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Long term monitoring of the foundation of a cable stayed bridge

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Abstract

The highway between Napoli and Formia, in Southern Italy, crosses the river Garigliano 65 km north of Napoli by means of a long viaduct with two intermediate cable stayed spans. In the alluvial plain of the river Garigliano; the soils consist of NC or slightly OC silty and sandy clays with a substantial organic content down to a depth of about 50 m, where a sand and gravel bottom layer is found. The foundation of the central pier is a thick raft resting on a rectangular group of 9x16=144 piles, arranged in a square grid with a spacing of 1,2 m axis to axis. The instrumentation installed since the beginning of the construction, started in 1991, was aimed to monitor the settlement of the pier and the loads taken by the piles. The loads were monitored by vibrating wire instruments, while precision geodetical survey was periodically carried out to measure settlement. The long term monitoring covers now nearly 30 years testifying an extraordinary long and accurate response of the large majority of the installed instruments. Important details of the measured performance will be described outlining the implications and lessons learnt in terms of soil-structure interaction. The settlement data obtained by geodetic surveys have been compared and integrated a posteriori with satellite-based measurements (ERS, ENVISAT satellites) for the first common monitoring period (1993-2004) which has been further extended until 2010 (ENVISAT satellite).

Keywords: Foundation Monitoring, Long term performance, bridge foundation

1. Introduction

Within a program of improvement of the connections between Rome and Naples, in the early 1990's the Italian Highway Board (ANAS) constructed near the city of Formia an important viaduct crossing the river Garigliano and overpassing some other infrastructures (Fig. 1). It has a total length of 1.132 m and includes 24x2 simply supported prestressed concrete or steel beams with length between 26.5 and 80 m and 2x2 stayed spans with a length of 90 m.

Within a few hundred metres from the new bridge, there are two other significant single span bridges: a suspension one, constructed in 1829 by Luigi Giura, on behalf of the Bourbon kings of Napoli, and a reinforced concrete arch with suspended deck, designed by Giulio Krall in 1934; both of them can be seen in fig. 1. The three bridges belong to the same culture and give evidence of the development of engineering: while the suspension bridge by Giura was at the forefront of his time, the two others are fine, but far from exceptional, structures. Due to the unfavourable subsoil conditions piers and abutments of the bridge have been founded on piles. The foundation of the pier n. 7, central pier of the stayed spans, has been instrumented to monitor the load transmitted to the piles and the settlement, starting from the construction stage.

The geotechnical properties of the subsoil, the design of the bridge foundations, the instrumentation adopted, and the early measurements results have been reported elsewhere (Russo, Viggiani, 1995; Russo, 1996; Russo, 1998). Some results of the load and settlement measurements have been included in State-of-the-Art-reports (Mandolini *et al.,* 1997; Mandolini *et al*., 2005) and textbooks (Viggiani *et al*., 2012). Recently satellite data (Tessitore et al., 2017) have been compared with ground observations which are still going on showing a satisfactory agreement.

This paper represents an update of the available results and a check of the health status of the equipment installed 30 years ago.

2. Foundation of the bridge and instrumentation

The original design of the foundations of the bridge was based on large diameter bored piles reaching the sand and gravel substratum. While such a solution was indeed viable, it had many shortcomings: executive difficulties of the piles and connected risk of constructional defects; environmental problems connected with the disposal of excavated soil and drilling muds; long execution time. The piles finally adopted, on the contrary, were tubular steel piles driven with a mandrel to the substratum essentially because free of all the above shortcomings. The piles are composed of two sections, each long around 24 m; the lower one has an outer diameter of 0.356 m (14") and the upper one of 0.406 m (16"), both with a thickness of 6.3 mm. The two parts are joined by welding during the installation and finally filled by concrete, adding a reinforcement cage in the upper 12 m.

The foundation of the main central pier of the bridge between the two stayed spans, is represented in fig. 1 together with an aerial picture. It rests on a rectangular group of 9x16=144 piles, arranged in a square grid with a spacing of 1,2 m axis to axis. To support the wall of the excavation for the reinforced concrete cap and to protect the foundation against scouring by the river, a peripheral diaphragm made by bored cast in situ piles with a diameter of 0,8 m and a length of 12 m had been provided. In an attempt to eliminate any tangential action between the concrete cap walls and the bored pile diaphragm, the interface has been provided with a plywood board covered by two PVC sheets with silicon grease. The reinforced concrete raft has dimension in plan LxB=19x10.6 m^2 and a maximum thickness of 4 m. The thickness decreases to 2 m on the long sides.

