Seismic Preservation of the Archeological Site of Pompeii. Preliminary Analyses

The seismic preservation of archaeological sites should certainly be targeted at the conservation of the historical and artistic values but cannot prevent these sites from being visited by a high number of tourists daily. A complete study should include the analysis of the seismic hazard in the area and of the seismic local response at each site, in addition to the analysis of the health status and the seismic vulnerability of structures. The site of Pompeii, recently interested by collapses, is probably the most interesting case in the world. The Soprintendenza Speciale per i Beni archeologici di Napoli e Pompei, in collaboration with ENEA, is organizing a study for the evaluation of the health status and the seismic vulnerability of some of the most diffused structural typologies in the archaeological site. The preliminary analysis pointed out the need for a detailed vulnerability analysis based on a comprehensive experimental investigation on both structure and site

■ *Immacolata Bergamasco, Valerio Papaccio, Bruno Carpani, Paolo Clemente, Fernando Saitta*

Introduction

The city of Pompeii was partially destroyed and buried under ash and pumice in the eruption of Vesuvius Volcano occurred in 79 A.D., and remained covered until its accidental rediscovery in 1749. The excavation has provided an extraordinarily detailed insight into the life of a city during the Roman period. Nowadays, Pompeii is a UNESCO World Heritage Site and one of the most popular tourist attractions in the world, with a very high number of visitors. Recently, it was affected by some collapses which brought to light the issue of safety of all the archaeological sites.

Due to the historical importance and to the daily presence of tourists, the seismic rehabilitation of archaeological sites is quite delicate, aiming at protecting both human life and cultural heritage.

The *Soprintendenza Speciale per i Beni archeologici di Napoli e Pompei*, in collaboration with ENEA, is organizing a study for the evaluation of the health status and the seismic vulnerability of some of the most diffused structural typologies in the archaeological site. Among these, the ruins of the colonnades of the Basilica and of the Forum, and the structures made of large blocks along *Via dell'Abbondanza* and *Via della Fortuna*, that are very representative of the most vulnerable situations. The scope of the analysis is to identify the

■ **Immacolata Bergamasco, Valerio Papaccio**
Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei
■ **Bruno Carpani**
ENEA, Unità Tecnica Ingegneria Sismica
■ **Paolo Clemente, Fernando Saitta**
ENEA, Unità Tecnica Caratterizzazione, Prevenzione e Risanamento Ambientale

seismic risk and formulate different hypotheses aimed at improving the seismic safety of these structures. These should pursue a suitable equilibrium between the two above-mentioned requirements, i.e. safety and conservation, so as to obtain a partial, yet effective seismic improvement, preserving the original cultural meaning and value.

The study is based, first of all, on the historical analysis of the structure and identification of the damage, including the seismic history of the site. Then, the characterization of materials and building techniques should be performed as well as the dynamic modelling of the structure and the evaluation of the seismic vulnerability. Finally the design of the intervention and the corresponding evaluation of the seismic improvement should be carried out.

In this paper some results of the preliminary analysis are shown.

Earthquakes in Pompeii

The strongest seismic event occurred in 62 A.D., only seventeen years before the catastrophic eruption. According to Seneca, who wrote about this event in the sixth book of his *Naturales Quaestiones*, Pompeii collapsed almost completely. The later excavations not only confirmed the occurrence of the earthquake but also shed light on an example, unique of a kind, of an ancient city during the post-quake reconstruction. On the basis of historical and archaeological data, the intensity at Pompeii was assessed as IX in the MCS scale. The earthquake was also reported by Tacitus with a brief note in his *Annales* (15.22.3). After the earthquake the reconstruction works proceeded somewhat slowly and in a disorganized way, so that at the time of the eruption they were not concluded yet. The examination of the methods employed by the ancient builders shows interventions revealing the clear-cut purpose of reinforcing structures against earthquakes [1, 2].

