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Small diameter jacked piles to stop long lasting differential settlements on fine peaty soils

Usage des micropieux à pousser pou arrêter les tassements différentiels dans les sols fins organique

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ABSTRACT: The paper describes a successful application of slender jacked piles to underpin a residential building, having a compact and regular r.c. structure with open ground floor, two stories and a top loft for ten apartments. Settlements were noticed at finishing of the structure (2007) when a rotation of the stiff r.c. foundation slab was detected; they have continued ever since and today the differential settlement is 0.28 m. Soil investigation showed layers of very soft clays, peat, organic clays, silty clays, to depths of 27-30 m. The eleven steel pipe piles, 114.3 mm o.d., have been placed along the shorter side of the slab, where the largest settlements occur, and jacked to depths of 27-30 m into a firm sand layer. Two piles have been equipped with a load cell to register load increase with time; presently tilting has stopped and a slight recover is measured.

RÉSUMÉ: L'article illustre l'usage des micropieux pur arrêter les tassements différentiels d'un bâtiment résidentiel. Le bâtiment a une forme régulière avec quatre étages au dessus du sol éd dix appartements au dessus du rez-de-chaussée pour garage. Les tassements ont commencé pendant la construction de la fondation (2006) et ont continué jusqu'à aujourd'hui. Les sols de fondation sont des argiles molles, tourbes, argiles tourbeuses, limon-argileuses. Les micropieux sont positionnés dans le côté court de la maison où l'affaissement sont plus grands. Les micropieux (diamètre 114.3 mm) sont longues 27-30m et ils s'appuient sur un sable dense. Deux micropieux sont instrumentés pour monitoire la charge sur la tête, la rotation du bâtiment a cessé.

Keywords: peaty clays; differential settlements; underpinning; jacked piles

1 INTRODUCTION

In recent years an increasing variety and number of residential and industrial buildings has began suffering from serviceability limit states; they are typically related to differential settlements and angular distortions. The origin of such SLS can be traced back to the extensive use of land, pushing the need to exploit also geologically complex areas with difficult subsoil conditions, the development of special materials that make it possible to adopt and construct newer and challenging architectural solutions, transmitting sever loads to the foundations, the depletion of groundwater and the severe climate changes.

Thus, a variety of remediation techniques has become available (Bullivant 1996); essentially they may be grouped in two classes; those aimed at improving the mechanical properties of soils and rocks, such as their strength and stiffness, as may occur injecting chemical resins or cement grout at low or high pressures; those based on the installation of structural elements to anchor, underpin, or support the construction.

In any case, the selection of the most effective and efficient remediation solution will depend on local soil conditions, characteristics of the structure, origin and nature of the SLS, available working space and local experience.

This paper presents an application of jacked micropiles to partially underpin a residential building suffering from long lasting settlements. Despite the building is relatively compact and only four story high, tilting began soon after the foundation was set (September 2006), and has continued rigidly ever since, with no cracks.

Underpinning has been attained with eleven micropiles (114.3 mm) pushed through soft clays and peaty soils into a bearing sand layer at depths of 27-30 m. These slender piles have been placed along one side only of the stiff slab foundation, where settlements are greater; they aim at reducing the rate of increase of the rotation and possibly to halt the differential settlements. If successful, partial underpinning might even produce a slow recover of the tilting suffered by the building. In any case, in future this partial underpinning might be extended to the entire foundation, if necessary.

2 MORPHOLOGY AND GEOLOGY

The residential building is located in the North-Eastern outskirt of Salorno, a small rural village near the Southern border of Alto Adige, South-Tyrol, Northern Italy. The village is easily traced on the Southern side of the Brenner Pass highway A22, almost midway between Trento and Bolzano (Figure 1).