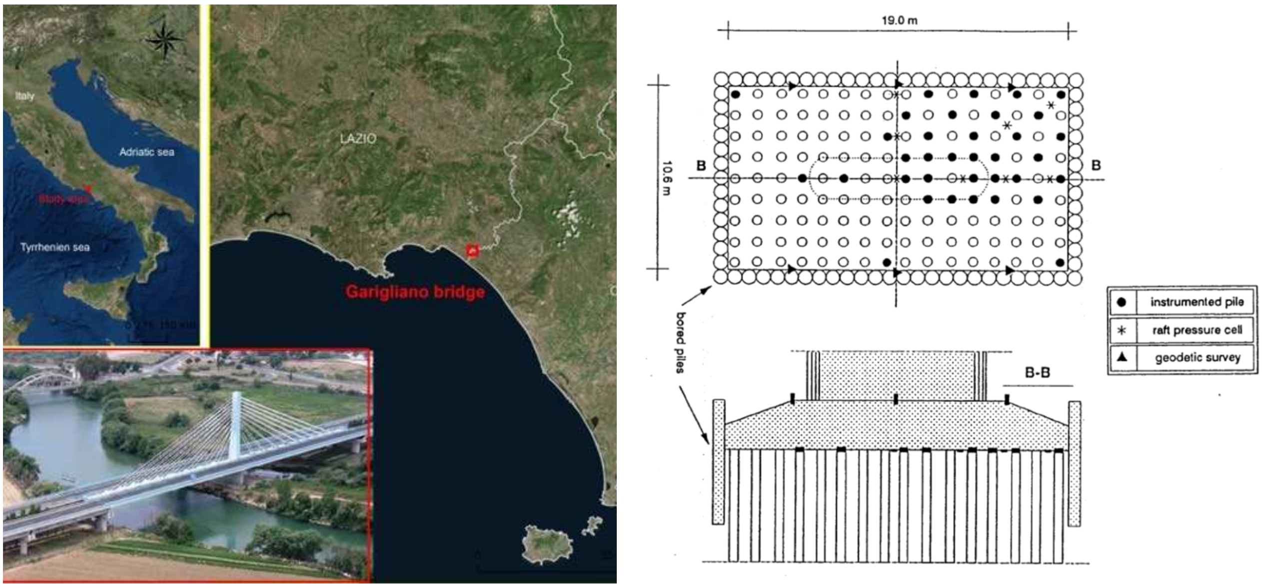

Figure 1: Aerial picture of the bridge and a plan view of the foundation

2.1 Instrumentation buried in the foundation

The load transmitted by the raft to the head of 35 out of the 144 piles have been measured; in fig. 1 the location of all the instruments is reported. The load sensing units adopted are based on vibrating wire strain gauges, particularly suitable and reliable for long term site monitoring. The load cells at the top of the pile were constructed at the site, using three load sensing units. The load sensing units were connected to three dywidag bars positioned at the vertex of an equilateral triangle. The total units were 105 on 35 piles. The pressure cells did not work satisfactorily, and their results will not be discussed. More details and pictures are given by Russo and Viggiani (1995), where three years of monitoring were presented as "long term" results.

2.2 Settlement of the foundation

The settlement of the pier n. 7 was measured by optical levelling, which started after the casting of the foundation raft. The measurements were carried out on 8 benchmarks, at the base of the central pier of the cable stayed bridge. Due to the high flexural stiffness of the foundation slab connecting the head of the piles, the 8 measurements are practically coincident, and their average is referred in the following as the settlement of the pier. In a recent paper by Tessitore *et al*. (2017) the data obtained from precision levelling have been compared and integrated with satellite-based measurements (ERS, ENVISAT satellites) for the period 1993-2010. DInSAR data have been then used to obtain cumulated LOS deformation profiles along the bridge longitudinal axis.

2.3 Applied load

During construction the bridge deck with its cables and the main antenna were only supported by the central pier and its foundation due to the construction procedure prescribed by designers, as shown in fig. 2. Once the deck reached the side piers on the opposite side of the rivers, no significant change in the load measured on the head of the piles was recorded testifying that nearly 100 % of the load is kept by the central pier and its foundation.

