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New evidences on the Phlegraean bradyseism in the area of *Puteolis* harbour

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ABSTRACT: Puteolis, the modern Pozzuoli, is located in the centre of Phlegrean Fields; because of this geographical position, it was the main seaport of the ancient Rome, so as to be remembered by the historian Polybius and by the poet Lucilius as “Delus minor”. The data resulting from a series of investigations for the design of infrastructures allowed to re-elaborate the complex paleomorphology of the area and New reconstructions thesis, thus affecting the succession of natural processes and human activities which have profoundly changed the coastal area of Pozzuoli from ancient times to the present. It is shown that bradyseismic processes were already active in The Roman Republican Age and probably influenced the urban expansion, having an impact on the various the various stages of development and restoration of the city. On the basis of reported data, a reconstruction is proposed by the uplift and downward distortion of the ground surface during the centuries, with particular reference to the Macellum, that has been often used as a “marker” for the reconstruction of the movements of the Phlegraean area. In addition, and specifically the analysis of the materials of the old port quays confirm the indications reported by Vitruvius (*De Architectura, V, XII*), which was the only literary source on the construction of harbours in ancient times.

1 OVERVIEW OF THE LOCATIONS

1.1 Geological geographical overview

The area in consideration is located in the western sector of the still active volcanic district of the Phlegraean. Specifically, the study area belongs to the town of Pozzuoli (NA) along the coast and near the dock below the promontory of Rione Terra (Fig. 1). The key feature of the Phlegraean area, and of the its main town Pozzuoli, is the phenomenon of volcanic bradyseism (slow movement of soil) which caused an uplift of the ground of about 90 m in the last 10,000 years. In the caldera of the Neapolitan Yellow Tuff the bradyseism began between 10,500 and 8,000 years ago; the peak of upheaval was reached about 5,000 years ago.

Direct observations of the soil displacements have been recently carried out in the Phlegraean Fields, starting in 1969–1982. The coast line of the Roman period is found at an average depth of 3–5 m below sea level, and numerous ruins of Roman and medieval times at different depths below the sea level furnish evidence of general subsidence in the last 2,000 years. A reversal of this trend occurred before the eruption of Monte Nuovo (Fig. 1) in 1538, since the beginning of the XIV century, there

had been a slow uplift of ground, with an advance of the shore line in the coast stretch between Baiae and Pozzuoli. The eruption was followed by a slow subsidence that stopped only in 1969, when a new phase of rising started. Between 1969 and mid-1972, the Phlegraean Fields were interested by a first bradyseismic crisis, with upward displacements up to 1.7 m in the area of Pozzuoli.

In early 1982 a new phase of intense upheaval began, that reached a value of 1.8 m at the end of 1984. Since the end of 1984, a general slow subsidence resumed, interrupted only by occasional negligible uplifts.

The phenomenon of rising bradyseism is always accompanied by seismic activity earthquakes with a variable intensity, depending on the magnitude of the event.

