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Safety assessment of the foundations of the Basilica of Maxentius in Rome

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Abstract

The construction of Massenzio's Basilica was begun in 306 A.D. by Marcus Aurelius Valerius Maxentius (278-312) and was ended in 313 by Costantine. Originally it covered an area of almost 6000 m^2 and was composed by three naves; two of them collapsed, probably after an earthquake, in the very early middle age. Today we can see only one of the naves composed by three big arches, 25 meters high and 20 meters wide, running for 80 meters parallel to the present day *Via dei Fori Imperiali*. The behaviour of the soil has a determinant role on the present condition of the Basilica, which resulted from various morphological modifications from the construction time to the last century. Thus a deep knowledge of the nature of the foundation soil and of its mechanical behaviour are elements of primary importance for understanding the static conditions of the Basilica and designing a conservative restoration. Many studies have been carried out on the Basilica foundations: three campaigns of borings in the subsoil, the definition of the mechanical characteristics of the soil layers; a campaign of borings into the masonry and the measurements of its mechanical characteristics. The recent studies on the building behaviour have been focused on the *Carinae* pier. Here new excavations are being made to reopen the *Arco del Latrone* passage, presently occluded by soil and demolition materials. This project is particularly delicate because of the seven-meter ground drop between the inner and the outer sides of the pier that impairs the whole structure stability. Therefore a numerical F.E. model of the behaviour of the structure was done, taking account of soil behaviour and of the building history. Studies and archaeological excavations are still going on in order to gather further elements on the behaviour of the equilibrium conditions of the Basilica, in the area close to the *Arco del Latrone.*

1 Historical background

The construction of the Basilica was begun in 306 AD by Marcus Aurelius Valerius Maxentius and completed by the emperor Constantine in 313 AD. The Basilica rose on the Velia, a steep hill on the eastern boundary of the Roman Forum, near the "*Templum pacis*" and the west gate of the "*Domus Aurea*". The Basilica was a building for public life and for town administration: actually it was used as a law court and a public forum.

The building was divided into a nave and two aisles, the nave being 35 metres high while the aisles were 25 m, and covered an area of almost 6000 m^2; the aisles were formed by three barrel vaults, the nave by three cross vaults. Originally the Basilica had only one apse on the west side and its main entrance was situated on the eastern side in front of the *Colosseum*, but during the construction, Costantine, the emperor who defeated Maxentius (and this is why the Basilica is also known as the Basilica of Costantine), changed the orientation of the Basilica by building a new entrance on the southern side (facing Rome's main street: the *Via Sacra*) and a new apse on the northern side. The design of the Basilica subsequently became the architectural model for all the Christians basilicas.

