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Geomatic and Geotechnical Monitoring of Settlements in the Venice Lagoon, Italy

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Abstract: The safeguarding of Venice and the Venetian lagoon (Italy) from rising water is of great national interest. Besides the normal tidal regime, the effects of an increase in the frequency and intensity of floods in the lagoon have been accentuated by a reduction in the elevation of the land in respect to the actual average sea level. With the aim of reducing the vulnerability of the lagoon, the Italian Ministry of University and Scientific and Technological Research financed the research project "The geotechnical model of the subsurface for the safeguarding of Venice and its lagoon", to study the compressibility of the lagoon deposits, both by natural causes and as a consequence of overloading with heavy structures. The project involved the construction of a large experimental embankment in the Treporti area of the lagoon, in order to perform a full-scale long-term compression test on the lagoon soils. By using various geomatic and geotechnical monitoring techniques, it was possible to appraise very small vertical movements of the ground induced by the compressibility of the highly heterogeneous silty formations. High-precision data was acquired by means of classical topographic methodologies integrated with continuous GPS (Global Positioning System) measurements. In addition, vertical displacements of the ground were obtained using geotechnical instrumentation. This cross-monitoring approach provided a valuable tool for analyzing both the natural and anthropic causes of settlement.

Key words: Foundation settlement, Venice lagoon, levelling, GPS.

1. Introduction

The subsidence of alluvial soils is a problem in many parts of the world, and real time monitoring strategies have become very widespread. Generally speaking, the term subsidence is employed to describe the vertical ground settlements in a given area, due to natural or anthropic reasons. In the Venice area, the detrimental effects of subsidence were enhanced by the sea level rise (eustatism). A reduction of the difference between ground elevation and the current average sea level (actually of about 23 cm) has been evident since the beginning of the twentieth century [1], thus inducing an increase in the frequency and the intensity of floods in the Venetian lagoon.

Extensive studies have been devoted to resolving this problem, with the aim of reducing the vulnerability of the lagoon to high waters and sea storms, a solution based on large moving dams, called MOSE (MOdulo Sperimentale Elettromeccanico), located at the three lagoon inlets (Lido, Malamocco and Chioggia), was chosen by the Italian authorities. This solution should make it possible to prevent the water level rising in the lagoon during exceptionally high tides.

The Italian Ministry of University and Scientific and Technological Research financed the research project "The geotechnical model of the subsurface for the safeguarding of Venice and its lagoon", with the aim of studying the compressibility of the lagoon deposits both by natural causes and as a consequence of overloading with heavy structures.

The project, carried out by the Universities of Padua, Bologna and L'Aquila, involved the construction of a large experimental embankment, 40 m in diameter and 6.75 m high, in the Treporti area of the Venetian lagoon, in order to perform a full-scale long-term compression test on the lagoon soils (Fig. 1).

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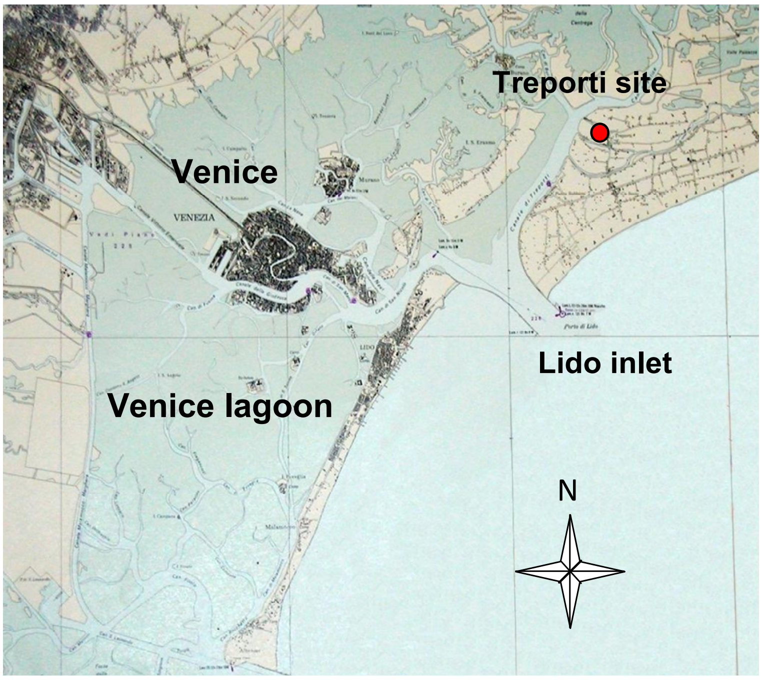


Fig. 1 A detail of the Venetian lagoon showing the study-site of Treporti.

The monitoring, which was performed using a variety of geotechnical and geodetic approaches, provided a valuable tool for predicting the geotechnical performance of the large moving dams [2] through a direct assessment of the vertical settlements.

Construction of the embankment began in September 2002 and ended in March 2003, comprising a period of about 180 days. Monitoring was carried out for a period of three years and eight months (about 1,330 days) starting from the first stages of construction. An overview of the monitoring of the settlements, using topographic and geotechnical procedures, is presented in this paper.

2. Geological Site Characterization

Due to the natural and anthropogenic processes which have affected the Venetian lagoon over time, the subsoil is composed of highly stratified deposits with sub-layer thickness rarely exceeding a few metres. The relative elevation of sea level in respect to the land has been widely variable in the past due to the geological sedimentary process of the Veneto Plain [3]. For example, during the last glacial age of Quaternary (120,000-10,000 years ago), sea level was about 90 m lower than at present. With the subsequent Holocene period (from 10,000 years ago to the present), the sea level began to rise due to the improvement in climate. A sea level similar to the current one was reached about 6,000-7,000 years ago, when lagoons of salty water began to grow (until about 4,500 years ago).

In the eighth century B.C., the sea level began to rise again, coinciding with the first Roman settlements in the area. Due to the combined effects of the sea level rise and lower ground level (due to natural subsidence), Roman ruins of the second and third century A.D. are now at a depth of about 2-3 m below sea water in the central area of the lagoon.

3. Design and Construction of the Full Scale Embankment

The construction of the embankment was preceded by a preliminary geotechnical investigation (Fig. 2a). A monitoring project was carried out to control all the geotechnical variables of interest, such as the stresses, pore pressures, deformations and displacements in time (Fig. 2b).

The embankment was constructed in successive stages, during which 26 layers of sand, of 0.25 m in thickness, were laid down. Alternating radial and circumferential levels of extruded HDPE (High-Density Polyethylene) geogrids were laid down with a vertical spacing of 0.25 m (Fig. 3).

