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Geotechnical studies to optimize the protection measures against flooding of St. Mark square (Venice, IT)

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ABSTRACT: The famous St. Mark square, located on an island characterized by the lowest gap between ground and sea level, is currently flooded during high tide, even though the MOSE barrier system is operative. To design cost-effective interventions to safeguard this historical heritage, a understanding of flooding mechanisms and the relationship between groundwater pressure and tidal oscillations was necessary. This paper presents the results of a recent monitoring campaign carried out at St. Mark square as well as a discussion on the selected interventions to protect the square against flooding.

1 INTRODUCTION

The historic city of Venice, located on several islands in the middle of a lagoon, and the surrounding environment are characterized by a rather precarious equilibrium, with the safety margin reducing at an accelerated rate. The rate of deterioration is due to the increasing flooding frequency of the historic city, that is caused by the natural eustatic rise of the sea level, by the natural subsidence and by the regional man-induced subsidence, which was significant between the ‘40s and ‘70s of the last century.

The city of Venice is located in the middle of the omonimous lagoon, whose origin is traced around 6000 years ago, when the sea water diffused into a preexisting lacustrine basin during the deglaciation period. The tide flows in and out from three lagoon inlets; its normal excursion is around 60–70 cm and lasts approximately 6 hours.

Since the gap between the ground level of Venice islands and the sea (lagoon) water level is small, at tides exceeding +0.8 m above mean sea level (referred to as mean sea level at the *Basilica di Punta della Salute* - s.l.P.S.), a few of island pavements begin to be flooded. At tide levels exceeding 1.1 m., occurring under low atmospheric pressure, strong winds blowing from Adriatic Sea and enduring rain, the flooding of a great part of the city is observed.

To protect the city of Venice against this recurrent flooding, several projects have been undertaken, the most important being the design and construction of movable gates located at the three lagoon inlets, namely the MOSE barriers (MOSE is acronym for *Modulo Sperimentale Elettromeccanico*: Experimental Electromechanical Module). These gates, controlling the tidal flow, temporarily separate the lagoon from the sea at the occurrence of high tides exceeding 1.1 m above s.l.P.S..

Other relevant interventions consisted in erosion mitigation of marshes and wetlands, morphological cost-line restoration, renovation of the existing jetties at the inlets, fishing farms reopening and, as far as the historic city concerns, raising the elevation of banks, pavements and sidewalks in some selected areas to prevent the floods due to tide below +1.1 m.

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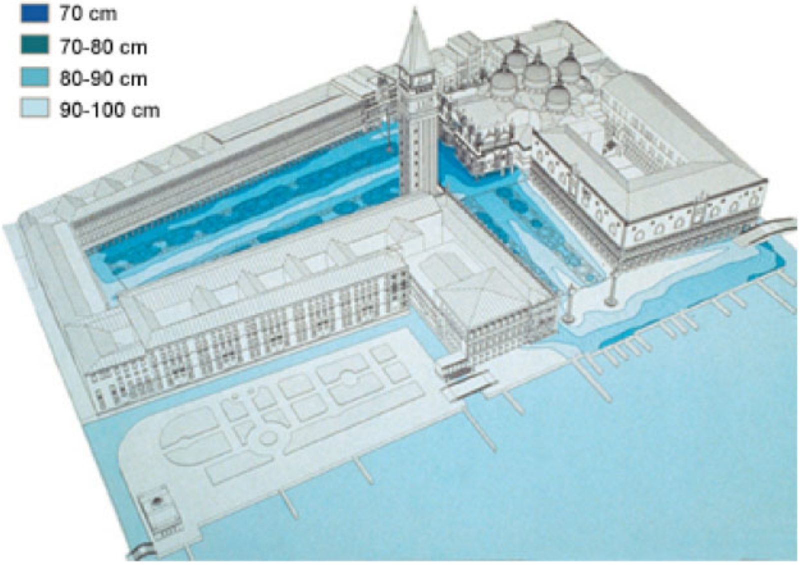

Figure 1. View of St. Mark's island with flooded area at corresponding values of tidal level (cm) (adapted from www.mosevenezia.eu).

The St. Mark's square is the lowest part of the historic center of Venice and is characterized by an elevation between +0.80 m and +0.90 m above s.l.P.S. More particularly the area facing the St. Mark's Cathedral is located at an even lower level, approaching +0.60 m above s.l.P.S.