After the rediscovery of the site in 1749, the seismic catalogue reports two significant earthquakes, one in 1930 (VII MCS) and the other in 1980 (VI-VII MCS), both with epicentre in Irpinia (South Italy) [3]. Despite the long distance from the epicentre, the 1980 event caused widespread, moderate damage to the archaeological remains, with few cases of collapse (such as that of the columns of the Temple of Isis). According to the official report [4], the damaged structures were in a bad state of conservation, a factor that obviously affected their seismic vulnerability; in particular, the observed damage was mostly due to the

FIGURE 1 Wall in Regio VII (Insula 2, No. 1), (a) before and (b) after the collapse
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

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deteriorated condition of the mortar. However, for this event we lack a detailed damage survey, such as the outstanding one carried out by Maiuri on the 62 A.D. earthquake [1]. During the structural restoration works many concessions to modern construction technology were made, including the use of reinforced concrete top string-courses, injections of cement mortar and reinforcing ties in walls and vaults (iron bars inserted into drilled holes and grouted with cement). These interventions represent a matter of some concern because they were invasive and not mechanically consistent with ancient structures. Furthermore, the problem due to degradation of reinforced concrete elements is well known, in particular the carbonation process leading to the oxidation of iron bars.

Structural Types of Masonry

Two basic typologies of masonry structures are considered:

- walls made of small blocks, or concrete walls, where the loading capacity relies on the nucleus of *opus caementicium*, and therefore on the good quality of mortar, which plays an important role;
- structures made of great blocks and colonnades, where the role of mortar is negligible and structural safety essentially depends on the mechanical quality, size, shape and arrangement of the stone elements.

The Romans developed several methods for constructing concrete walls [5, 6]. They made use of stones (*opus incertum, opus reticolatum*), bricks (*opus testaceum*) or a mix of both (*opus mixtum*). All these types are found at Pompeii, but the opus incertum *"is the fundamental structure of the whole Pompeian building works"* [1]. These techniques essentially differ in the way the face walls are assembled and bonded to the inner core of opus caementicium. In the case of opus incertum, faces and nucleus were built in parallel with thin horizontal layers; the masons firstly set the elements of the outer faces using stones of polygonal shape, choosing the ones with the smoothest surface, then the core space were filled with rough stones (caementa) laid in a generous amount of fluid mortar [7].

Most of the structures, now exposed to various agents of degradation, were originally covered and plastered. The walls inside the housing units and made of two faces in opus incertum, are particularly degraded. In fact, even though the volcanic stones have quite good mechanical characteristics, mortar is poor. Besides, the mortar joints are sometimes more than 3 cm thick, and the masonry has no brick courses, nor brick bands that could make the texture regular and guarantee layers horizontality; these courses, when run through the full thickness of the wall, also perform as diatoni (bonding elements between masonry sheets), giving a monolithic behaviour to the wall [8, 9]. In this regard, it must be stressed that, although these structures were to some extent reinforced after the 62 A.D. earthquake, many walls (mostly belonged to private owners) were reconstructed without any anti-seismic reinforcement, employing salvaged materials and poor quality mortar.

Fig. 1 shows the walls of the Termopolio of P. Paquius Proculus, a commercial building excavated in 1943-1944. The partition wall that separated two adjacent workshops had a total thickness of 40 cm, a length of 5.0 m and a height of about 3.0 m, and the two opposite faces are N-W and S-E, respectively. Its collapse pointed out the absence of internal cohesion. In fact, the collapsed portion is completely disaggregated, the mortar is pulverized and the stones scattered on the ground look like those of a drywall.