The radial reinforcement was made up of 13 levels of wrap-around geogrids, other geogrids were installed along the circumference, forming 13 reinforcing annular rings spaced equally along the embankment height.

During the preliminary site investigation, a soft clay layer was found at a depth of 1-2 m from ground level. The presence of this layer would have led to some stability problems due to both its low shear strength and bearing capacity, in addition to the settlement/consolidation risk. To overcome this problem, reclamation was carried out with vertical geodrains in order to prevent pore pressure excess in the soft clay during the gradual loading of the foundation. At completion, reinforcement was made at the base level of the embankment, at a depth of 0.2 m from ground level, using a polypropylene geotextile.

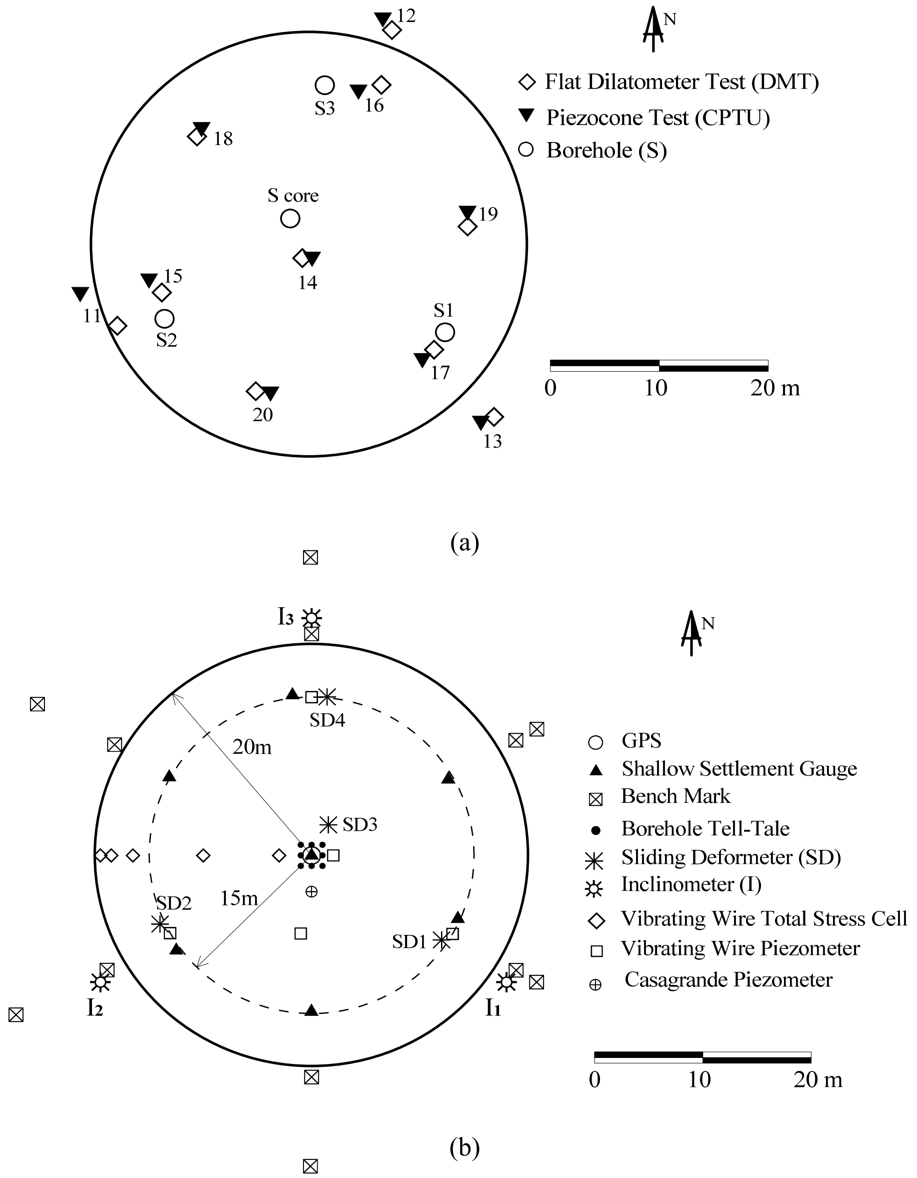


Fig. 2 Plan of the embankment showing: (a) in situ geotechnical characterization; (b) monitoring instrumentation.

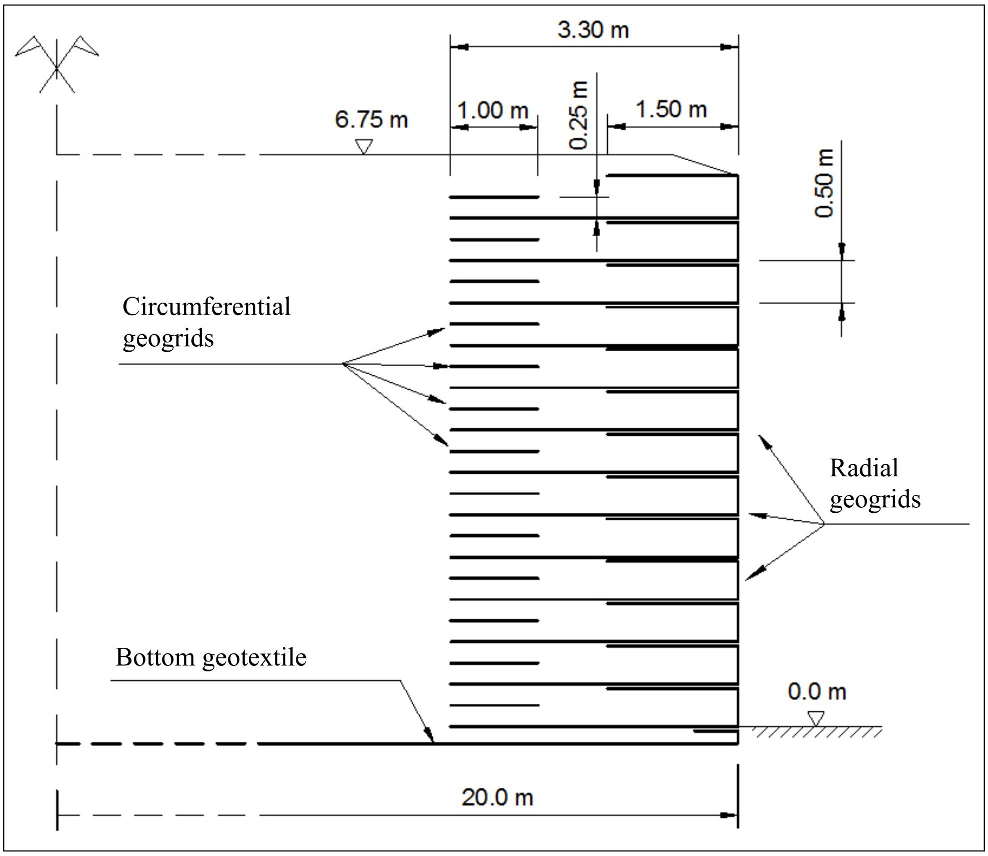


Fig. 3 Cross section of the instrumented reinforced earth.