The increasing frequency of flooding of the St. Mark's square induces considerable deterioration of masonry walls, foundations and decorative architectural elements of very important ancient buildings (Bettiol et al. 2015; Ceccato et al. 2014; Fletcher & Spencer 2005), jeopardizing the historical heritage of city and especially of that facing the St. Mark's inner square. When the water level reaches +0.60 m above s.l.P.S., a small zone in front of the Basilica and its narthex begin to be flooded. At +0.90 m, approximately 65% of the square is covered by water and at 1.15 m it is fully submerged. A tide exceeding +0.90 m is currently recorded at around one per cent of the time on the annual basis, but this percentage will rise considering a small effect of natural subsidence (0.5 mm/year) and sea level rise due to climate change.

The activation of the MOSE gates, when +1.10 m above s.l.P.S. (or higher) is forecasted, does not prevent the historical area of St. Mark's square to be flooded. Specific protection countermeasures are therefore needed, but selecting optimal solutions in this special context was not straightforward as it might be respectful of the historical heritage, compatible with the touristic activities as well as cost-effective.

Figure 2 shows a cross-section of a typical quay-wall facing the surrounding canals or the St. Mark's basin with an indication of different flow paths potentially concurring to flooding:

1 Back-flow through the existing drainage system;
2 Overtopping, from the St. Marks' basin;
3 Heavy rainfalls;
4 Seepage through the soil.

As shown in Figure 2, seepage flow may currently occur through or below the quay-walls, through the ancient and pervious drainage network, the open joints between the stones forming the pavement, which are in hydraulic connection with the water basin through the soil.

To protect the square against flooding a preliminary project was proposed in 1998, in which several countermeasures have been planned, the most important being the construction of vertical cut-off continuous sheet pile walls around the perimeter of St. Mark's island to avoid water infiltrating through and below the quay walls and the installation of an impermeable membrane below the stone pavement, to prevent seepage flow through the permeable joints between the stone elements of the pavement. Some doubts of the need and effectiveness of such huge interventions arise in the late '10 s and therefore different studies have been undertaken. More particularly, mechanisms 1–3 have been investigated in maritime and hydraulic studies (Ruol et al. 2020; P. Salandin 2020;) while mechanism 4 was investigated by specific geotechnical investigations presented and discussed in the following.

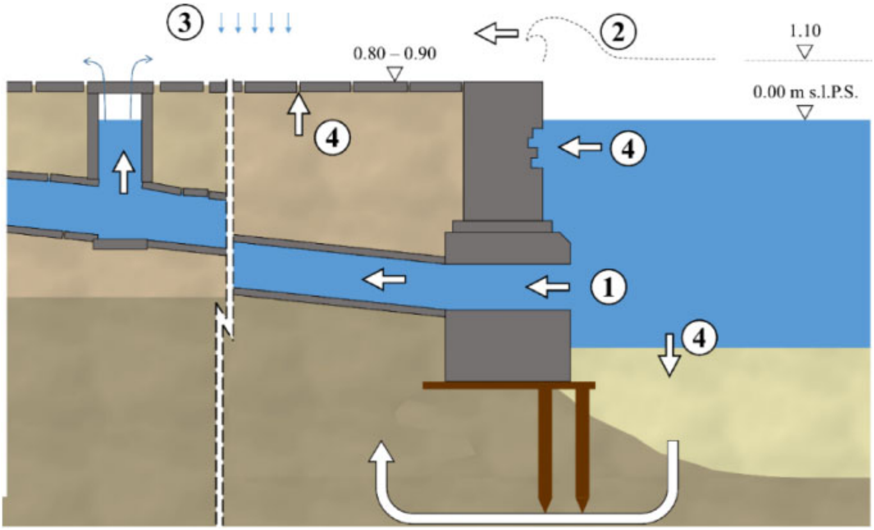

Figure 2. Main flooding mechanisms of St. Mark's Square: 1. Back-flow through the drainage system, 2. Overtopping, 3. Heavy rainfalls, 4. Seepage through the soil.

2 THE OLD DRAINAGE NETWORK

The still active ancient drainage system of the St. Marks' square, formed by a network of masonry tunnels (referred to as *gatoli* in Venetian language) collecting both rainfall and wastewater, was mostly constructed in the 18th century by the Republic of Venice.