Figure 2: Bridge deck construction

3. Measurement results

The load-settlement monitoring was firstly carried out from October 1991 to October 1994, when the construction was practically completed. Later measurements were carried out to follow up the slow settlement increase with time and the possible change in the load sharing at the foundation level. Under the maximum live load (see fig. 3) of about 110000 kN the settlement in October 1994 was slightly larger than 4 cm. The maximum settlement increased further in the following years reaching more than 6 cm in 2019. The load acting on the pier is considered constant, because no significant changes have occurred to the bridge deck and the resultant load measured on the foundation was also unchanged, as it will be shown in the following figures. In figure 4 the plot of the settlement of the foundation against the time is reported. The data are those obtained by optical survey on the 8 benchmarks fixed at the base of the central pier. The satellite data reported by Tessitore *et al.* (2017) are reported in figure 5, where the comparison with the levelling data covers the period 1993-2010. The two curves have been overlapped in correspondence of 20th May 1993, because of the low quality of the ERS images acquisitions in the period 1991-1993. It is important to note that TS show yearly cyclical oscillations with a range of 0.8±0.3 mm on average; this could be due to the interaction with groundwater level oscillation whose effects are present in various types of measurements. The topographic measured settlement do not reveal such oscillation because of the frequency of the surveys as clearly shown in Figure 4. Figure 5 shows that the deformation highest picks are usually detected during summer periods and become more evident after 1998, when the initial consolidation can be considered concluded. Similar fluctuation has been observed on the pile load and the two evidence confirm the likely cause of the buoyancy change during the year.