The vertical ground displacements were monitored from three reference horizons (Fig. 4): the sky (GPS), ground level (optical measurements), and from a depth of 60 m below ground level (geotechnical monitoring). Horizontal displacements of the foundation soil were obtained by means of three inclinometers, placed in proximity of the toe of the embankment. Both vertical and horizontal soil displacements were detected up to a depth (60 m) to which the stress variation induced by the embankment was considered negligible. Fig. 5a is a photograph of the completed embankment, bordered by safety scaffolding, and one of the two ramps used for the conventional leveling, Fig. 5b shows a satellite-recognition image of the working area, in which two ramps are visible together with the embankment.

4. Site Characterization and Monitoring

In order to define a geotechnical model of the subsoil, a site investigation was carried out at Treporti by means of boreholes, piezocone tests, dilatometer Marchetti tests and geoseismic surveys, a maximum depth of about 60 m was reached with the boreholes and of about 40 m with the Marchetti dilatometer and the piezocone tests (Fig. 2a). A comprehensive analysis of the in situ test results was presented by the various authors involved in the project [4-7]: The subsoil was composed of an alternating succession of silty layers with variable contents of sand and/or clay, depending on the cycle of sedimentation. The successions were rather regular over the entire area covered by the embankment. As previously discussed, the first soft clay horizon, between the depths of approximately 1-2 m, was reclaimed by means of vertical 3 m long geodrains with plant layout following a triangular equilateral mesh, with side of 1 m, to avoid pore pressure excess in the soft clay during the gradual loading of the foundation.

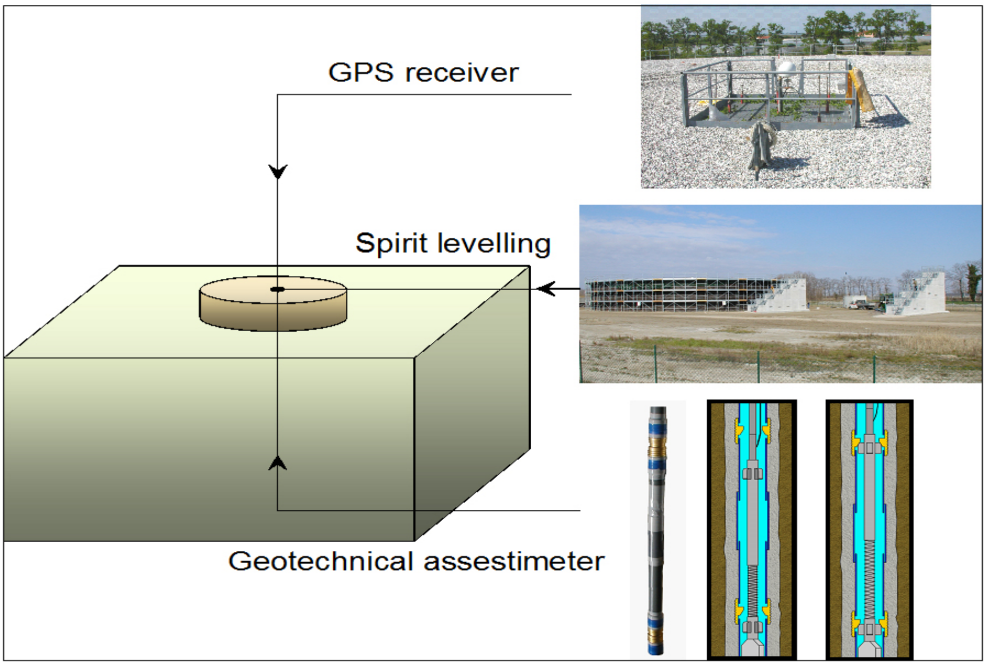
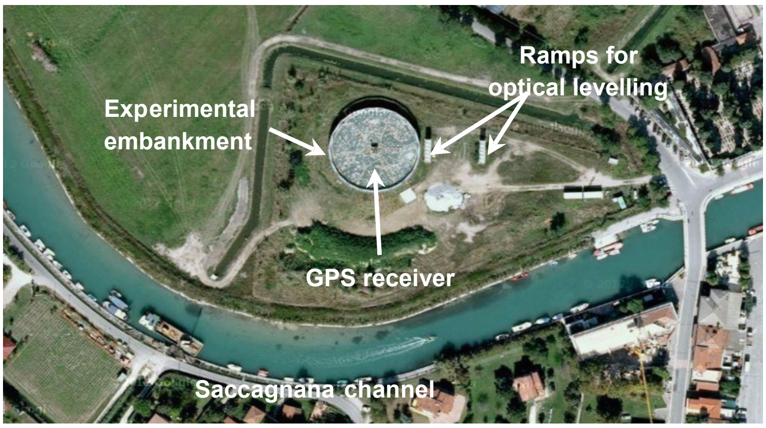


Fig. 4 The three procedures used in monitoring settlement.

(a)



(b)

Fig. 5 The experimental embankment: (a) landscape view of the structure with the first ramp necessary for spirit leveling methodology; (b) aerial view of the site.

A second compressible formation was present at a depth of between 8-20 m, it was found to consist of sandy-clayey silts, within which a sandy lens was found at an average depth of about 16 m. The lens, having a variable thickness, was absent in the N-E quadrant but evident in the remaining three.

A synthesis of the subsoil stratigraphy is shown in Fig. 6 with respect to an N-S cross section containing the embankment axis. It highlights how the two compressible formations were responsible for about 70% of the total subsidence of the structure: Referring to the axis of the embankment, the shallower compressible layer gave a settlement of almost 6 cm over the total subsidence of 52 cm (about 12%), while the second gave a settlement of nearly 30 cm (about 58%).

Thin layers of peat were identified in the depths of subsoil investigated, among which the main layers were located at the mean depths of 27, 35, 40, 44 and 46 m.