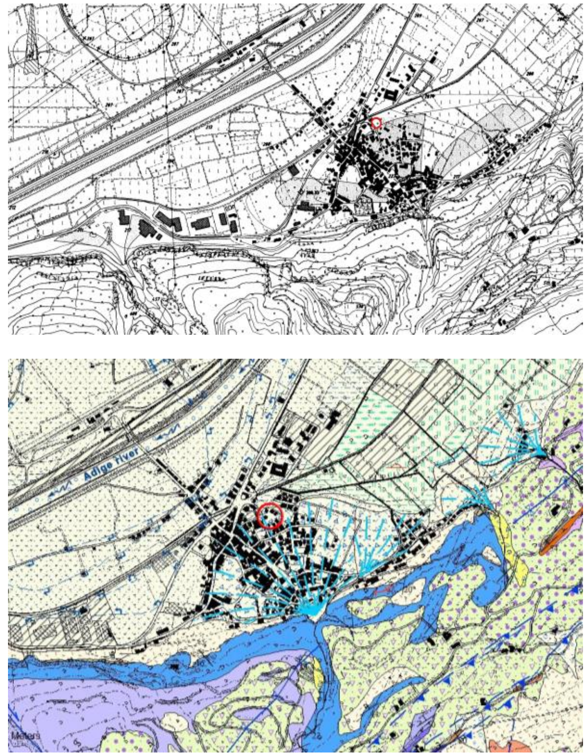

Figure 1. Area of Salorno: morphology (top) and geology

Most residential and industrial buildings are located on the narrow alluvial plain of the Adige River at average elevations of 210-220 m m.s.l. (Figure 1). The available space for constructions is confined between the left bank of the river (North-West) and the toe of the steep slopes of Monte dell'Orso (1570 m m.s.l.), one of the peaks that bound the river valley on the East and on the South-East of Salorno.

The historic part of the village is clustered at the mouth of Rio Tigio, a steep narrow creek that springs at about 500 m m.s.l. and flows South to North onto the alluvial plain. This creek has been diverted along the North-Eastern border of Salorno to protect the village from floods and debris flow.

The landscape of this part of the Adige valley is governed by the local geology combined with the reshaping actions of water and ice. A part of the geological map of Alto Adige is shown in Figure 1 (Amministrazione Provincia Bolzano);

Salorno is lined by a mountain chain rising to the East and South of the village and running parallel to the Adige River. These mountains are mainly stratified dolomites, locally covered by till, debris, and diamicton, non homogeneous eroded materials. Toward South-East they give way to volcanic lapilli and tuff.

At the base of the dolomites, the thick alluvial deposit of the Adige River is encountered. In the center of the U shaped valley the alluvium may reach depths of about 500 m; it consists mainly of sands and silty sands with layers of gravelly materials. Away from the main streamline, finer soils are encountered, including silt, clay, peat and organic matter. Along abandoned meanders, sands and silty sands are generally predominant. In depressed areas extending to the base of the mountains, where vegetation grows in shallow waters, a swamp environment originates; here organic clays and silty clays are abundant and with time thick peat deposits are formed. One of these is now exploited at the outskirt of Salorno; here large volumes of peat have been excavated to depths of 4-6 m below natural ground.

Where narrow and steep creeks exit onto the plain, alluvial fans are deposited; they consist of interbedded layers of gravelly sands and sandy gravels spreading out towards the Adige.

Thus, within Salorno subsoil conditions are quite variable. In general, upper layers consist of coarse soils, from debris flow and detritus. With increasing distance from the apex of the fans, sands and gravels give way to silts, clays, peat and other organic matter. They rest on the coarse alluvium of the Adige River, reached at variable depths depending on local geological conditions.

Water seeping from the main stream and the minor creeks, enriches the aquifer and keeps the ground water close to the surface; its seasonal oscillations respond to the flow regime in Adige.

3 BUILDING CHARACTERISTICS

The residential building was designed with due consideration of the geological conditions and of past experience on the long time behavior of various existing constructions. It was known, in fact, that even light buildings suffered from SLS due to differential settlements and distortions.

Thus a regular and compact shape, with two axis of symmetry and an almost square footprint was adopted (Figure 2). The living area was arranged around the central stairway, opposite the lift block, to obtain an even distribution of dead and variable loads to exert an essentially vertical action to the foundation.

The final design includes an open ground level, for storage rooms and parking spaces, two floors divided into 4 apartments each, a top loft with 2 apartments. The maximum height reaches 13,5 m atop the roof (Figure 2).