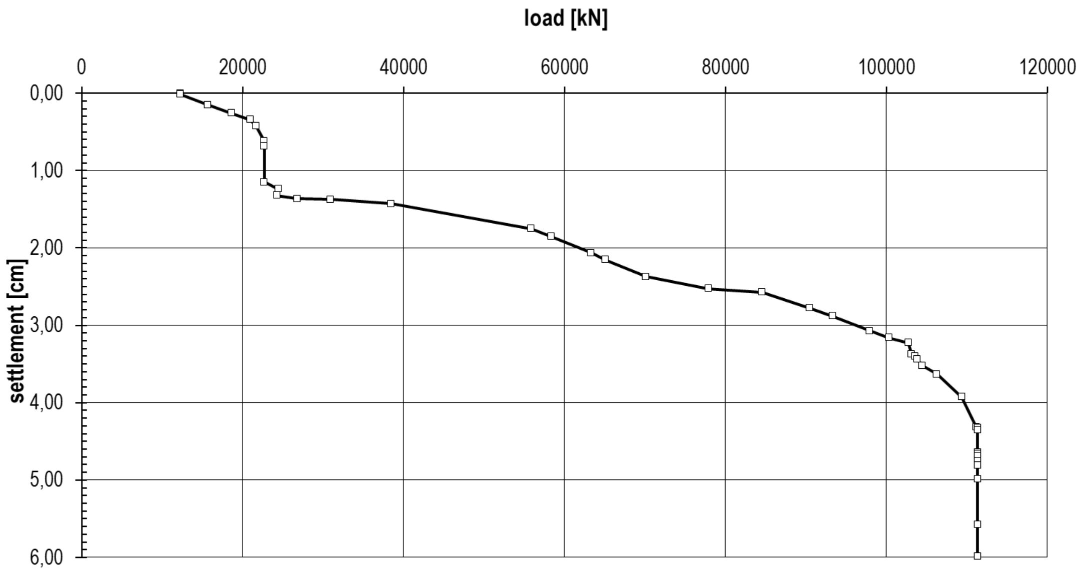

Figure 3: Load-settlement behaviour of the foundation of the central pier

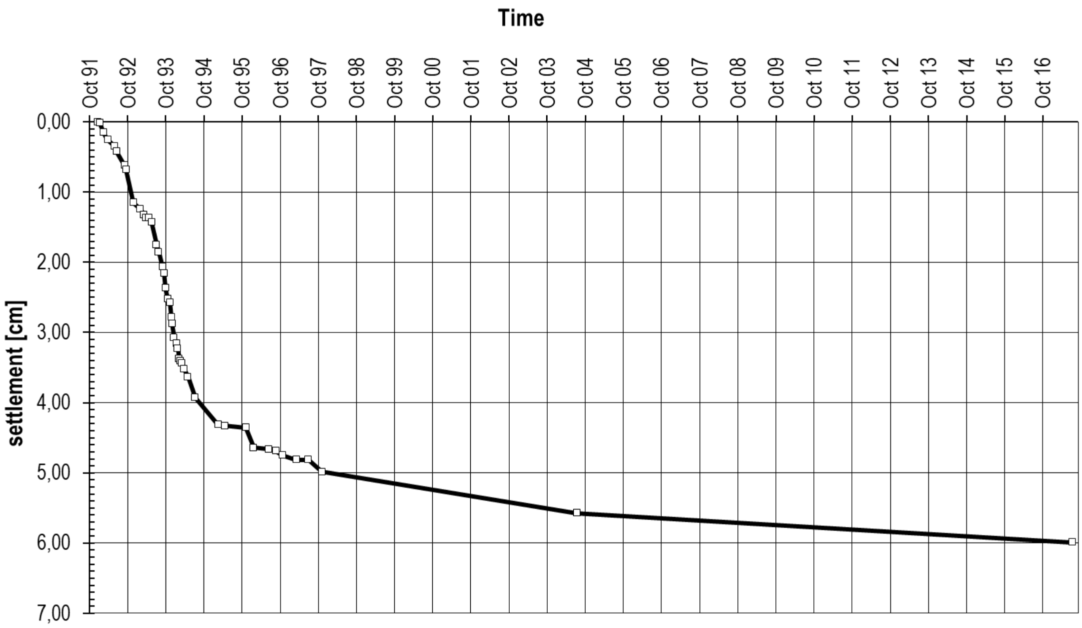

Figure 4: Measured settlement of the pier 7 vs. time

Fig. 6 reports the total applied load, the net load, the load taken by the piles and that taken by the raft, computed as the difference between the net load and piles load. It may be seen that during the first stage of construction the raft took up to 24% of the applied load; this percentage decreased to 15% at the end of construction and went on slowly decreasing in time, till the present 10%.

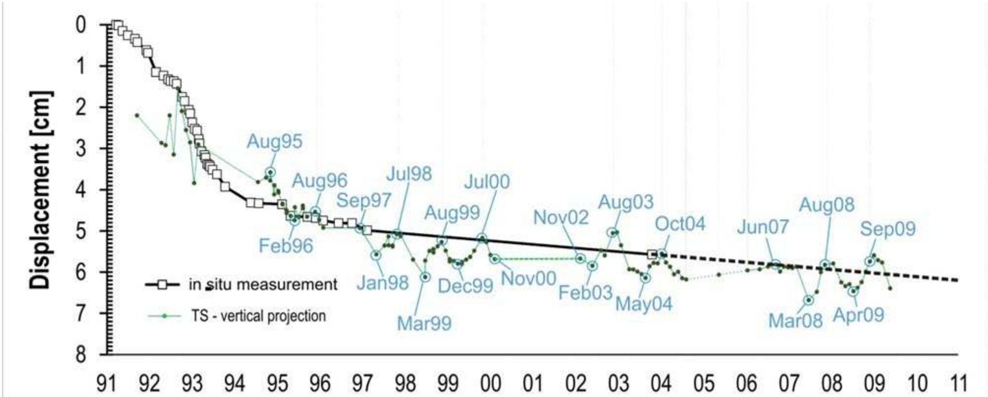

Figure 5: settlement of the pier 7, satellite and levelling data.