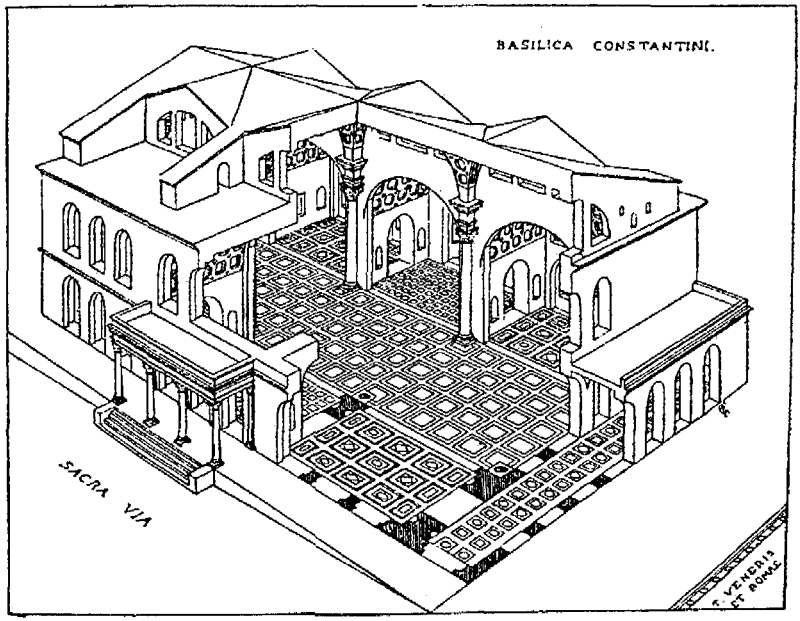

Figure 1: Reconstruction of the Basilica

Major earth movement works were carried out to create the flat ground where the Basilica rises: the south-western part of Velia hill was excavated and the cut was sustained by a retaining wall running parallel to the north-eastern side of the building; the southern part of the Basilica's floor plan was built on the ruins of ancient spice warehouses (*Horrea Piperataria* and *Horrea Margaritaria* destroyed by a major fire in 284 AD), that were incorporated into the foundation of the Basilica and filled with earth taken from the Velia hill excavations. The walls and the piers were built with two external faces of triangular baked bricks held together with mortar and filled with tuff, travertine and concrete; the two faces of the wall were linked together at intervals of one and a half meter by a layer of *bipedales* (a baked brick about 60 cm, or 2 feet, long). The foundation walls were made of *opus caementicium* (concrete with travertine aggregates), probably cast in situ in timber-lined trenches. Every pier has its own foundation; their depth increases from east to west according to the Velia's natural slope, from 4 meters below the Basilica's plan (*Colosseum* pier) to 14 meters (*Carinae* pier).

Nowadays only one of the naves is still standing; the other two collapsed, probably as a result of an earthquake, in the very early Middle Ages; this nave covered by three barrel vaults runs for 80 meters parallel to the present day *Via dei Fori Imperiali*.

2 Present conditions

Recent studies on the static conditions of the Basilica and of its present behaviour have been initiated in conjunction with the plan to reopen an old passage way, in the Medieval Ages called *Arco del Latrone* (literally the Burglar's Arch), passing under the apse to connect the north-eastern side to the *Via Sacra*, and presently occluded by soil and masonry deposits. Therefore attention have been focused on the *Carinae* pier, close to the passage, where the ground level drops by about seven meters from the Basilica's inner and outer sides, subjected to the unbalanced vault thrust. The static condition of the *Carinae* pier is therefore critical for the equilibrium of the entire structure. The collapse of the upper part of this pier removed a large portion of the weight that was necessary for the stability of the vault; the critical equilibrium condition of the *Carinae* pier is confirmed by two horizontal cracks on its inner side.

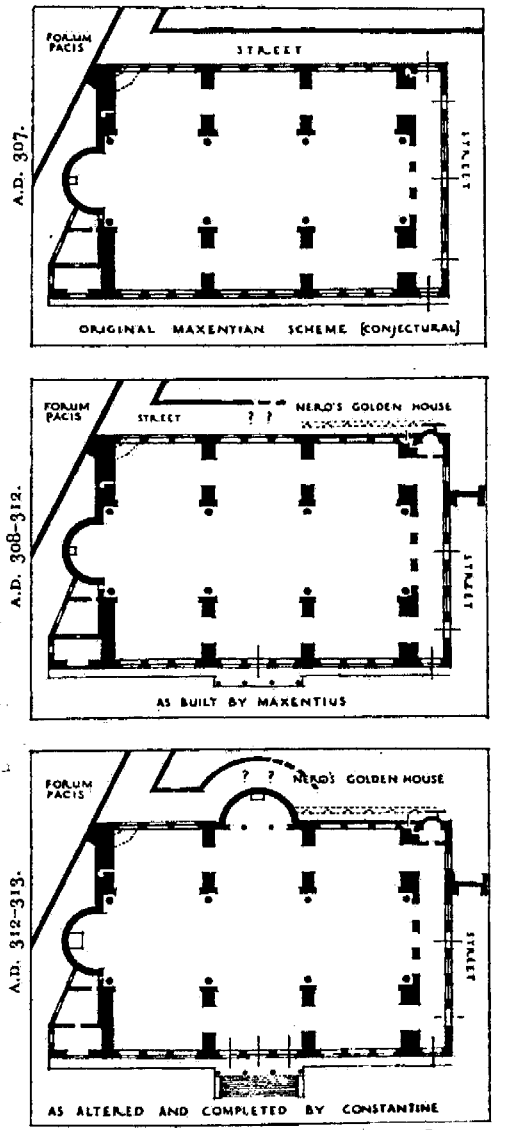

FIG. 3. STAGES IN THE DEVELOPMENT OF THE BASILICA, SHOWING DEPARTURES FROM THE ORIGINAL PLAN.