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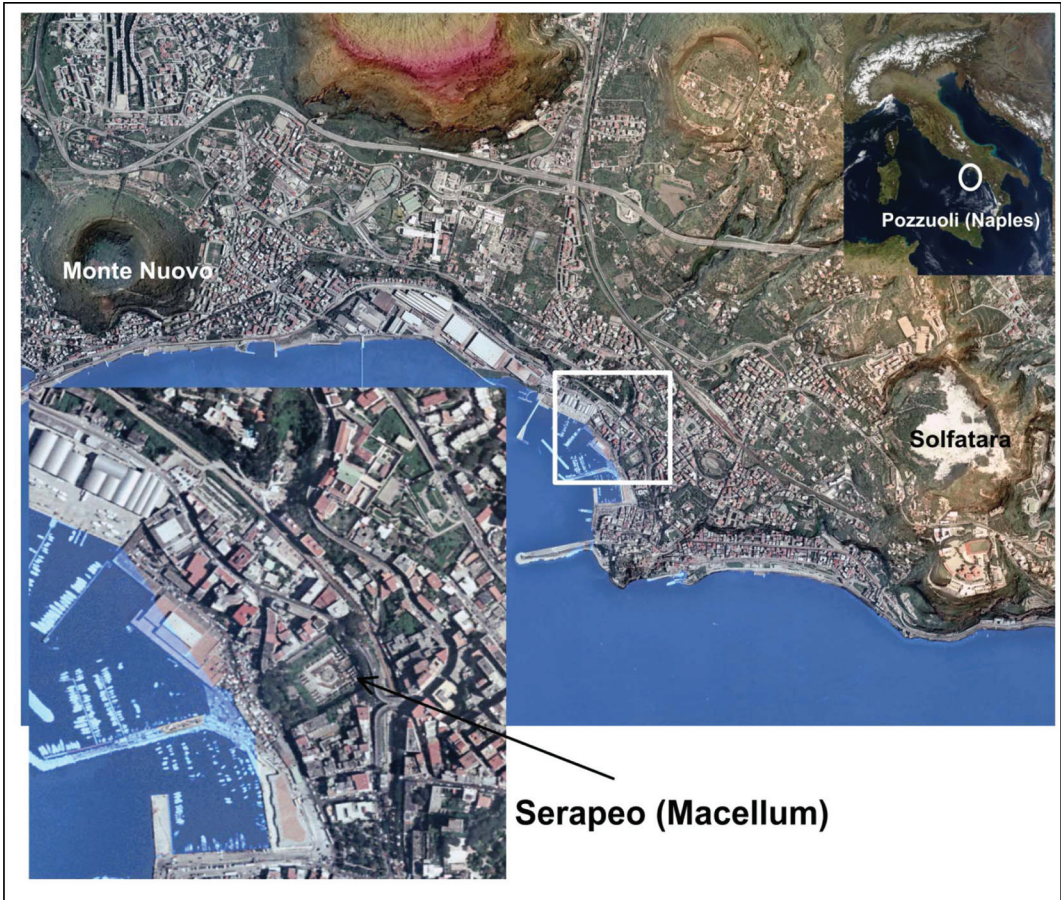


Figure 1. General overview of the Puteolis coast.

1.2 Historical overview

Information about the pre-Roman Pozzuoli is poor. In Roman times, the unique geographic position of the city and its status as a Roman colony, together with the increase of trade in the western Mediterranean, made the city soon become the main port of Rome, collecting the intense maritime traffic from Sicily, Africa and Orient to (supply) provide Rome of any kind of goods. Throughout the second century AD and up to Severian Age, Puteolis experienced a great edification phase. A restoration of the port establishments placed near Macellum, attested by an inscription (394 AD CIL X, 1692), shows that at the end of the fourth century AD the port was still in activity. Not many years later, however, the decline of the commercial activities of Puteolis and the increasing bradyseismic movements led to a progressive deterioration of the coastal district.

The so called Emporium, the great harbor district of Puteoli, developed along the coast north of the piers and north west of the acropolis; commercial traffic was concentrated in the Emporium, and large warehouses were built behind (at the back) starting probably in I or II century BC. Macellum (Serapeum) was its main building. The whole area was surrounded by piers with arcades towards the sea.

Little is left of Emporium and ripa structures. At present they are partly under water, partly covered by major reclamation works carried out over the centuries in order to raise the ground surface as a result of subsidence phenomena. Macellum (so-called Serapeum) is still visible; it was found in the mid-700 and early 800. The building, one of the largest known in the Roman world, is dated between the late first and second century AD. As we will see later, during the Saverian age substantial works of resettlement were carried out. The floor now visible and the central tholos with columns

that have always been considered the measure and the symbol of bradyseism, belong to this period.

2 RESULTS OF INVESTIGATIONS

2.1 *The reconstruction of the coastline*

The reconstruction of the coast line during the Roman Republican Era is characterised by a coastal strip much smaller than the reconstructions made in the past (fig. 2); The analysis of the sediments of the environment under water allows us to assume a bradyseismic uplift between The Republican and Augustus Giulius Claude Era, testified of sedimentary transition environment. Such phenomenon causes an advance of the coast line (to go forward).