The structure is a reinforced concrete frame, rigidly connected to a stiff base slab measuring 17.6x22.6 m^2 and having a thickness of 0.55 m. This r.c. slab was placed near the South-Western corner of the appurtenant area, 30.1x33.0 m^2. The slab, and its blinding layer, 0.1 m thick, rest on a granular fill, compacted in an excavation, 0.5 m deep below natural ground, whose base was lined with a geotextile+geomembrane. Atop the slab, a heavy-duty industrial pavement, with thickness of 0.25 m, was placed to resist the vertical and shear forces of parking vehicles.

Excavation was kept to a minimum to avoid using wellpoints, deep wells or sump pumps to control seepage and keep the site dry. In fact the water table is encountered at 1.0-1.5 m below ground surface, and drainage might have caused consolidation and settlements of the soft clays and peat encountered to depths of about 30 m.

To make the r.c. frame stiff, shear walls were placed near the corners, along the staircase and in the lift cage; these structures would form a strong-stiff nucleus in the center of the building and down to the foundation slab.

The structure was cast in place with concrete from an outer plant; steel class is B450C (450-540 N/mm^2); concrete class is 30 MPa for base slab and walls, 35 MPa for beams, pillars, floor slabs. Average steel quantities are 0.65 kN/m^3 in base slab, 1.30 kN/m^3 in pillars and floor slabs.

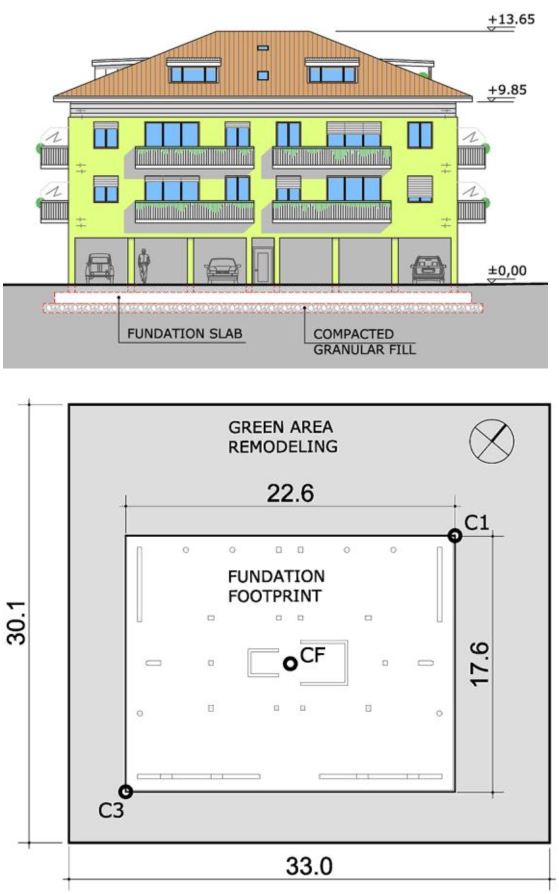

Figure 2. The longest façade, looking North, and the area of the building and the foundation slab (C1, C3, Cf: points where settlements have been calculated)

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Construction work began on 15-09-2006; the r.c. frame and the roof were finished early April 2007; the building was completed in April 2008.

To facilitate access to the building and the top of the industrial pavement, the area around the foundation was remodeled with a compacted fill, placed on the natural ground to an average and max thickness of 0.5-0.9 m. Fill material was selected from byproducts of porphyry extracted in local open mines. Water supply and sewage lines, and storm water drainage pipes, were buried inside the fill. Its surface was finished with green areas and footpaths to the building.

In the final state, average vertical stresses of σ_v = 60 kPa and σ_v = 10-12 kPa were estimated at the slab-soil contact and at base of fill.

4 SOIL INVESTIGATION

The subsoil conditions at the building site were investigated twice, after settlements initiated. In April 2007 three CPT tests were performed to a depth of 15 m, using a mechanical cone (Meigh 1987). In February 2008, when the differential settlement had reached 110 mm, two boreholes were drilled to 38 m (S1) and 30 m (S2). No samples were retrieved; no laboratory tests and no in-hole tests have been performed. Figure 3 shows the position of CPT and boreholes; Figure 4 shows CPT profiles (q_c and f_s). At the design stage, only data of three other CPT, pushed to 15 m in a neighbor site (2005), were available.