The typical sections of these *gatoli* (Figure 3a) are characterized by rectangular sections between 0.4 m and 0.8m wide and between 0.6 and 0.9 m high. The vertical masonry walls are about 0.30 m-thick; the *gatoli* are closed above by a massive calcareous block, called *stelere*. For larger *gatoli*, an arch vault reaching a width of 1.50 m and a height of 2 m is used (Figure 3b). As a consequence of the construction technique, they are relatively pervious and seepage water can flow through the fissures between the *stelere* and the lateral walls, and, for the most deteriorated ones, between the brick elements forming the lateral walls.

Figure …shows an inner view of one conduct in good conditions and one in worst conditions.

The embedded drainage elements are gently sloping toward the canals or the St. Mark's basin. The water discharge rate is therefore very slow, thus fostering sediment deposition, which can reduce over time their cross section to 50–75% or, completely obstructing it in some cases (Volpato 2019). Hydraulic measurements and models (Volpato 2019) showed that the hydraulic head inside the *gatoli* coincides with the lagoon water level, i.e. the system is fully connected to the lagoon such as water can flow in and out according to tide oscillation.

Due to the perviousness of the *gatoli*, the water flowing into drainage system, is in direct connection with the surrounding shallowest soil forming the foundation ground of the entire square.

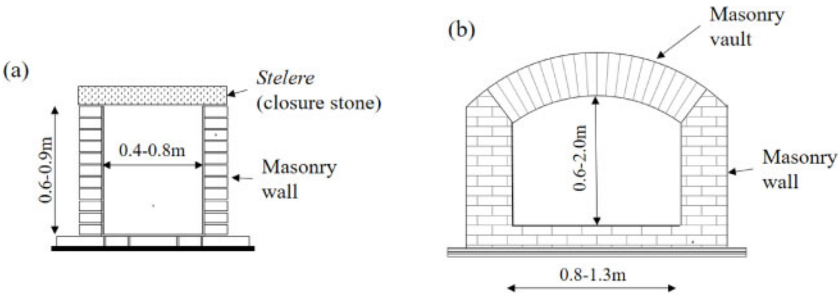

Figure 3. Typical cross section of Venetian *gatoli*.

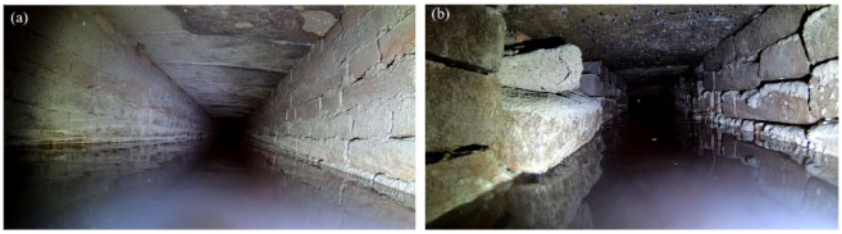

Figure 4. Inner view of two drainage conducts in S. Mark's square: (a) gatolo in good conditions, (b) gatolo in bad conditions.

3 GEOTECHNICAL SITE INVESTIGATIONS

The heterogeneity of the soils in the Venice lagoon is well known (Biscontin et al. 2007; Cola et al. 2008; Ricceri 2007; Simonini et al. 2007) and the island of St. Mark is no exception. Given the complexity of the system, three main geotechnical campaigns have been carried out in St. Mark square in order to define the geotechnical model of the subsoil. The first set of site investigations was commissioned by CVN in 1993 and included 6 geotechnical boreholes (16 m-deep) with collection of undisturbed samples, 10 standard penetration tests (SPT), 6 Lefranc permeability tests, 3 Piezocone Cone Pentration tests (CPTU) with dissipation tests. In 1997–1998, 6 geotechnical boreholes up to 20 or 32 m depth (with undisturbed sample collection), 9 standard penetration tests (SPT), 8 Piezocone Cone Pentration tests (CPTU), Boutwell in situ permeability tests were conducted. The third campaign was carried out in 2019 and consisted in 10 geotechnical boreholes up to a depth of 20 m, with collection of undisturbed samples; 13 CPTU, 5 seismic piezocone tests (SCPTU), 5 Dilatometer tests (DTM); 5 Seismic Dilatometer tests (SDTM) driven 20m-deep. Geotechnical laboratory tests included classification tests (grain size distribution, specific gravity, water content, Atterberg limits, etc.), permeability tests in triaxial cells, with constant head and variable head permeameters and one-dimensional oedeometric compression tests. The locations of the tests are shown in Figure 4.