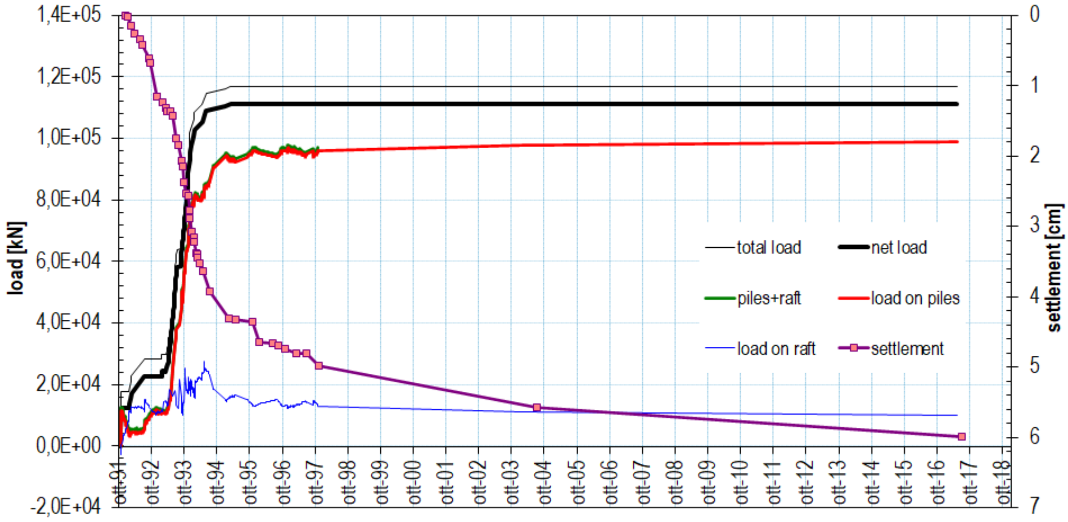

Figure 6: Applied load and load shared in the foundation measured during more than 25 years.

In figure 1 a plan view of the foundation with the location of the 35 instrumented piles is reported. The behaviour of the various piles can be grouped into four distinct categories, corresponding to four zones underneath the pile cap. In table 1 the average values of the pile load for each of the selected areas are reported, as a ratio to the mean value of all the piles. The values reported refer to four different stages: end of construction, three years later, ten years later and twenty-five years later. At the end of construction, the measurements show a significant edge effect, as it was to be expected under a stiff cap, and some load concentration below the pier.

Table 1: Pile load ratio as a function of the location beneath the raft

Load ratio on piles	Corner piles	Edge piles	Internal piles	Piles under the pier
End of construction	1.30	1.00	0.80	0.90
3 years later	1.16	0.96	0.90	0.98
10 years later	1.10	0.93	0.94	1.03
22 years later	1.04	0.86	0.90	1.20

Three years later the load distribution was undergoing significant variations: the load on the peripheral piles was decreasing, while that on the piles below the pier was slightly increasing. Ten years later this trend is still confirmed. Finally twenty two years later the piles directly located below the pier have taken the largest load ratio well above the average followed by corner's pile. To the writers' knowledge, such a phenomenon had not been observed before; the observed trend of variation suggests that the main factor is creep of the reinforced concrete raft. Figure 7 reports the values of the load on some typical piles as a function of time, starting from the construction of the bridge deck in January 1993. While the total pile load keeps almost a constant value with only a slight increase for 25 years after the end of construction (figure 6) the loads on the single piles undergo a cyclic variation, with a period of 1 year. The values reported in table 1 have been taken always in the same month of the year, in order to minimize the influence of the observed cyclic behaviour.

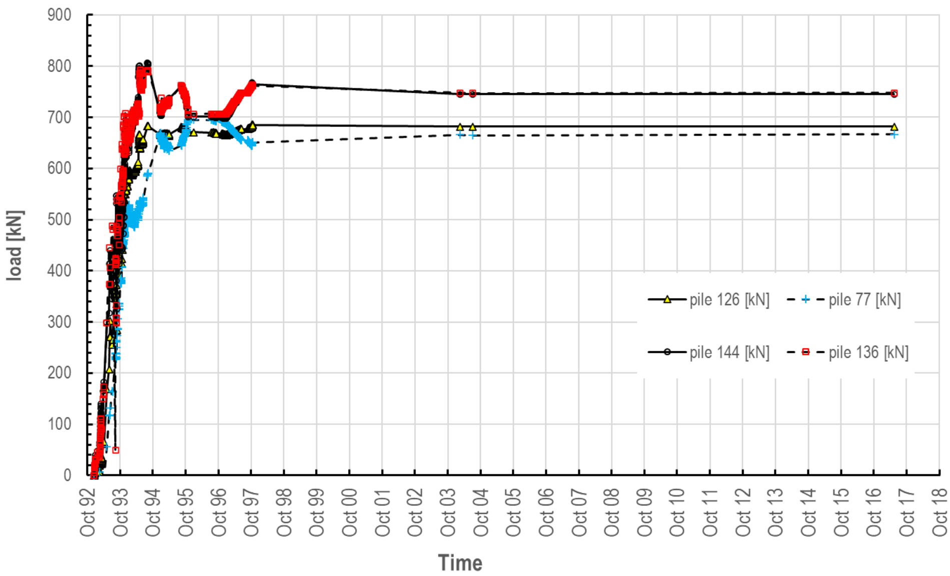

Figure 7: Load on piles measured with vibrating wire load cells during more than 25 years. (144 and 136 corner piles – 126 edge pile – 77 central pile)