The bradyseismic uplift, together with the development of the port of *Puteoli* and in relationship to the stockage of wheat in Rome, could be one of the factors which has contributed to the high development of the city plan and has radically changed the lower part of the city. The significant presence of structures found through the surveys, especially in unknown areas, confirm the conservation intervention of the *ripa*, with the accomplishment of an enormous system of quays, which allows to gain ground and therefore let the costal line go forward.

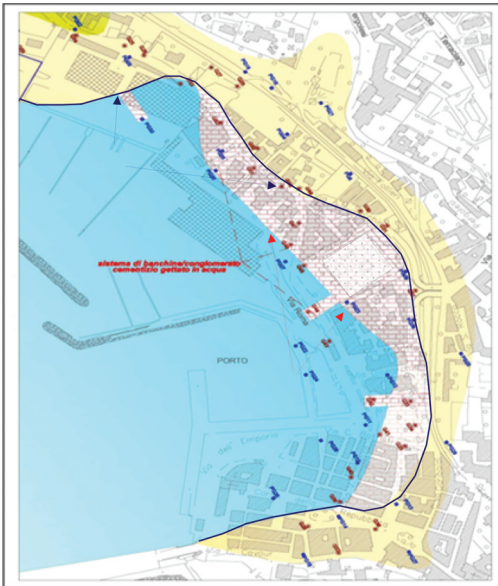


Figure 2. Reconstruction of the costal line in The Republican Age and development of the extension of the port quays towards the sea during the Imperial Age.

Survey, in fact, intercept a first level of structures made of conglomerate cement (*opus caementicium*) of substantial thickness.

The characteristics of the material, as well as the height of placement above the grade level built by submersed sands, thrown in water, within wooden formworks. The dating of archaeological material unearthed, consisting of fragments of Italian ceramic and sealed thin walls, allows you to frame the complex of actions at the first Imperial age, starting from the Augustan period.

It is on this impressive work of filled that builds the *Macellum* (market), prominent position overlooking the sea. Below, in order to clarify the development over the centuries of bradyseism phenomenon and, therefore, of the various phases of the monument, referring to the annexed section rebuilt sequence (fig. 3), positioned on the *Macellum* has always been used as a “marker” for the study of the deformation area. Recent surveys made it possible to clarify the development over time of the area and to add new information to those deriving from the eighteenth and nineteenth century excavations that signalled a further floor subjected to 2 metres at that age currently visible Old Flavia-Trajan.

In particular, it was found a floor plan in *Opus signinum* (*cocciopesto*) at about -3.5 MASL (I floor-cf. S21 S23 and S24), place in opera immediately above the quay of the Augustan period, created by a thrown overboard in *opus caementicium*.

The discovery of the same floor with more core, located further north, suggests that this pavement was extended to cover the entire surface of the platform. In such a case, unless caught, the flooring was destroyed or eroded by the sea during the next phase of subsidence.

Returning to the area of the *Macellum*, the floor above was the first floor of frequentation, dating probably to the Augustan period. The tempering of the roof of the docks (about -3.5 MASL.), together with the pavement plans dimensions allow to hypothesise an average sea level to an altitude of era $-5.00/-5.50$ m than at present.

Next, you pick the signs of a cleanup construction, probably made in Old Flavia, suspect in S21 (fig. 3) the construction of a structure resting on the floor in *Opus signinum* described above.

This structure was to be part of a broader intervention including the walls intercepted in PG23 and S22 (collapse); there are no items to define whether the structure caught in S24 was in the same building or stage, being more backward, might be already there.

Noting that survey PG23, S21 and S22 are located in the most advanced portion towards the sea, although missing clues of a marine ingressión