The results of these site investigation campaigns allow us to identify a superficial anthropic layer (Unit 1/1A) with a thickness of 3.0 to 4.5 m. This layer is extremely heterogeneous because it experienced several different anthropic actions along the centuries and it hosts the drainage network (Bortoletto 2019). In particular, the permeability varies along 7 order of magnitudes, depending on the type of test, the depth, and the location. Higher values, up to 1.210^{-3} m/s, are measured for Boutwell permeability tests at very shallow depth; lower values, up to 210^{-10} m/s, are obtained from CPTU dissipation tests and oedometric tests.

A low permeability layer (Unit 2/2A) lies below Unit 1 and it has a thickness between 2.0 m and 7.0 m. The material ranges from sandy silt (2) to clayey silt (2A). The permeability varies between 110^{-10} m/s and 110^{-7} m/s. Beneath this layer there is a more permeable sandy formation, characterized by uniform fine sand (Unit 3) and silty sand (Unit 3A). The thickness varies from

0.50 m to approximately 8.0 m. From the depth of −9.80 m below s.l.P.S., up to the maximum sounding depth, there is the typical alternation of prevalently clayey layers (4A) with lenses of moderately silty sand (4). A typical stratigraphy is shown in Figure 6.

Figure 5. Position of in-situ geotechnical tests (CPTU, SCPTU, DMT, SDMT), boreholes, piezometric stations and old drainage pipes (*gatoli*).

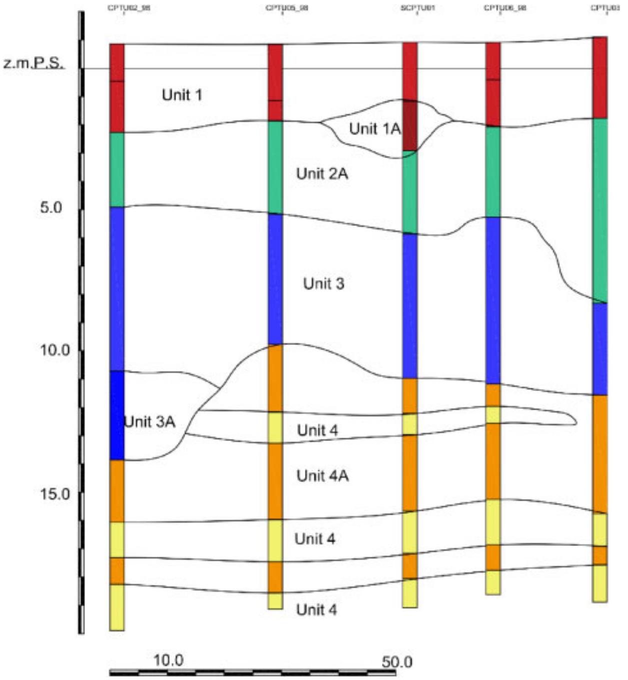

Figure 6. Typical stratigraphic section of St. Mark’s Island (Section AA’ in Figure 3).