Data from the two boreholes and from all CPT tests are consistent and coherent with the behavior of the residential building.

Using well known correlations (Jamiolkowski 1985 Lunne 2002) the undrained shear strength c_u of clayey soils and the relative density Dr (%) and effective friction angle φ' of granular layers were calculated from values of tip resistance q_c:

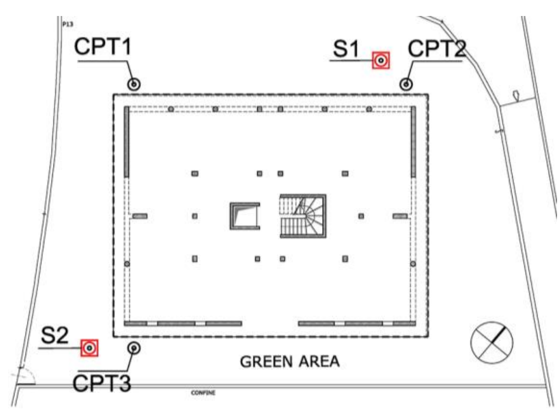

Figure 3. Plan of soil investigation, CPT and boreholes

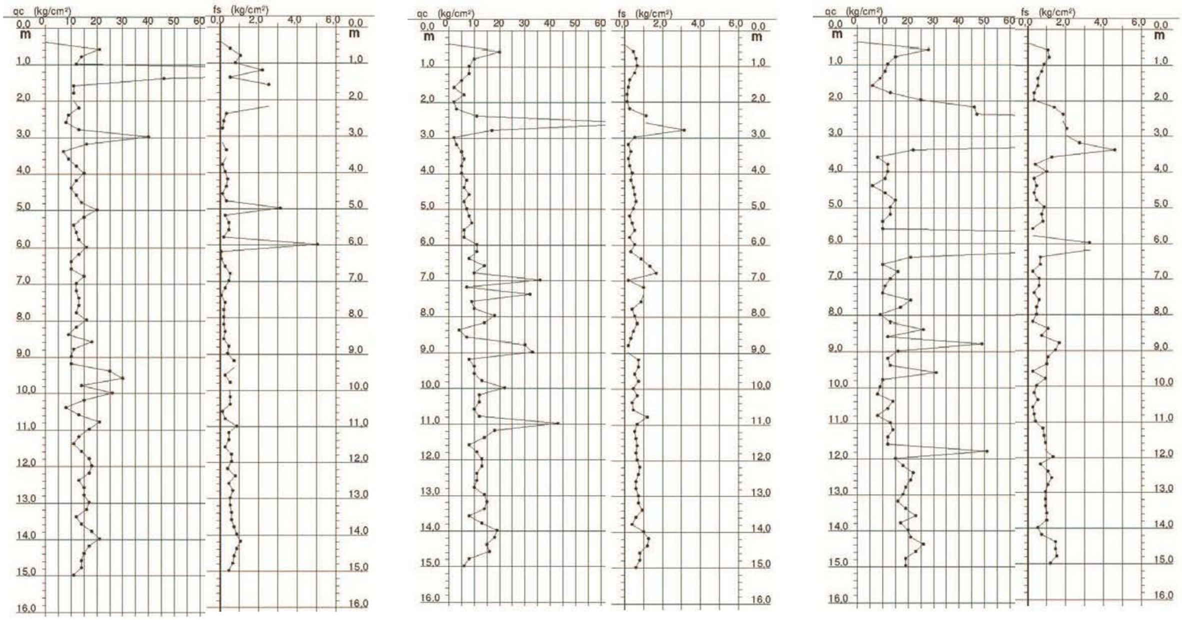

Figure 4. Values of cone resistance (q_c) and sleeve friction (f_s) registered during the CPT tests (April 2007)

