumed boundary and loading conditions-consistent with field observations.

The site inspection revealed a translational displacement of the sedimentation tank of approximately 8 to 10 cm. Along the same sliding band, lateral wall displacement was also observed, likely caused by the same movement affecting the treatment plant

To improve stability, a reinforcement solution was proposed using inclined high-capacity micropiles (diameter: 600 mm; inclination: 45°; length: 12 m; disposition: symmetric around the tank). Micropiles were analyzed using empirical methods and verified in the numerical model. And the end, micropile reinforcement provided an effective solution to stabilize the structure and prevent further displacements, because after introducing micropiles into the PLAXIS 3D simulation was found that the maximum displacements reduced to <2 cm and the Factor of Safety (FS) increased to above 3.0.

This case study offers valuable insight into addressing similar challenges in cohesive soils and provides practical guidance for the use of PLAXIS and micropile systems in infrastructure rehabilitation.

6 ACKNOWLEDGEMENTS

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