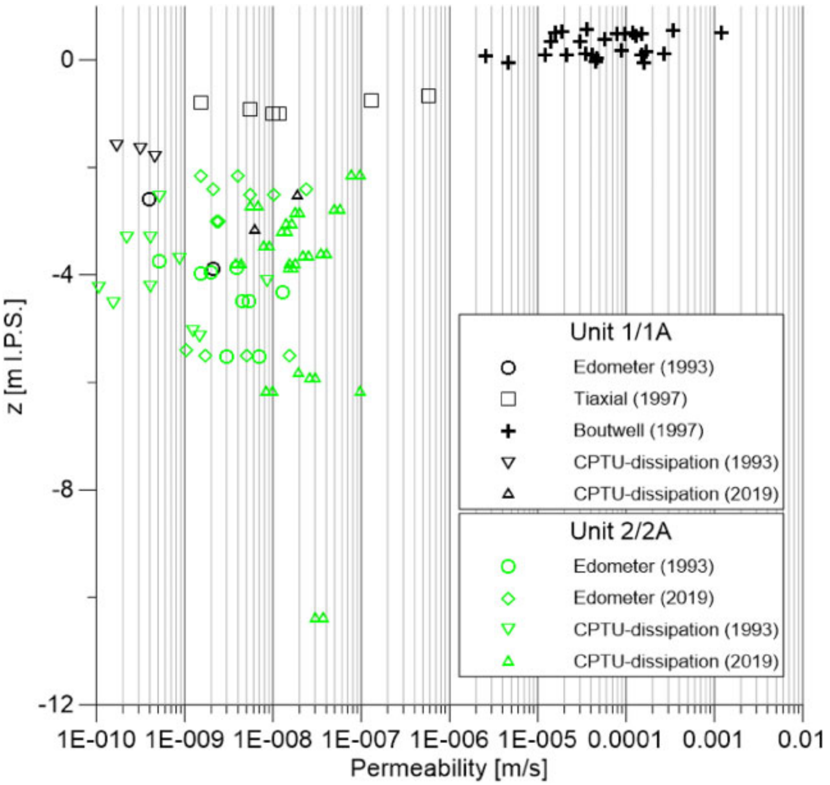

Figure 7. Results of permeability measures along depth.

4 MONITORING OF PORE WATER PRESSURES

4.1 *Pore-water pressure readings*

One of the key aspects for the optimization of the safeguarding measures is understanding of the seepage flows and the pore pressure distribution under St. Mark square in response of tidal oscillations. To achieve this goal, 9 Casagrande piezometers were installed at 2018 in a pilot site at the south of St. Mark's Basilica (piezometric station P in Figure 5). 4 piezometers are located in Unit 1 at a depth between 2.0 m and 2.3 m, 4 piezometers are located in Unit 2 at a depth between 3.2 m and 3.8 m, and 1 piezometer is located in Unit 3 at a depth of 7.6 m. The Casagrande cell was instrumented with a pressure transducer collecting readings every 6 minutes and transferring the data to the server, where they could be easily inspected and downloaded for elaboration.

Figure 8 shows the oscillation of the average piezometric level measured in soil units 1, 2, and 3 and the sea water level from October 16 to November 15th, 2018. In this period, the water level increased above ground level several times and the square was repeatedly flooded for a few hours. Moreover, a 156 cm (above s.l.P.S.) very high tidal level was registered on October 29th due to a storm surge. The amplitude of the pore pressure oscillation is reduced compared to the tidal wave in all layers, but the reduction is minimum for soil Unit 1, which reaches pressure levels closer to sea level when the floor of the square is flooded because water can easily enter from the permeable pavement. During this observation period, the maximum piezometric level measured in Unit 1 is 129 cm, in Unit 2 it is 106 cm and in Unit 3 it is 91 cm.

During high tide, higher water levels are observed in Unit 1 compared to Unit 3, thus the hydraulic gradient is directed downward. This proves that during high tides seepage flow from deeper layers could be excluded. During low tide levels, lower groundwater levels are observed in Unit 1 compared to Unit 3 and, therefore, the hydraulic gradient is directed upwards.

The average piezometric level in Unit 3 is slightly higher than the average level in Unit 1, meaning that these two layers can be considered hydraulically disconnected and Unit 2 can effectively prevent the flooding mechanism 4.

Since local soil heterogeneities, distance from the perimeter quay walls and the *gatoli* network, as well as their geometric features and state of preservation, significantly influence the hydraulic response of the entire subsoil system, 25 new piezometers were installed in 2019 at 10 monitoring sites distributed throughout St. Mark's square. According to the local conditions, it was decided to use 2 or 3 piezometers for each specific site, measuring the absolute pore water pressure in the different soil units (1, 2 or 3).

The main findings of the pilot site highlighted above are confirmed; moreover, new interesting considerations can be drawn. Figure 9 shows the pore pressure response in units 1 and 3 as a function of sea level for piezometer S05. The minimum ground level near this piezometric vertical is +84 cm l.P.S. When the tide increases, water enters the *gatoli* and can infiltrate the soil through their permeable walls; thus, the piezometric level in unit 1 increases. When the paving becomes submerged, the pressure response in the superficial layer is very fast because water can infiltrate from the top boundary. The maximum piezometric level may eventually be higher than the maximum sea level, as a consequence of some other significant contributions, such as rainfall or anthropic sources. After the peak, while the tidal level decreases rapidly, a slower response is observed in Unit 1, and for a certain time the pressure can be higher than the sea level. This can be explained considering that for medium water levels, water drains out mainly from the walls of the *gatoli*, and then, for very low tide level, only from quay walls or very deep ducts, resulting in a slower pressure dissipation rate. In addition, part of the superficial layer may become unsaturated during low tide, thus reducing its permeability. Numerical analyses considering different boundary conditions and unsaturated material properties confirmed this explanation (Ceccato et al. 2021).