$$c_u = [(q_c - \sigma_v)/17] \tag{1}$$

$$Dr = -98 + 66 \{Log [q_c / (\sigma'_v)^{0.5}]\} \tag{2}$$

$$\varphi' = 31.5 + 0.115 (Dr) \tag{3}$$

In the upper 3-6 m, layers of gravelly and silty sands, 1.0-1.5 m thick, are encountered. CPT tests yield q_c = 7-15 MPa and φ' = 38°-42°. Other sand layers, 0.5-1.0 m thick, are found at depths of 8-12 m; these are somewhat weaker, with q_c = 2-5 MPa and φ' = 32°-37°. In between the sand layers, soft clays, organic and silty clays and peat are detected; here q_c drops to 1.0-1.5 MPa and 1.2-2.0 MPa (CPT3), yielding the ranges c_u = 45-75 kPa and c_u = 70-100 kPa (CPT3), and c_u = 20-50 kPa (lower bound).

Hence, for depths below 8-9 m, it is noted that the amount of sand increases from North-East (CPT2, S1) to South-West (CPT3, S2); also the relative density and the shearing resistance are greater. At depths greater than 11-12 m q_c drops to q_c = 1.0-1.5 MPa.

The logs of the two boreholes indicate a thick layer of peat at depths of 11.2-15.0 m (S1) and 9.8-15.2 m (S2). Thereafter, layers of soft clays and organic clays, normally consolidated, and silty clays with thin beds of peat, extend to 27 m (S1) and 30 m (S2); here coarse gravelly sands are reached. A layer of silty sand at depths of 21-22 m is indicated in the two borehole logs.

It is clear that the subsoil is quite variable in the building area, especially in the upper 10-15 m; also, fine compressible soils extend to great depths, thus the CPT performed are too short.

5 SETTLEMENTS

Tilting was detected in April 2007, when the r.c. frame was finished. A survey showed a 70 mm differential settlement of the base slab over the 22.6 edge, thus a rigid rotation of 0.18° in less than one year. Hence, a topographic survey was initiated to monitor the settlements of the four corners (C1-C4) of the base slab (Figure 5).

At the same time, on the side of the structure that settled at a faster rate, lightweight materials were used to complete the industrial pavement on the base slab and the floor slabs. Nonetheless the max differential settlement increased to 110 mm in February and to 120 mm in June 2008.

As shown in Figure 5, the settlements of the 4 corners (C1-C4) have continued increasing since 2006, though at a reducing rate. On 15-01-18 a max differential settlement of 285 mm was measured at C1-C3, with a rotation of the base slab of 0.71° and a resulting angular distortion of 1/80 (Burland 1975, Lambe 1979).

Because the slab and the r.c. frame behave as a rigid body all angles (rotation, tilt, …) are the same. Despite such a severe tilting, all structural and partition elements, walls and floor tiles, are free from cracks. However, windows and doors swing on hinges if unlocked; further it has been necessary to reverse the slope of the Western balconies to stop rainfall from seeping inside.

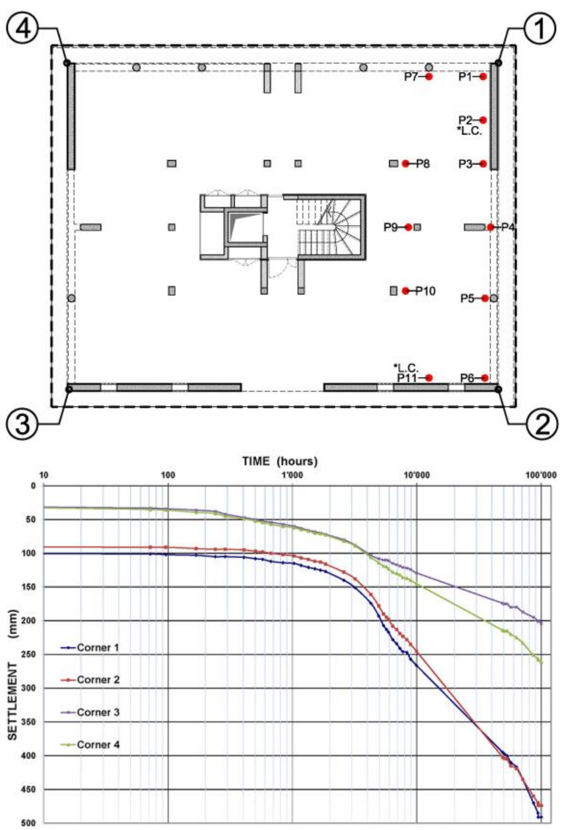

Figure 5. Settlement monitoring targets (C1-C4) and recorded values; plane above shows underpinning piles