The groundwater level was at an average depth of 1 m below ground surface, it was affected by the tide level in the neighboring Saccagnana channel of the lagoon, located at a distance of about 80 m from the embankment.

During the monitoring period, daily, weekly and seasonal groundwater fluctuations were no higher than ±0.9 m in respect to the mean sea level, thus inducing potential variations of groundwater pore pressure not exceeding ±9 kPa, even so, a substantial independence from the tide was highlighted by the response in the time of the piezometers, justified by the brevity of the tidal cycles in proportion to the response time of the subsoil.

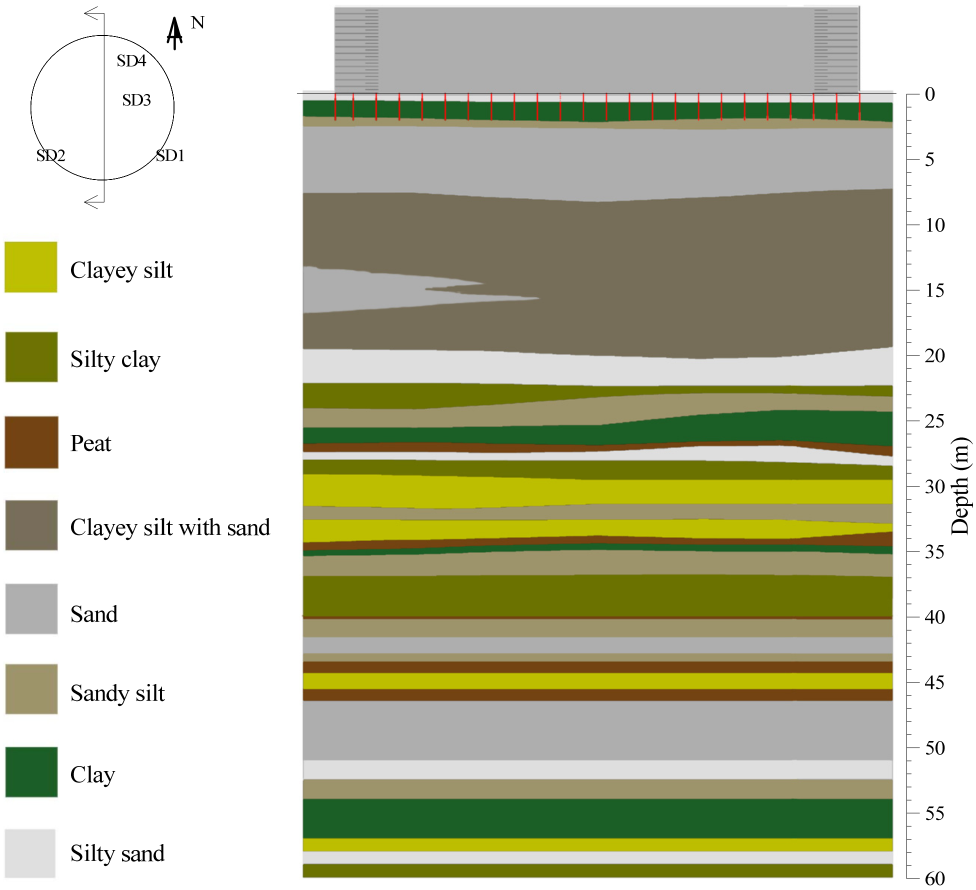


Fig. 6 Soil stratigraphy along the N-S cross section.

The consolidation process of the compressible silty formation, found at depths between 8-20 m, was controlled by means of the two piezometers at depths of 14 m and 17 m beneath the loaded area. Thanks to the high permeability of this formation, the consolidation process led to very modest neutral overpressures: Primary consolidation already ended during the construction stages and the secondary compression took place in the further time. Extensive monitoring allowed the whole process of soil-structure interaction to be analyzed.

With reference to the foundation soils (refer to instrumentation plan in Fig. 2b), the subsidence of the ground beneath the embankment was detected through seven plate-assestimeters, carrying finders for optical leveling on the top of the rod; the central one was also provided with a Leica SR530 GPS Geodetic RTK Receiver carrying an antenna AT504. The operational precision on distance was ±3 mm and ±1 ppm in differential mode. Such an arrangement provided a standard deviation of about ±2.50 mm compared to the spirit leveling.

The subsidence of the ground surface, outside the footprint area of the embankment was detected by means of 12 plate-type benchmarks, carrying finders for conventional leveling at the top of the rods, and increasing in length during construction.

The deep subsidence of the subsoil was monitored by means of eight long-base assestimeters with optical control, located in the centre of the embankment, and with embedment depths of 2, 4, 8, 20, 25, 32, 38 and 60 m.

In addition, four multi-base sliding assestimeters were installed inside the footprint area of the embankment, up to a depth of 60 m from the ground level.

The measurement of displacement vectors along a measuring line (borehole) can provide information on the local soil deformation. By integrating local soil deformation, a cumulate settlement profile can be made. With the multi-base sliding assestimeters, displacement and deformation are measured metre by metre. The single line is a linkage of measuring tubes, which are connected by telescopic moveable connections, the so-called telescope couplings. The conical precision measuring stop is located within the telescope coupling. When taking measurements, the probes are placed tightly between two neighboring measuring stops.

The probe uses the ball-and-cone positioning principle in the measuring marks of the measuring tube. The spherically shaped heads of the probe and the circular cone shaped measuring marks ensure a precise positioning of the 1 m long probe during measurement; thanks to high-precision sensors a very high accuracy of measurement and long-term stability is achieved. The typical accuracy of measurement of the sliding assestimeter is better than ±0.03 mm/m at the operating temperature ranging between $-20\ ^{o}C < T < +60\ ^{o}C$. This monitoring system has a calibration device to control the zero reading and to check the calibration factor. The calibration of the probe is carried out before and after each series of measurements.

The measuring tubes have a range of displacement of 80 mm/m in compression and 20 mm/m in extension; they were suitably cemented into boreholes to preserve the compressibility of the system in comparison to the surrounding soil.

An example of the monitoring data obtained by the multi-base sliding assestimeter SD3 is shown in Fig. 7, with reference to both the local strain (Fig. 7a) and the cumulated ground settlements in the time (Fig. 7b).

The horizontal displacements of the subsoil were detected using three inclinometers with a length of about 60 m, arranged at 120^{o} along the perimeter of the embankment (Fig. 2b).