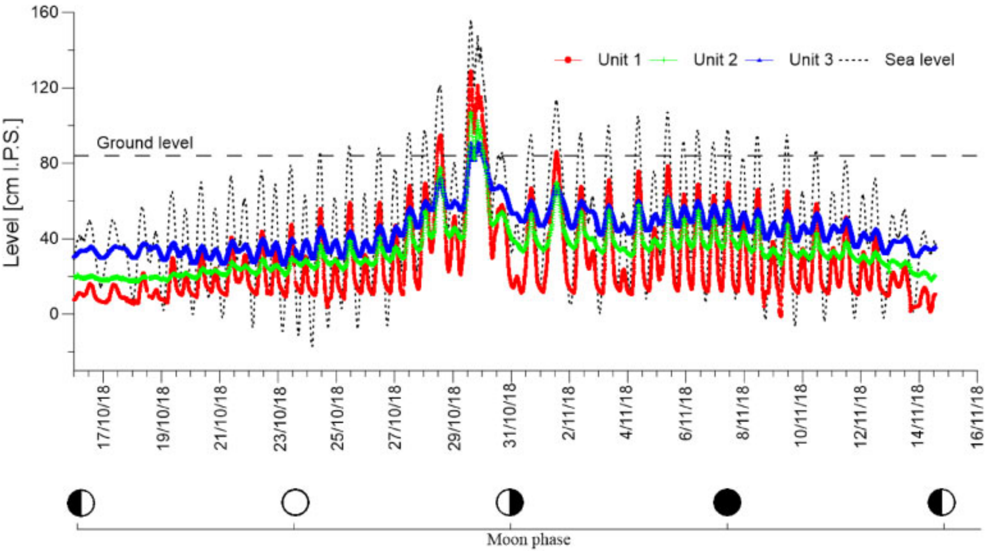

Figure 8. Piezometric level in different formations and sea water level along time.

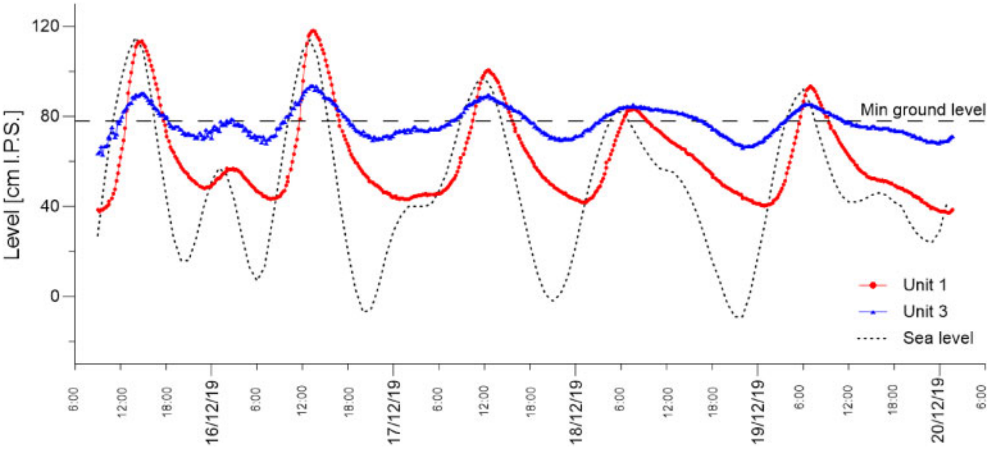

Figure 9. Piezometric level in different formations and sea water level along time in station S05.