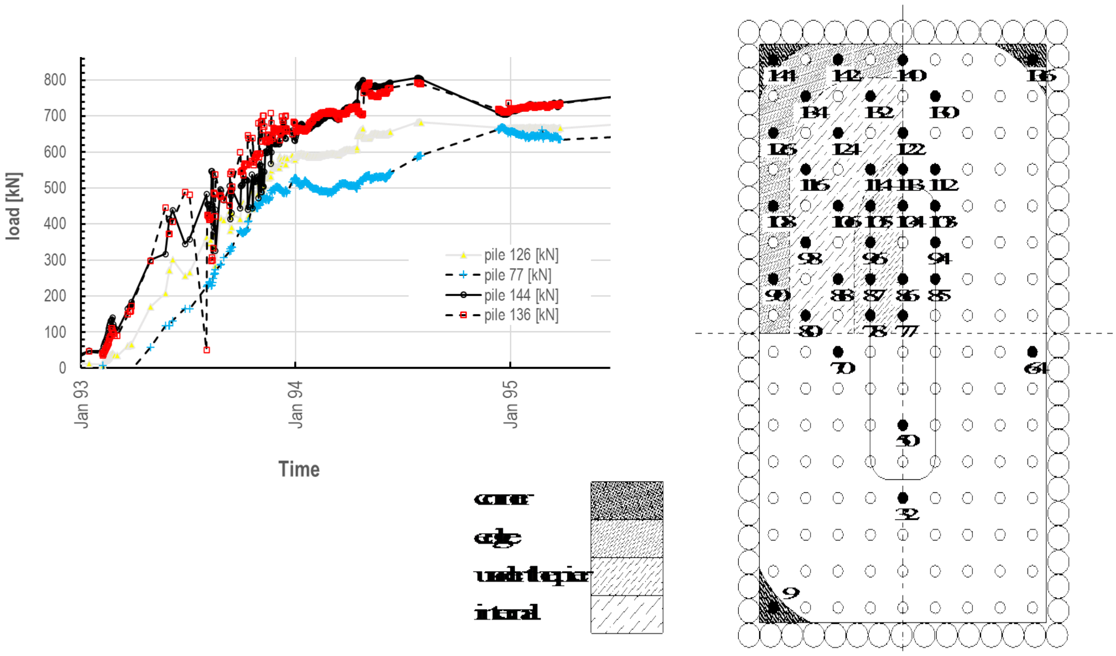

Figure 8: Zoom view on the construction period with the two corners piles (144-136) showing at the same time opposite peak loads and load corner effects disappearing with time after construction.

In figure 8 finally a zoom view of the load on some typical piles of the group during the period of the construction of the bridge deck and soon after the end of the construction is plotted. In this figure different details can be appreciated partially confirming the high quality of the monitoring data and also showing details of the performance that are indeed very interesting by a scientific point of view. First of all the pile 144 and 136 two corner piles on opposite sides of the central pier show very similar loads at the end of the construction period. The black dots and the red ones followed during the construction period on the other hand show the presence of contemporary opposite peaks in the context of an increasing average compression load. These opposite peaks are a clear consequence of the procedure adopted to build the bridge deck using cable suspended bridge desk segments alternatively installed on the two opposite sides of the central antenna.

Finally the higher loads on corner piles recorded at the end of the construction period and typically associated to the well known interaction effects among piles beneath a stiff raft as a matter of fact tend to vanish with the time after the end of the construction.

4. Conclusions

The monitoring of the load sharing among piles and rafts in the piled foundations has allowed in recent years a deeper understanding of the mechanisms governing the interaction. Design strategies have been developed to take into account such a deeper understanding and codes and regulations have also changed their framework considering at the design stage the possibility of exploiting the natural capability of any piled foundation to share the load between piles and raft. In the case study presented in the paper the piled foundation is a conventional one with piles designed to carry the most of the load as shown by the monitoring data. The extraordinary long lasting performance of the monitoring device buried in the foundation together with the comparison with remote monitoring based on satellite data makes this case study nearly unique and the lessons learnt are indeed very valuable.

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