In the attempt to predict the settlements of the foundation, an analysis was performed using a solution of the Boussinesq equation for uniform loads on rectangular areas. The net pressure at the soil-slab interface and the weight of the fill were taken into account. The increase of vertical stress was calculated to a depth of 30 m and values of the oedometer stiffness modulus were estimated from CPT data and logs of borehole, supplemented with literature information. The settlements obtained for the case of flexible load areas are equal to Cf = 415 mm, center of slab, C1 = 217 mm and C3 = 184 mm. Settlements of these corners were obtained using data from S1 and S3 respectively; Cf is averaged from the two logs. Notwithstanding the differences between center and corner, the calculated and measured values of settlements are quite different.

6 UNDERPINNING

When the rigid rotation of the base slab reached 1/100 and the building had tilted by 0.573°, the owners greed to underpin the building and asked the to design a solution capable to reduce tilting. Hence it has been proposed to install 11 jacked micropiles in a portion of the base slab (Figure 5), considering the distribution of settlements and the subsoil condition, available clearance and work area, the strength and stiffness of the base slab and the relative facility to provide a fixed connection with the micropiles.

Figure 6 describes the selected underpinning system. Micropiles are made of steel tubes, 10 mm thick and outer diameter 114.3 mm, in 2.0 m long pieces screwed together when jacked. A steel bucket, 220 mm o.d. and 700 mm high, is welded to the base tube, which is slotted in order to grout the pile hole. When the piles are pushed downward, the bucket displays the soft soils laterally and leaves a 220 mm hole behind. This hole is kept open using water, rarely bentonite mud; both have a stabilizing effect and prevent the soil, compacted and smeared by the bucket, from caving in. Here, water was sufficient.

Jacking continued till refusal, occurring as the enlarged base was set firmly in the deep sand layer. Thence, cement grout was poured in the pipe column until it was seen emerging at the base of the slab; at this stage the 220 mm hole had been filled and the micropile completed.

The equipment used (Figure 6) comprises a reaction steel frame with four piston jacks welded on two base beams. When oil pressure is applied, the pistons slide inside the cylinders to pull the pile downward. Reaction was provided by 4 threaded bars, 40 mm, fixed into the base slab with a special quick-set cement grout. Push capacity is 400-500 kN, corresponding to a unit pressure at pile base p = 10.5-13.2 MPa. In this case a max force of 400 kN was applied.

In mid January, the installation of the 11 piles was completed in less than 2 weeks. Piles are 27-30 m long, except for one pushed to 34 m. Two piles have been equipped with an electric load cells to monitor load build up.

The usual survey yields an increase of the differential settlement C1-C3 to 290 mm in mid February and a reduction to 287 mm on 27-09-18. The two load cells indicate a load increase, from March to September, from 43 to 56 kN and from 50 to 64 kN for piles n.2 and n.11.

7 CONCLUSIONS

A case history of using slender jacked steel pipe micropiles to underpin a compact and relatively low residential building subjected to long lasting settlements has been presented. Piles have been pushed to depths of 27-30 m, one pile to 34 m, through soft clays and peaty soils into a bearing sand layer, when the max thrust was reached.

The experience gained has enlightened the role of soil investigation in selection and design of the most effective solution, from a structural and geotechnical point of view. It also gives evidence that stiff structure may sustain large differential settlements with no visible damage.

In the case of small sized buildings, a strong and stiff raft foundation may allow for partial underpinning to limit the remediation costs; to this aim the risk of settlements and distortions must be known and taken into account already at the design stage. Depending on specific subsoil conditions, partial underpinning might reduce tilting. Long time settlement monitoring and control of load build up on piles is necessary to check the response of the structure and apply necessary correction to the remediation solution.

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Figure 6. Steel tube and base bucket (top left); pushing equipment with micropile (top right); load cell embedded into the slab foundation (bottom left); removable load cell between head of micropile and reaction frame (bottom right)