Figure 2: Stages in the development of the Basilica

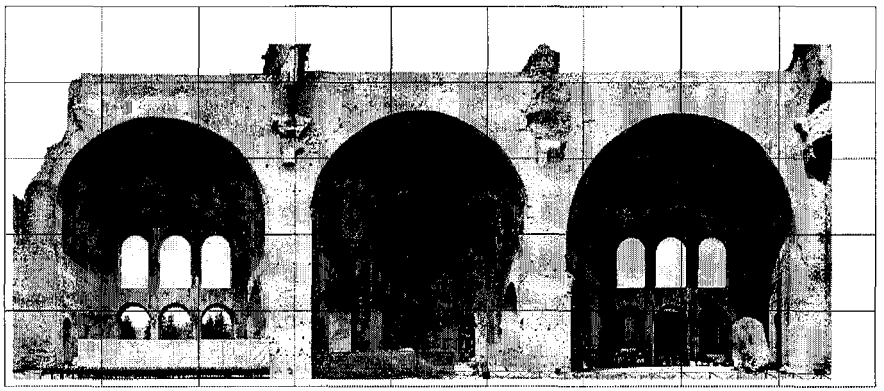

Figure 3: Massenzio's Basilica

3 Analysis and mechanical characterisation of the subsoil

Therefore in 1999 a campaign of borings into the masonry were carried out in the area of the Basilica in order to gather further elements about the mechanical characteristics of the masonry and about the bearing surface of the foundations. Twelve rotary drillings were executed in the walls and the foundation of the Basilica. Several samples have been taken and tested in the structure laboratory of the University of Rome.

Right from the beginning of the studies on the Basilica it was clear that thorough knowledge of the subsoil and of the morphology of the foundations was essential to understand the equilibrium conditions of the Basilica; therefore a campaign of borings in the subsoil was carried out in the area in 1999. It consisted in five geotechnical boreholes with a maximum depth of 32 meters and in six structural drillings through the foundations of the piers of the Basilica. Geotechnical boreholes (S1-S5) were aligned along two parallel sections in order to reconstruct two stratigraphic sections of the subsoil of the Basilica, in order to better understand the sequence of the soil layers in the area, while structural drillings (F1-F6) had the aim of defining foundation depth and morphology. Since all the foundations of the Basilica rest on the same light brown silty layer, ten undisturbed samples were taken from it for laboratory mechanical tests. The structural drillings allowed to examine the masonry characteristics and to ascertain the depth of the foundation base which increases according to the natural slope of the hill, following the traditional technique of Roman constructions.