The monitoring system also included five vertical total pressure cells along a radius of the embankment to detect the pressure distribution in the foundation, twenty vibrating wire piezometers and four Casagrande piezometers for pore pressure measurements inside the two more compressible layers. The monitoring was completed with a survey of the tide level in the adjacent Saccagnana channel, and data regarding the weather comprising temperature, pressure, humidity and rainfall.

The entire set of data from the multi-base sliding assestimeters, long-base assestimeters, surface-plate assestimeters, GPS and conventional leveling, allowed a clear identification of the ground vertical settlements over the time.

5. Spirit Leveling

High precision data were necessary to detect small vertical displacements. For this reason, spirit leveling topographic methodology was used: This is the technique that provides accurate data using staff and level. In fact, the precision of this methodology is in the order of few millimetres per kilometre [8, 9] when appropriate operating procedures are adopted.

In this work, multi-temporal spirit leveling was performed by placing a hemispherical brass adapter for high precision measurements on the top of the assestimeters (Fig. 8).

The monitoring network was composed by all the benchmarks both internal and external to the embankment, the reference points were located about 250 m away from the structure in a stable area (on artefacts with consolidated foundation). Forty-four conventional leveling surveys were performed from September 5, 2002 to May 27, 2008, by means of a digital level Leica NA3003, which was able to provide a standard deviation of 0.4 mm (1 km double leveling). They were performed more often during the embankment rising, with the height increasing by 50 cm every two weeks (15 surveys were carried out between September 5, 2002 and February 27, 2003).

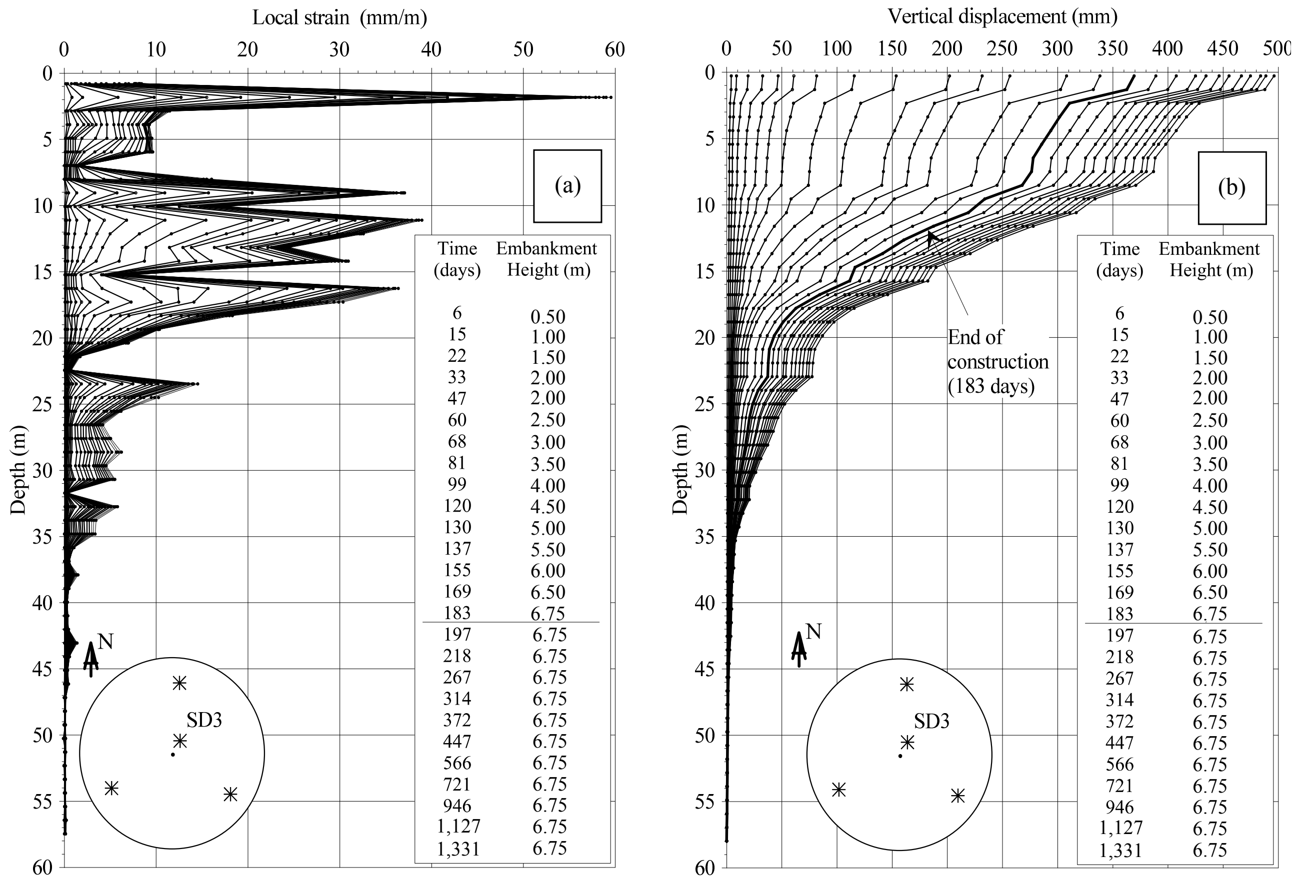


Fig. 7 Monitoring data of the multi-base sliding assestimeter SD3: (a) local vertical strain; (b) cumulated settlement.

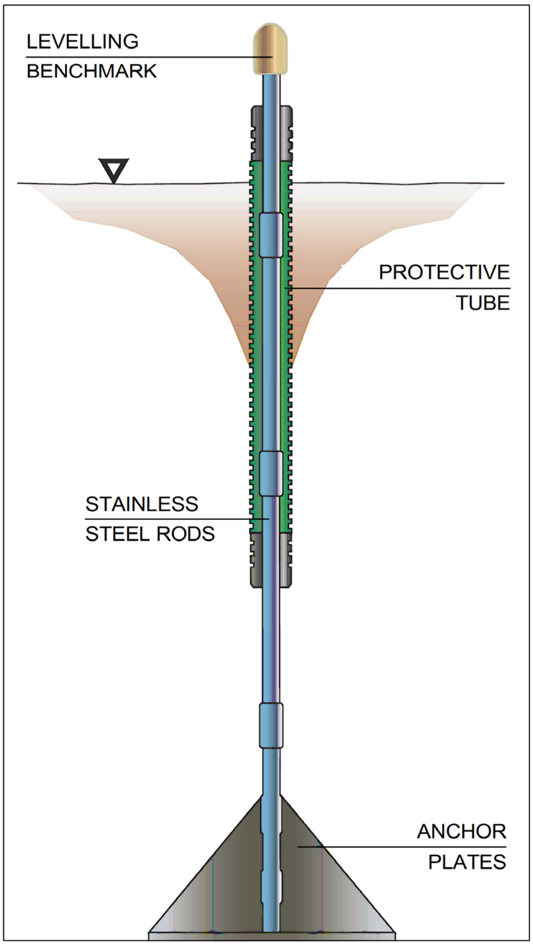


Fig. 8 Scheme of the surface-plate assestimeter.