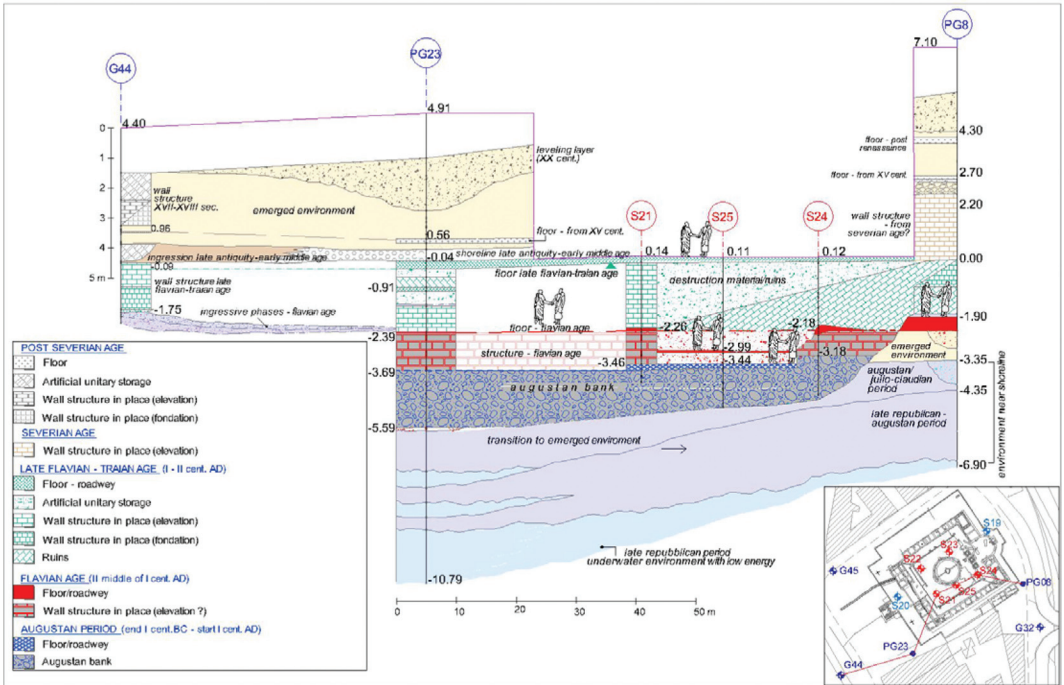


Figure 3. Geoarchaeological and lithostratigraphic section in correspondence to the Macellum (Serapeum) of Pozzuoli.

and subsidence phenomena, we cannot exclude the possibility that these structures represent the elevation of the platform in order to counter the advance of the sea and protect the rear area of the *Macellum*. The hypothesis is comforting in its evidence of attendance plans makeover of *Macellum* in higher dimensions (S25: -2.99/-3.09 MASL) first at about -3 MASL current (II floor) and later a -2.2 MASL current (3rd floor). The latter level is well connected with the dimensions of these floors to the top of the structure in high on the quayside. They stood at about-current 2.3 MASL—about 1 m above the previous 1st floor in Opus signinum (S23: -2.07/-2.27 MASL; PG23: -2.44 2.39 MASL.; PG21: -2.26/-2.36 MASL), almost the same height of a stone pavement, that can be related to a road plan, found in PG8 (-2.35/-2.60 MASL).

Unfortunately, the absence of material dating in accumulations ranging from floor plans of the *Macellum* does not allow a precise chronological sweep of remakes. However, the finding of coarse sands in the accumulation on which rested the last floor in S25, strengthens the hypothesis of marine ingression as determining cause of resets, which would then be linkable to the Late age of Flavia—Trajan subsidence.

The data is also consistent with the lower floor plan of *Macellum*, unearthed in the excavations made in the last centuries, dating to the flavian time, testified about -2.00 MASL. (fig. 4).

Already in Late Flavia Age, the data indicate a reversal of the processes for all bradyseism, with the beginning of a phase of subsidence which causes the surfacing of the aquifer. The deposition of silt on the quays leads to significant works of renovation and elevation of floor plans. The investigations have identified, in coastal areas affected by the construction of the quays in the Augustan Age, levels of collapse and breakup with silt and deposits silt-sandy soils, with thicknesses ranging from a few centimeters to about 2.00 m. The characteristics of these deposits bear witness to the presence of ingressive phenomena of an aquifer outcrop, sub-that does not cause the submergence and the abandonment of the area, but require a series of interventions by raising and reconstruction of port facilities and their floor plans.