5 OPTIMIZATION OF PROTECTION MEASURES OF ST. MARK'S SQUARE

As pointed out in Section 1, to protect the square against tides up to 1.1 m above s.l.P.S. a preliminary project was proposed in 1998, in which several countermeasures were planned such as:

- installation of vertical cut-off continuous sheet piling around the perimeter of St. Mark's island to avoid water infiltrating through and below the quay walls;
- installation of an impermeable membrane just below the stone pavement, to prevent seepage flow through the permeable joints between the stone elements;
- closure of the ancient drainage network by realizing a new one, collecting the rainfall water to be pumped and then discharged into a specific caisson realized close to the quay-wall facing St. Mark's basin.

This type of intervention appeared to be not only highly expensive, but also to impact heavily on the delicate equilibrium of the entire square subsoil. The main questions that arise in the more recent years are concerned with the real need of the sheet pile walls, which is very difficult to realize along with the island perimeter, as well as the effect of the impermeable membrane below the pavement, which could be subjected to uplift water pressure that rises into soil Unit 1 after high tides, as observed and shown in previous sections and in Figures 8 and 9.

For these reasons, a more gentle approach was discussed and selected, taking into account that:

- the seepage rate from the surrounding canals through the quay walls might be not so relevant as hypothesized in the project of 1998;
- the water uplift pressure could affect the long-terms stability of pavements if no free dissipation is allowed;
- the old drainage network system could be restored (as already done in the past) and used in a proper way to discharge the rainfall water.

To examine the effect of this updated approach to the design of the long-term safeguarding protection measures, a pilot test site was set up around the St. Mark's Basilica, whose narthex is the first one to be flooded, being its minimum level located at +0.62 m above s.l.P.S. The outcome of this field trial is discussed in the next section.

6 PROTECTING ST. MARK'S BASILICA

In 2018 specific protection measures for St. Mark's Basilica were realized to reduce the frequency of flooding of its nartex and surrounding areas that are the lowest of the entire island. The intervention consisted in the restoration of the old drainage pipes next to the Basilica with the installation of closing systems (valves) to avoid water backflow during high tides and a pumping station (Figure 10a).

The system is designed to operate for medium-high tides, i.e. between 62 cm above s.l.P.S. (the lowest level of the nartex floor) and 88 cm above s.l.P.S. (maximum ground level around the nartex). For sea levels lower than 62 cm, water can freely flow in and out of the system (Figure 10b). When the tidal level rises above 62 cm, the valves close and eventually the pumping station turns on, preventing the flooding of the nartex (Figure 10c). If the sea level rises above 88 cm, an overflow occurs, nartex flooding cannot be avoided and the pumping system is turned off (Figure 10d).

The MOSE system is currently operating to limit the maximum tidal level at 130 cm s.l.P.S. and in the next future this level will be progressively lowered to 110 cm s.l.P.S. The protection measures of the St. Mark Island is designed with this reference value and will be progressively realized in the coming years. Meanwhile, additional measures to prevent overflow are currently under discussion. The construction of a transparent and impermeable barrier of 1.20 m height around the basilica is being considered, among others.

The piezometric station at the south of St. Mark Basilica, that is, station P in Figure 5, is very close to the pumping system and these measurements offer information on the effects of the operating protection system on the pore water pressures in the subsoil.

Figure 11 shows the average piezometric level in units 1, 2, and 3 during the activation of the system. Only the piezometric level in Unit 1 appears to be influenced. When the sea level reaches 62 cm, the system switches on and the pressure immediately decreases. Afterward, it increases again following the tide, but the maximum piezometric level is lower compared to the case without an operating system. After the peak, when the tide decreases below 62 cm the system is deactivated and the pressure increases slightly, but it reduces rapidly following the descending sea water level.