Subsequently, the frequency of the surveys was progressively reduced during the stage in which the load remained at a constant (13 surveys were carried out between March 14, 2003 and October 17, 2006). Finally, 16 surveys were carried out between April 19, 2007 and May 27, 2008, the period during which the embankment was progressively dismantled.

To control the elevations of the plate-assestimeters located inside the embankment, conventional leveling was carried out with the aid of two topographic ramps to satisfy the symmetry conditions, to transfer the elevation from the terrain to the top of the embankment, a difference of about 6 m had to be overcome: for this reason, a distance of 25 m was adopted between the first and the second ramps, and from the second ramp to the centre of the embankment (Figs. 9 and 10).

Finally, the leveling network included 47 benchmarks: 27 monitoring points (12 benchmarks external to the embankment, 6 radial assestimeters and 9 central assestimeters), 18 connection benchmarks (located on the two ramps and along the path of the leveling network), and 2 reference benchmarks located in a stable area. For each leveling survey, 90 differences in elevation were measured (forward/back) by different operators (Fig. 10).

The data were adjusted with least square method, providing the elevation and the rms for each benchmark: The error was less than 0.8 mm due to the small distances for each leveling.

6. GPS Measurements

Spirit leveling provides discrete data that allow more precise monitoring when the measurements are performed frequently: To overcome this disadvantage, we used a methodology that provides data continuously. GPS technique, in fact, using static method, allowed the monitoring of the subsidence acquiring data 24 h per day for a long period. The disadvantage of this approach is due to the precision of data: In fact, while spirit leveling provides data with precision in the order of some millimeters per kilometer, GPS data (in particular for the elevation) provides coordinates with precision in the order of 1 cm or worst. For these reasons, to obtain a complete monitoring of few millimeters changes, the two methodologies should be used in the same time.

Permanent monitoring was performed for the benchmark located in the centre of the embankment (on the central assestimeter) using a choke-ring antenna GPS of the Leica SR530 receiver.

The data were acquired continuously, with a sampling of 30 s, from September 2002 to June 2008. Data processing was performed using the data from two permanent stations:

- Cavallino (belonging to the Consorzio Venezia Nuova permanent GPS network). The station includes a AT504 antenna with Leica SR500 GPS receiver;

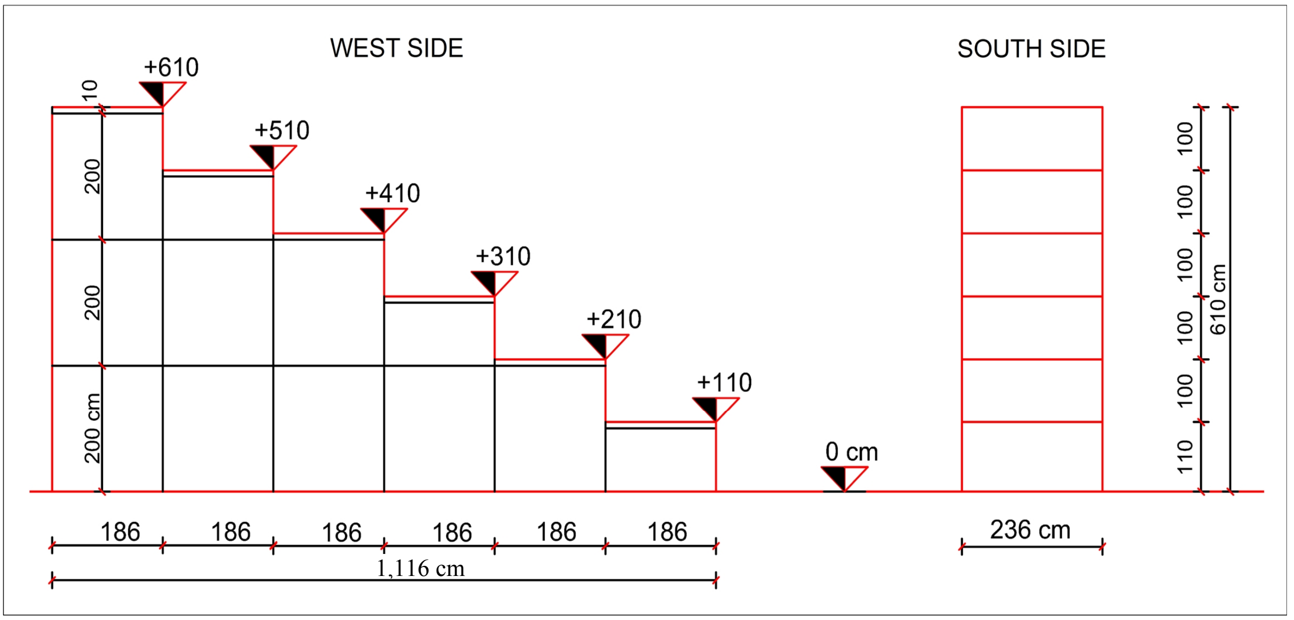


Fig. 9 Prospect of the topographic ramps.