In this phase can be attributed the current flooring (4th floor) of the monument, come to light as a result of the excavations taken in 1750 by Charles III of Bourbon, King of Naples, and later King of Spain, in the place known as la Vigna of the three columns. The most backward sectors, on the other

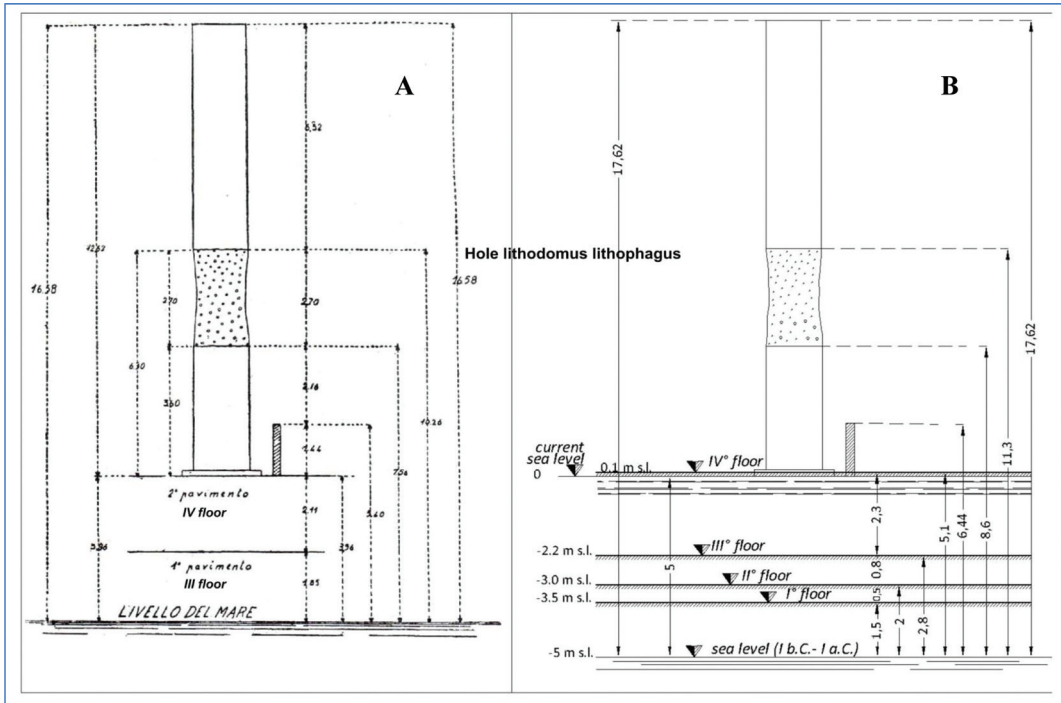


Figure 4. A) Section of the columns of the *Macellum* (Temple of Serapis) with highlighted dimensions for the holes of litodomi, the first floor of Flavia Age and the second of Late Flavia-Trajan (*Parascandola*). B) Modified Section in relation to 2012 data with evidence of four trampling found plans and quotas.

hand, for all bradyseism movements are witnessed by the presence of thin layers of silty granulometry abandonment, but without the powerful melt-downs that characterize the coastal area.

Currently available data indicate a partial rearrangement of some surrounding areas the *Macellum* is rearranged, too, as evidenced by a fistula plumbea with the name of Septimius Severus and the construction of the tholos in the middle of the marble Court.

In ancient and medieval age the negative bradyseism phenomena, well attested and known from the analysis of the sources, as well as the study of the traces of the litodomi (*lithodomus lithophagus*) on the columns, cause sea level rise up to +7/+8 m and abandonment and the submergence of the lower town. That period does not have testimony from investigations being predominantly erosional ingressive this stage.

During Vicerealand Bourbon Age, sedimentation consists generally of beach sands, which testify to the emergence of post medieval city, with an advancement of the coastline. These are, in fact, the full emergence stages of lower town area in relation to the eruption of Monte Nuovo (1538). This leads to a new urban development plan of the city,

of which we find traces in the investigation with the discovery of remains of structures in the area in front of the *Macellum*. Later, between the 18TH and 20th century large sectors of the coastal area of Pozzuoli are affected by drainage and levelling works tending to raise the floors, in relation to new stages of active subsidence since the first half of the 20th century, when the well-known lifting crisis between 1984 and 1972 have reversed the “trend”.