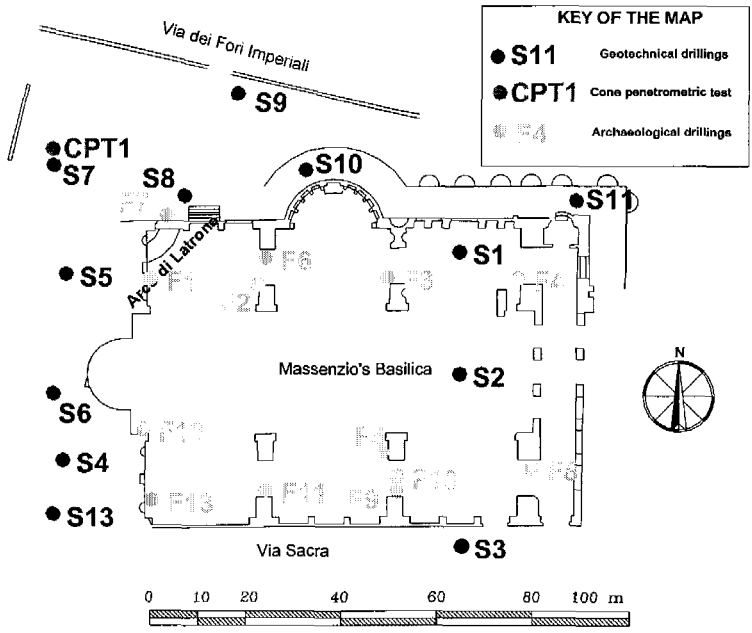

Figure 4: Drillings map

Two years later, in January 2001, a new geotechnical investigation became necessary to supplement the first campaign. It aimed at defining a more precise longitudinal stratigraphic section, which could be used in a F.E. analysis of soil and structure behaviour. A second purpose of the new campaign was to gather additional information about the soil characteristics in the area between Via dei Fori Imperiali and the Arco del Latrone. The national archaeological authority proposed new excavations, very close to the structure of the Basilica, that were liable to undermine the stability of the whole structure by decreasing the retaining action of the backfill on the pillar of the north-western vault. The new investigation consisted in seven geotechnical boreholes, close to the north-western corner of the Basilica, and seven archaeological drillings, six through the foundations of the southern piers and one in the northern side of the Arco del Latrone, designed to ascertain the thickness of the arch basement. A geo-radar investigation carried out on the north-western corner of the Basilica to locate underground structures showed the existence of masonry remains all around the Basilica. The whole set of investigations allowed to define sufficiently accurate geotechnical sections, which showed the presence of the light brown silt layer under all the piers of the existing nave; this is followed by layer of brown clay a few meters think, then by a thick stratum of gravel and sand with clay intrusions; the Pliocene clay bedrock was found at about 35 meters under the Basilica's plan.

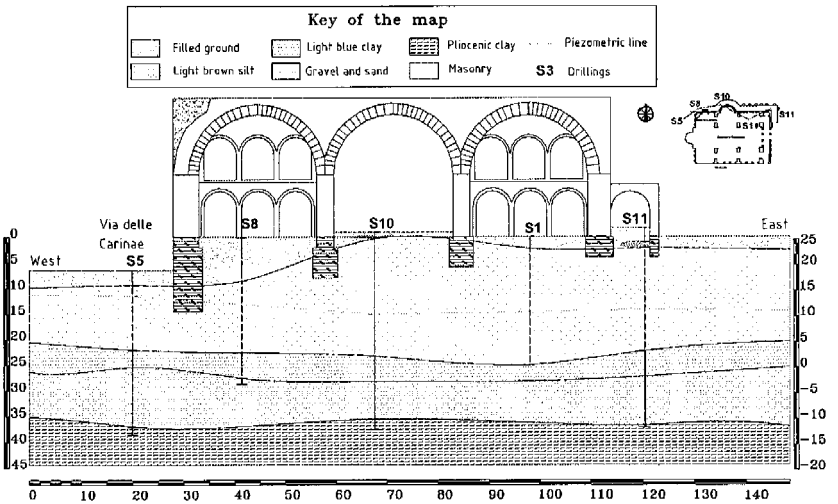

Figure 5: Stratigraphy under north nave

The undisturbed samples of the light brown silt layer were thoroughly tested in triaxial cells. The shear modulus at very small strains (γ<0.001%) was measured by means of bender element tests. Small electromechanical transducers, set in the cell bases, transmit a transversal wave train from one base of the sample to the other; the shear modulus is derived from the run time of the wave train through the relationship between the material density and the wave speed:

$$G_0 = \rho \times V_s^2$$

where G_0 is the initial shear modulus, Vs the transversal wave speed, r the volume density. The relationship proposed by Viggiani [1992] was applied to derive the in situ shear modulus from laboratory tests, taking into account the influence of the OCR (over-consolidation ratio) and p' (effective pressure in situ):

$$\frac{G_0}{p_r} = S \times \left(\frac{p'}{p_r}\right)^n \times \left(\frac{p_e'}{p'}\right)^c$$

where c takes into account the OCR, p' is the mean effective stress, p_e' the equivalent pressure and S,n,m are empirical coefficients correlated to the plasticity index. The results of strength and deformability tests on the light brown silty samples are gathered in the following tables:

Physic characteristics		
Unit weight γ	kN/m^3	19.6
Water content w	%	24.9
Liquid limit LL	%	40.5
Plasticity Index IP	%	19.5
Activity A		0.7
Grain size		
Sand	%	25
Silt	%	60
Clay	%	15
Mechanical characteristics		
Compressibility index C_c		0.2
Swelling Index C_s		0.03
OCR		1.8
Cohesion c'	kPa	60
Friction angle ϕ'	°	27

4 Numerical F.E. model

The analysis of the Basilica's present condition was carried out by means of a numerical F.E. model taking into account the mechanical behaviour of soil and structure, their interaction and the monument's history. The program chosen to perform the analysis., Plaxis, allows solving bi-dimensional non linear problems of soil-structure interaction.

Because of Plaxis's features the structure of the Basilica has been ideally cut with a vertical plane going from east to west, trying to represent all the principal characteristics of the building. The representative section of the Basilica's geometry is 80 meters long and 25 meters high and runs parallel to *Via dei Fori Imperiali*: this longitudinal section shows the existing nave, with the *nartece* on the east side and the seven meters drop from the Basilica's plan to *Via delle Carinae*, on the west side. The construction sequence and the history of the masonry structure was taken into account thanks to a particular feature of the program that allows the activations and deactivations of model portions. Four subsequent steps were analysed:

- building of the foundation and of the Basilica's plan;
- construction of the naves;

- fall of the upper part of the *Carinae*'s pier;
- ground level decrease on the west side;

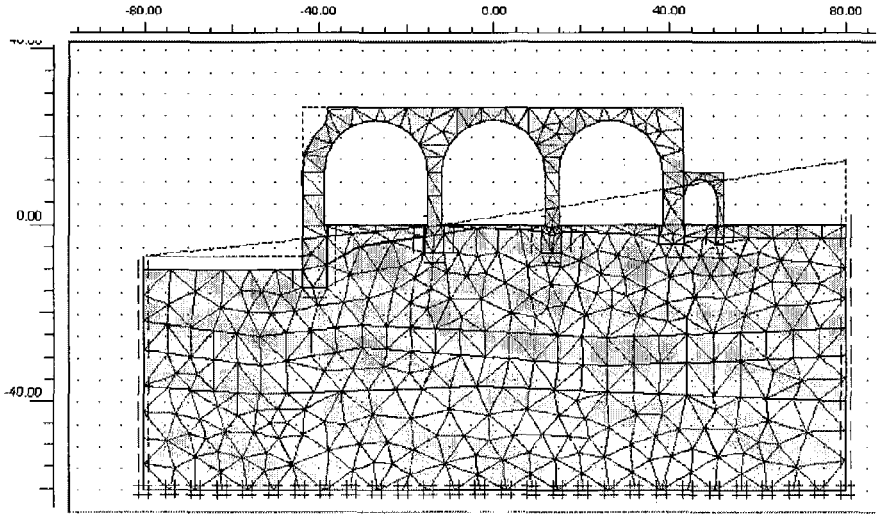

Figure 6: Model's mesh.

In the initial conditions the hill's natural profile is assumed going from east to west at a constant slope. Then the Basilica's internal plan and the foundations are created together with the ground level modification. Then the construction of the naves follows; the structure of the Basilica is modelled without taking account of its cracks and of the present deformation. The fall of the upper part of the *Carinae*'s pier is then examined with the variation of ground level on the west side. The Basilica's masonry is implemented in Plaxis as an isotropic material with a elastic linear behaviour, because a more complex behaviour is not justified, since the ancient roman concrete has an elastic behaviour up to the 50% of top strength in simple compression, whilst we don't know the masonry's behaviour for more complex stress states.