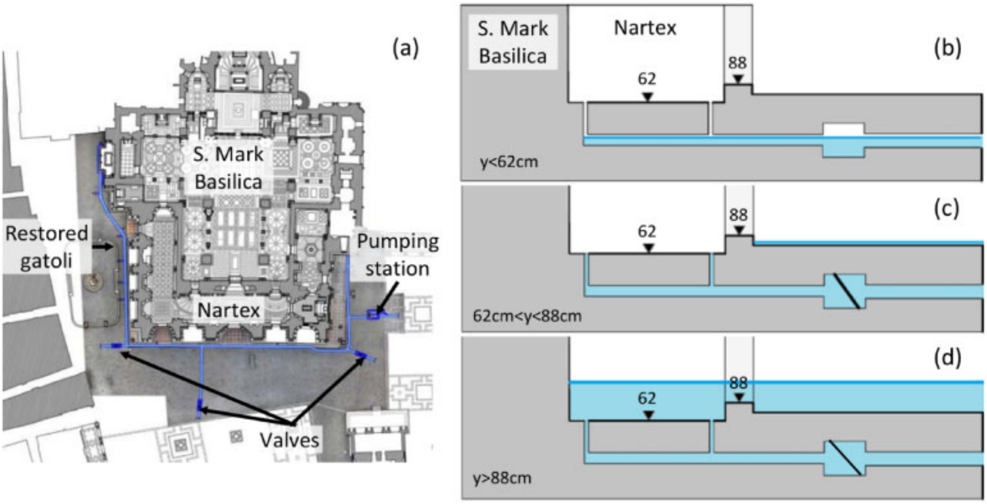

Figure 10. Protection measures of the St. Mark Basilica: (a) plan view of the improved drainage system, (b-d) simplified view of operating phases.

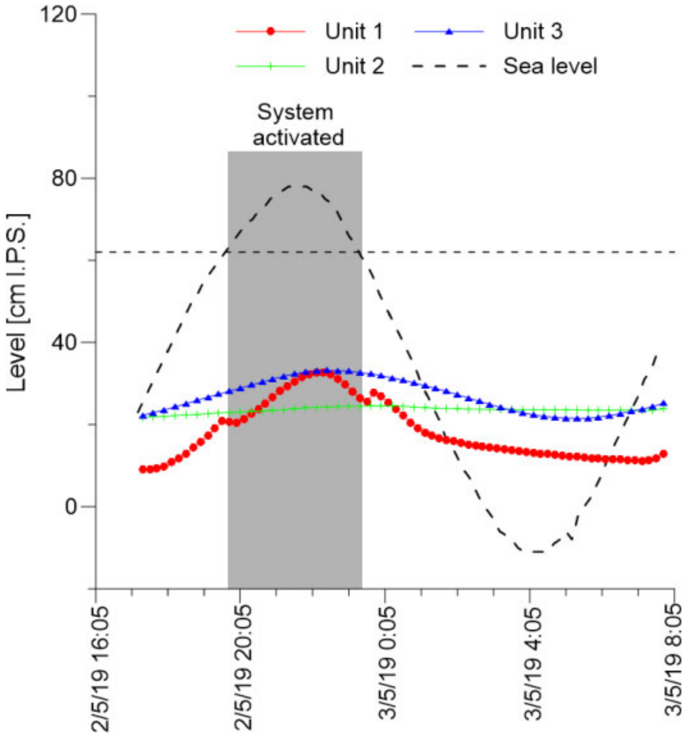

Figure 11. Average piezometric level in the ground measured in station P and sea water level during the activation of the protection measures.

7 CONCLUSIONS

The design of suitable flood mitigation measures to protect St. Mark's square against tide less than 110 cm required a multidisciplinary approach within which the geotechnical study played a fundamental role.

Within this frame, the results of geotechnical testing as well as the measurements of pore pressure oscillations in the soil of St. Mark's Square in Venice provided relevant information to guide the designer to optimize the most effective solutions that must also be respectful of the ancient situation of the entire area.

The local soil profile is characterized by a heterogeneous alternance of layers composed of a mixture of sand, silt, and clay in different proportions, but basically subdivided in three layers, whose intermediate one is composed of a fine-grained soil separating the upper permeable anthropic layer from the lower natural fine sands.

Fluctuation of the tide influences the pore pressure in both formations 1 and 3. The local vertical component of hydraulic gradient between these two layers is directed downward for higher tides and upward for the lower ones. Thus, seepage flow from deeper layer is impossible during high tide peaks. In the shallower layer, maximum water levels are close to lagoon level, whereas minimum ones are higher; moreover, the pore pressure may remain higher than the water level during tide decrease. This is a key phenomenon when carrying uplift analysis for the long term stability of paving especially in the more depressed area of St. Mark's Square.

In addition, it was noted that the seepage in the formation is characterized by very small flow rates, thus the actual infiltration flow to be drained is very low.

From all the observations and interpretation carried out so far, it was clear that the intervention such as the one selected for the area surrounding the Basilica and its narthex, could be extended to the whole square, showing that the previously hypothesized impermeabilization systems could not the proper solution to prevent the flooding due to seepage.

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