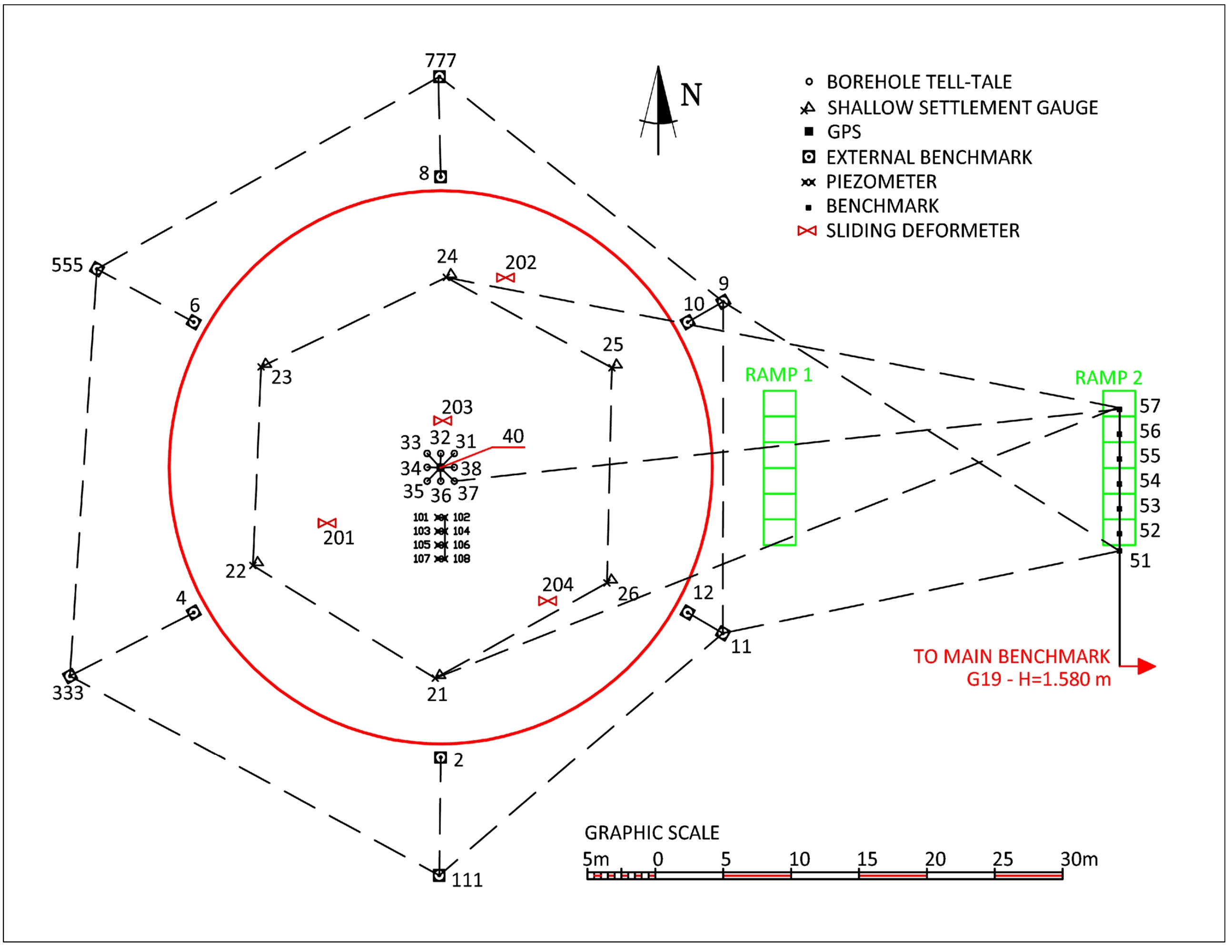


Fig. 10 Scheme of the leveling network.

- Venezia (belonging to the EUREF permanent stations), with a Trimble 4700 GPS receiver.

The GPS data was influenced by various external factors, such as men working near the antenna, movements of operating machines at the base of the embankment, oscillations of the pole of the GPS antenna, etc.. Since these disturbances provided noise in the signal, Geogenius software, with suitable processing of 24 h/session, was used. Once the baselines were obtained, the adjustment of the network provided the ellipsoidal elevation with rms varying in a range from few millimetres up to 15 mm (Fig. 11).

During the loading stage, vertical displacements detected, of about 400 mm, were higher than the precision of the method: for this reason, GPS allowed to identify the overall trend of the soil subsidence in accordance with the results of the spirit leveling. During the constant load phase, GPS allowed to detect a secondary settlement of about 100 mm, even at a minimum rate of only 15 mm/year. During the subsequent stage of removal of the embankment, the total uplift ground movement of about 20 mm was an order of magnitude lower than the previous ones, and therefore was not well detected by GPS, being it lower than the precision of the method. Thus, only the spirit leveling and the multi-base sliding assestimeters allowed the survey of these latter small displacements.

7. Final Results

Referring to the N-S cross section, incorporating the central axis of the embankment, Fig. 12 shows the evolution of settlements from the beginning of the construction through to the conclusion of the loading phase.

It is possible to note a maximum settlement of 52 cm at the centre and about 20-25 cm in proximity to the edges.

Regarding the precision of the different techniques, Fig. 13 shows a comparison of the measurements of ground settlements in time along the central axis of the embankment.

The GPS data is reported together with the multi-base sliding assestimeter SD3 and the geodetic optical measurements (conventional leveling) at the central plate-assestimeter.

The small difference in amplitude (about 20 mm) between the SD3 and the remaining two systems was due to the position of SD3, a few metres from the centre of the embankment, where the GPS and the plate-assestimeter were located.

In any case, all the methods were able to give the settlement trend even in the creep phase, during which the settlement velocity reduced up to 15 mm/year.

8. Conclusions

In this paper, the results of the monitoring of a large experimental embankment were discussed. The embankment was built in the Venetian lagoon in order to perform a full-scale long-term loading test to study the soil compressibility.

Three different methodologies were used to evaluate the vertical ground displacements: high precision spirit leveling, continuous GPS monitoring, and geotechnical monitoring by means of multi-base assestimeters buried into the soil.

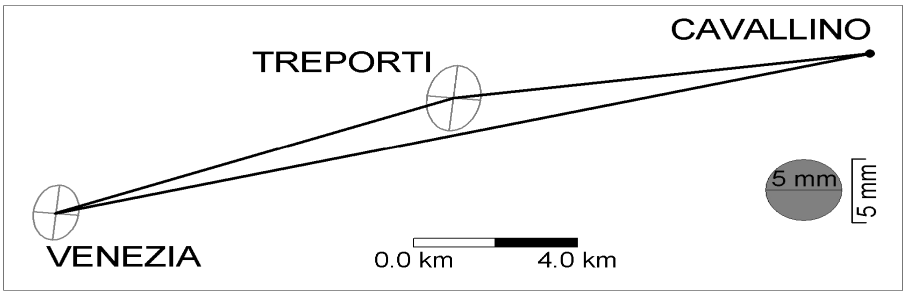


Fig. 11 Scheme of GPS processing and error estimation.