Soil's stratigraphy is very homogeneous all over the area of the Basilica and the thickness of the layers are almost regular along all the nave. The soil stratigraphy has been described by five principal layers. The ground water level is found at about five meters from ground level, as measured by the piezometers installed in different borings.

Different constitutive models implemented in Plaxis required different inputs. The soils' mechanical characteristics implemented in Plaxis are taken from the results of the laboratory's mechanical tests and from the bender elements tests for the light brown silt: these tests consent to recognize the elastic modulus of

soil from very little deformations and therefore to define with high precision the very first elastic modulus.

	Constitutive model	Friction angle ϕ (°)	Cohesion c' (kPa)	Elastic modulus E (MPa)
Filled ground	Mohr-Coulomb	29	15	125
Light brown silt	Hardening soil	27	60	73
Light blue clay	Hardening soil	24	15	63
Gravel and sand	Mohr-Coulomb	40	0,2	150
Pliocene blue clay	Mohr-Coulomb	25	30	400

5 The present static conditions and the effects of the proposed excavations

One of the purposes of numerical analysis was to follow the history of the existent part of the Basilica, with the intention of recreating the same conditions: for that reason in the model only the north nave is represented. Another intention was to analyse the behaviour of soils: therefore Plaxis's calculations were set taking account of the flow of the time, changing in every step the characteristics of soils, in particular in relationship with water.

The outputs of Plaxis's analyses show a deformed condition of the structure that is comparable to the present situation of the Basilica as it is possible to see in the deformed mesh image; moreover in the plastic points' image we can observe that points of traction and compression well agree with the main visible cracks and deformations:

- a horizontal compression crack runs on the inner side of *Carinae*'s pier, well evidenced by the plastic points that cover all the external (traction) and the internal (compression) surfaces;
- cracks that run all along the intradoses of the vaults are showed by the white plastic points that indicate traction;
- the observed maximum deformation on the external face of the *Carinae*'s pier is comparable with the estimated one in the deformed mesh.

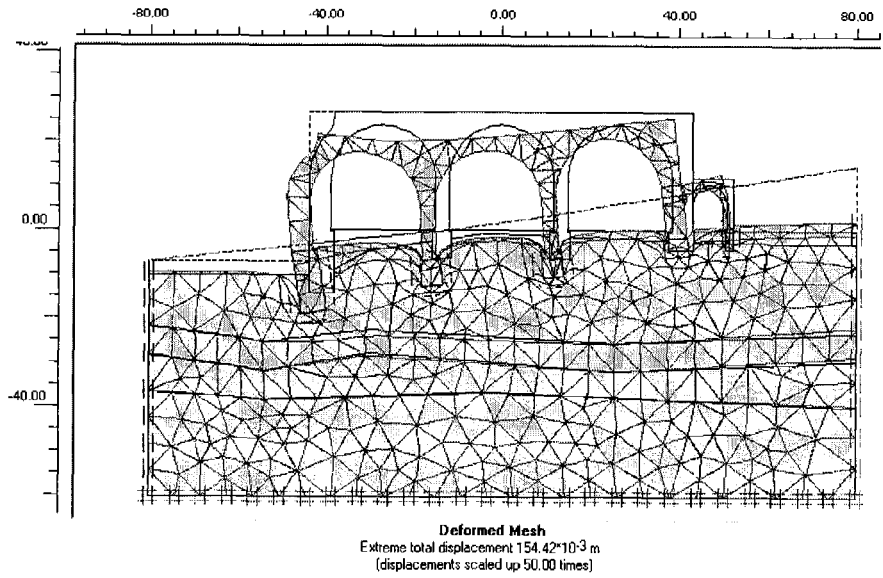

Figure 7: Deformed mesh (scaled up 50 times).