3 THE FILLED OF QUAYSIDE

Particularly important is Pozzuoli in the history of port engineering, for the use of *Opus caementicium* in dispose of wharves and dams. The fact is already highlighted by Strabo (V,4,6) that, talking about the “huge” trading port of Pozzuoli, recalls the “artificial anchors (which could do) thanks to the favourable nature of the dust”, the *pulvis Puteolanus*, still called *pozzolan*.

We have already mentioned material characteristics of *opus caementicium* consisting of building debris of tufa, in plenty of Pozzolan mortar, extremely rich in lime nuclei not dissolved and, in some cases, not completely wrinkled, which is the

backbone of making enlargement of the quays in the Augustan period. The material composition confirmed as reported by ancient sources, in particular by Vitruvius, on the implementation of ports, describing in *De Architectura*, V, XII fundamental techniques of construction of water structures, based on three methods: the first two illustrate the works to be done directly at the point of destination, using discarded in wooden formworks; the third contemplates the implementation ashore of prefabricated blocks to throw then into the water. Only for the first way, Vitruvius explicitly prescribes the use of *opus caementicium* with pozzolana: “the structure of the pier will remain under water must be made with powdered pozzolana imported from that region that stretches from Cuma until Minerva promontory (Punta della Campanella—Sorrento), mixing it so that it is in proportion of two parts for one (lime)”.

The same author also describes the properties of *pulvis Puteolanus*, implying: Pozzolan aggregate quality that allows the mortar to resist water and solidify even in very humid environments, thanks to the presence in a considerable quantity *pulvis* of aluminium silicate. In summary, adding the pozzolan lime to lime, this is transformed into hydraulic lime.

In our case, the manufacturers had added as *caementa* and fragments, blocks of tufa, material rich in zeolites, which are of silico-aluminate hydrates of alkali metals and/or alkaline-earth metals (chabazite and phillipsite). It follows, unknowingly, an improvement of the hydraulic reaction.

The pozzolan was also exported from Pozzuoli to the shores of Palestine, such as the construction of the port of Herod to Caesarea Maritima, as was, in fact, a perfect return for cargo ships carrying grain from Alexandria to Puteoli.

As regards the construction of docks, given the opportunity of convenient supply of *pulvis Puteolanus* and thrown directly on the sand, we can assume that the realization has occurred according to the dictates of the first method illustrated by Vitruvius, or “formwork flooded”. This was, in fact, the simplest and cheapest method. The salient feature for the thrown in water consists in absence of tinning of this type of case, which, according to Vitruvius, was not to even get the Fund.

In fact, once assembled the structure, “(the) inferior pars sub aqua was exaequanda et purganda. Quote: “then, at that point, you must sink and secure with safety of formwork systems held together by oak uprights and cross ties; then, in the inner compartment, (working) from sleepers to level and clean the bottom (*exaequanda et purganda*) and throw the mortar, prepared as is explained above, mixed in the debris of stone, until the space between the bulkheads is not filled with concrete”. Vitruvius gives, however, a “partially improper” explanation

of the chemical quality of the pozzolan: improper, because he doesn’t know the reaction that occurs in the transformation from the lime hydraulic lime and the chemistry that implies; partly because in his description of *pulvis Puteolanus* (*De Architectura*, II, VI.1) writes: “and this seems possible because on the slopes of Mount there are lands and hot springs for the presence of underground deposits of sulfur, alum and bitumen that feed huge fires”.

4 DATA ANALYSIS

4.1 The curve of ground deformations over time

As already stated, the *Macellum* is always identified as “marker” for the study of deformative movements the Phlegraean area. The importance of Phenomenology of bradyseism is presented in the masterful artwork of C. Lyell, ‘Principles of geology’ of 1830–33, in which the author, in order to support the principle of actualism which interpretation of the phenomena of the past, as an example the bradyseism phenomenon of Pozzuoli, where the columns of the *Macellum* had recorded the slow and steady ground motion over the centuries. (Lirer, et al. 2010). It is worth mentioning that, along with a number of distinguished scientists, even W. Goethe had expressed his opinion on the Phenomenology, however, attributing the cause to changes in sea level.

The data emerged from the studio, allow a re-reading of the curve of ground deformations over time (fig. 5).