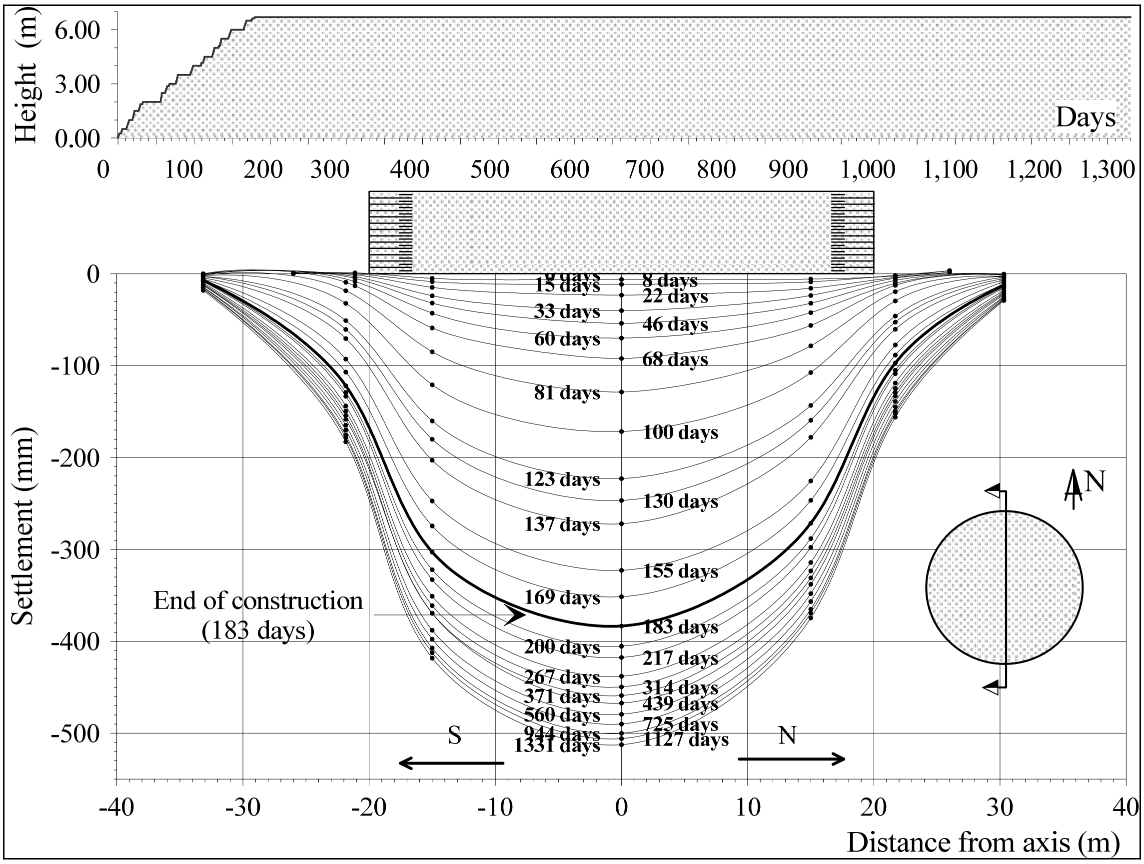


Fig. 12 Vertical ground settlements over time along N-S cross section of the embankment.

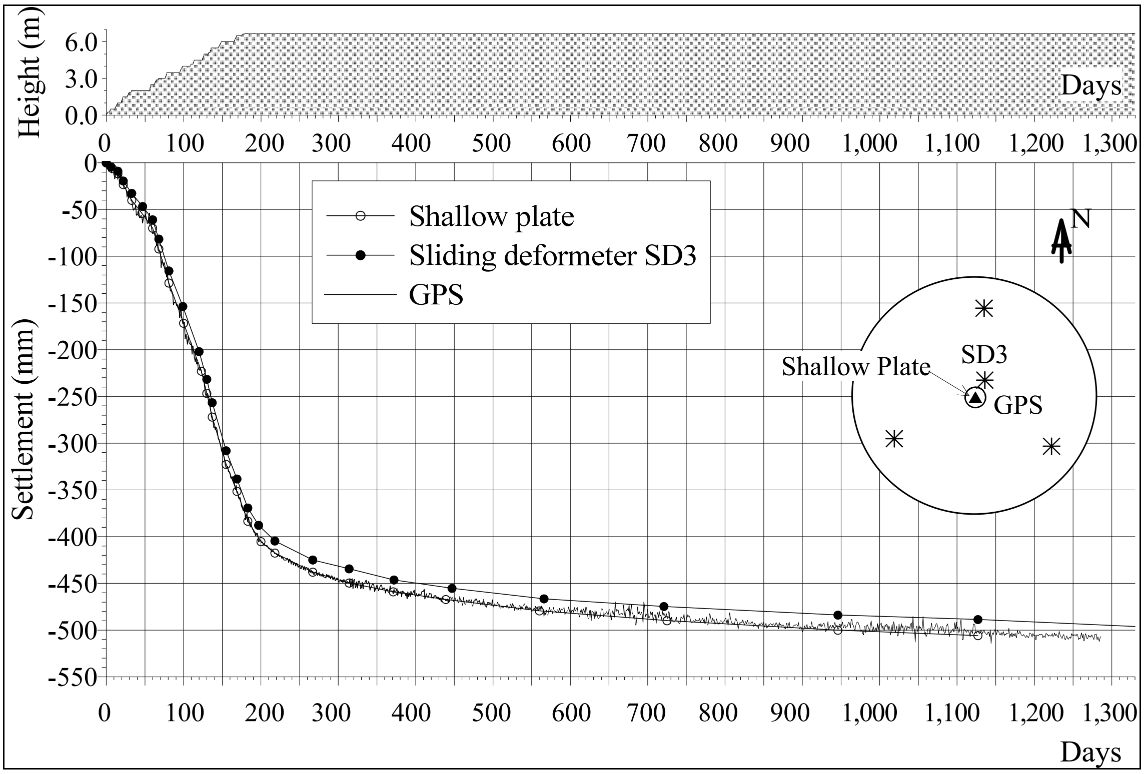


Fig. 13 Vertical ground settlements over time at the axis of the embankment.

The first methodology provided data of adequate accuracy in the whole settlement monitoring. This was true both in the first loading stage, during which more significant displacements occurred (about 400 mm), and also in the second phase, when the load remained constant and smaller displacements were detected (up to 100 mm), with a minimum rate of 15 mm/year.

In the last stage of monitoring, the removal of the embankment, the total uplift ground movement was very small (about 20 mm) and therefore was not well identified by GPS. Nevertheless, GPS allowed the axis of the embankment to be monitored continuously, even when leveling was not available.

The high precision geotechnical instrumentation (multi-base sliding assestimeter) gave ground displacements always comparable with those coming from the spirit leveling, and allowed the vertical displacements inside the foundation soil to be surveyed in time.

As a final point, all three methodologies provided results supporting each other, therefore their joint use is recommended for the complete monitoring of similar problems.

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