The analysis of the interaction between structure and soil evidences the particular state of the foundation of the *Carinae*'s pier, that also sustains the seven meters' drop between the inner and the outer side of the pier and consequently retains the earth's thrust. In fact in the relative shear image it is possible to observe that portions of light brown silt get to the maximum shear resistance achievable under the foundation of the pier facing *Via delle Carinae*. The analysis evidences the difficult conditions of the foundations of the other piers under which soils' stress are very high. Therefore Plaxis analysis and the present condition of Massenzio's Basilica point out the particularity of *Carinae*'s pier and its involvement in the stability of the entire structure. This is very important because in this area new excavations and new works are planned by the roman archaeology authority.

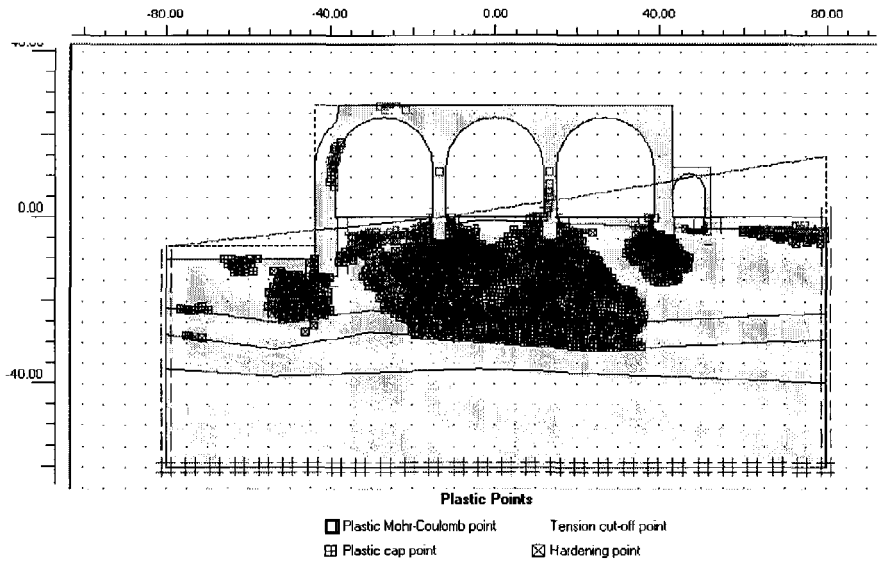

Figure 8: Plastic points.

6 Future works

In past years different works have been carried out in the area of Massenzio's Basilica in order to improve general safety conditions of the structure:

- completely rebuilding of the roof, with a new pavement of bricks that upgrade the waterproofing of the structure, avoiding dangerous percolations that could weaken masonry;
- realization of an accessible terrace for tourists on the new roof ;
- rebuilding of a portion of external masonry on the top of the *Carinae*'s pier to replace the existent one and to improve the durability of the structure exposed to meteorological phenomena;
- reinforcing with tie-rods parts of decoration that could fall.

These preliminary works intend to improve the general safety conditions of Massenzio's Basilica and to be a first step of restoration works that the roman archaeology authority wants to carried out in all the area; these future works aim to reopen the *Arco del Latrone* passage, now occluded by soil and masonry, and to create a new access to the *Fori Imperiali*'s area from the subterranean tunnel. A very first step of this general plan has already started after the drilling campaign of January 2001, in the north-west area outside the Basilica, new archaeological excavations are carried out to discover the hidden structures under ground level. These excavations are necessary to preserve ancient structures and to avoid unexpected situations during future works. Archaeological excavations reveal an ancient wall nearby the north exit of the *Arco del Latrone* passage, if this wall is found to be toothed with the three

mullioned window's wall and its foundation deep enough, it is possible to considerate it as a support to the strengthening of this part of structure.

New excavations in the *Carinae*'s area and in the north-west side of the Basilica are foreseen in the next few years and the behaviour of the equilibrium of the Basilica being very complex in that area, these excavations could compromise the stability of the entire structure. Therefore it has been highly recommended to work under a constant monitoring of both the structure and the ground, to understand every little movement that could indicate a possible dangerous situation.