Rebuilding takes as its reference the first floor of the Augustan period, assuming a share of tax of 1.5 MASL. This was necessary in order to reconstruct the pattern of landuse changes in ancient times, and have a reference level of course. On the basis of those data also the curve is rebuilt on the 4TH floor (currently visible) dated to late Flavian-Trajan Age.

The two curves are proposed in consideration that you can rebuild properly the ground deformations without considering the fillings made in ancient times.

Currently the floor is at an altitude of around –3.5 MASL. The values on the curve are relative to the likely location of the floor in relation to the distances that separate it from “markers” above. For example, in the case of the fourth floor, there is a thickness of 3.5 m. Assuming, then, a set of the fourth floor of 1.5 m above sea level, the floor will be at an altitude of –2.0 MASL.

The maximum depth of sinking is normally considered about –6.3 m, in relation to the litodomi holes present on the columns of cipollino marble of the *Macellum* from current level of marble flooring (in this note IV floor—fig. 4), which are

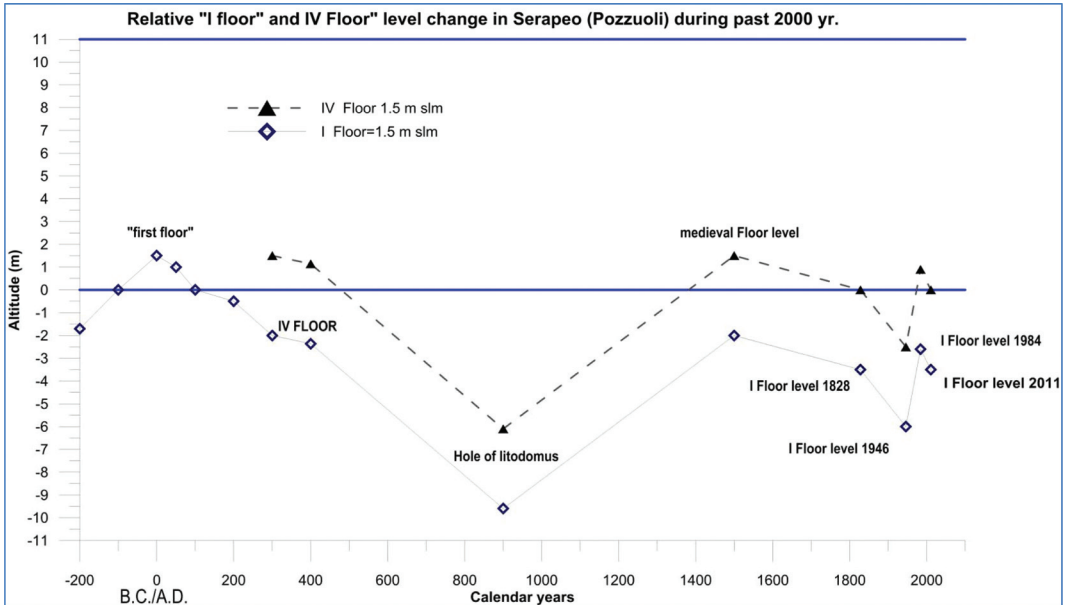


Figure 5. Curve reconstruction of ground deformations with reference to the fourth floor and the Augustan age of the *Macellum*.

supported by columns, which, as we have seen, is placed on an artificial grabbing works of about 3.5 meters compared to the floor to counteract the phenomena of soil sinking. Therefore we believe that the correct measure of maximum depth of soil sinking, with reference to the floor plan (fig. 4), or -9.8 m, or -11.3 m if referring to likely sea level.

If we take into account the curve on the 4th floor of the late Severan flavia-age, placing it at an altitude of 1.5 MASL. at the time of its realization and maintaining intact the relations underlying floored, it notes that the proportion of an litodomi holes on the curve at a depth of -6.2 m, very close to the real measured as distance from the 4th floor and also by the reported *Parascandola* (1983). Analogue of speech can be done to the medieval floor, whose share was approximately 1.3 MASL. As regards the measures starting in 1828, they know the odds of the fourth floor and then is easy to reconstruct both curves.

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