Many other walls in the same area (*Regio VII*) are in the same condition, as pointed out during the survey of March 2009. Actually, the surface degradation observed in almost all masonry units examined is determined by chemical and mechanical degradation phenomena. These structures are subject to continuous cycles of wetting and drying. A recurring and widespread mechanism of decay was pointed out, in which the erosion of the mortar is particularly advanced in the mid-height of the walls. The mortar within joints is completely pulverized in these parts, probably because it is less wet both by the rainwater and by the water rising from the soil. Indeed, the faces on the South-East side are the most damaged (Figs. 2 and 3). The situation is often complex with overlapping causes and effects of degradation. Many of the walls are damaged or out of plumb. In such conditions even

FIGURE 2 Regio VII (Insula 2, No. 41 and 42)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 3 Regio VII (Insula 12, No. 34)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 4 The Forum area: free standing colonnades (in the back)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 5 Walls showing different structural behaviors and resultant damage
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

small settlements could determine instability and collapse (Figs. 4 and 5).
Actually, the alternation of dissolution and crystallization of the salt deposits at the surface can lead to disintegration of mortars, and flaking of plaster, bricks, paints, etc. Once the mortar that holds the blocks together is consumed, the most degraded masonry becomes unstable and eventually the wall breaks. To avoid that, the mortar should be consolidated, the lacunae in the masonry faces reintegrated, and the walls protected.
It is worth noting that what said about the dynamics of the observed damage suggests the possibility of correlation between the weather and the progress of degradation processes. Therefore, further research requires reliable data on rainfall and environmental

FIGURE 6 Colonnade of the Basilica
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

FIGURE 7 Blocks in grey tuff in Regio VIII (Insula 5, No. 19)
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

conditions in the area, and also in different locations of the area. Further analyses would allow to identify timescales and procedures for proper maintenance, as well as the composition of mortar for masonry restoration.

Different types of vertical structures are present in the Pompeii excavations. Among these, the ruins of colonnades in the Forum area and the Basilica (Fig. 6) deserve particular attention. Besides, there are very common vertical structures in opus quadratum forming the jambs of the shops along the main roads. These are composed by the superposition of large blocks of gray tuff, having size of 100*70 *cm* and thickness equal to 40 *cm*. All these structures are very dangerous for visitors due to their position and size. Moreover, they show diffused cracks and significant degradation processes (Fig. 7). It is necessary an in-depth study of the stability of these structures, by carrying out the analysis and evaluation of mechanical characteristics of masonry, and understanding its texture and quality. Furthermore, foundation features and lying, as well as possible past structural interventions which could affect both static and dynamic behaviour should be investigated [10].

Several covering structures were built after the Second World War to protect wide areas, which are important also for their size and weight. They are made of reinforced concrete of uncertain quality, and span up to 11 *m*, with cross section 20-30 *cm* wide and up to 100 cm high, besides being supported by reconstructed masonry walls up to 10 *m* high. It is important to stress that these structures were built without earthquake-resistant design, therefore, according to the EM-98 scale they must be assigned to a low vulnerability class.

A Case Study

A case study related to the seismic reliability of the stacked blocks shown in Fig. 8 is analysed in detail. The blocks constituted the angular elements of the perimeter walls in a building ruin in Pompeii, largely collapsed.

The seismic action is defined according to the recent Italian code, assuming the highest return period of 2475 years, which corresponds to a peak ground acceleration of 0.224 g. Obviously, for such kind of structures, as largely recognized in the scientific literature, the motion under dynamic loads could be related mostly with the slipping along discontinuities and/or rocking motion of the blocks, whereas the deformability of the blocks could be negligible. It is well known that for a single block the rocking is possible if $\mu_s > b/h$ [11], where b and h are the length of half base and height, respectively; μ_s is the static friction coefficient. The damping is assured by friction forces. Thus, the

FIGURE 8 Stacked blocks of tuff for the case study
Source: Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei

classic response spectrum analysis cannot describe the behaviour of the system completely.
Due to the angular configuration of the structure, with indented joints between the two orthogonal wall pieces, a prevalent rocking motion of single parts seems not to be likely. Instead, sliding motion of single parts is possible. The friction at the horizontal interface between blocks is modelled as Coulomb type and the static and kinetic friction coefficients are assumed to be equal. The model has been defined in Ansys® software. The blocks are modelled by means of mass elements applied at the barycentre of each block, which allow the definition of inertial characteristics of the blocks. Fictitious, infinitely rigid beams have been considered to define the edges of each block and connect the mass element to the corners. At the contact points, elements capable of giving a Coulomb type friction in the horizontal plane have been introduced. Only horizontal motion of the blocks has been allowed. In this way, the nonlinear response to the base acceleration represented in Fig. 9 has been derived. The soil acceleration time history, assumed to act along the z principal axis (of the total system), has been simulated according to the code. Fig. 10a shows the displacement of the centers of mass along one horizontal direction, whereas the displaced system at time 2 sec is represented in Fig. 10b. The first figure shows that for a time close to 4 sec the displacements of some blocks become larger and larger, until the numerical integration cannot converge to solution. Thus, this first analysis indicates the possibility of a failure under an earthquake such as that used in the simulation, for sliding of the blocks.
A second model is based on the rocking behaviour of the whole structure, assumed to be a single rigid block. More complex models, involving several blocks are under study. The geometry of the structure suggests to resort to a complete three-dimensional analysis, unless strong simplifications are accepted. Assuming a density of the tuff ρ = 2100 Kg/m^3, the total mass of the block is $m = 7555.85\ Kg$. The inertial characteristics

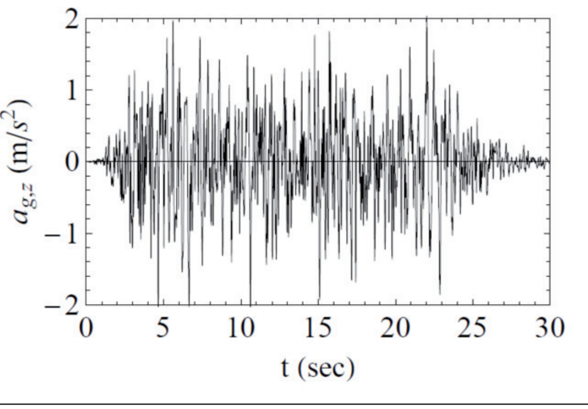

FIGURE 9 Acceleration time history for horizontal and vertical seismic component
Source: ENEA

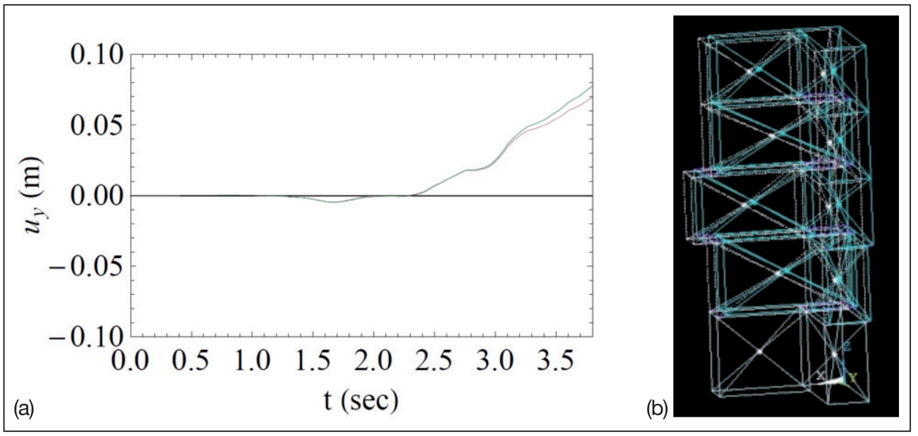

FIGURE 10 Displacement of the centre of gravity (a) and displaced system (b) at time 2 sec
Source: ENEA

of the whole system are: $I_x = 2372\ Kgm^2$, $I_y = 9068\ Kgm^2$, $I_z = 10295\ Kgm^2$. The equations of motion of the block can be written as follows [12]:

$$\mathbf{M}\ddot{\mathbf{x}} = \mathbf{F} + \mathbf{f} \qquad \mathbf{B_c}\,\ddot{\Phi} = \mathbf{Q} - \mathbf{A_F} + \mathbf{M_q}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{x} \equiv (x_c, y_c, z_c)^T$ and $\Phi\ (\phi,\psi,\theta)^T$ are the vectors of the Lagrangian coordinates, chosen as the three coordinates of the center of gravity and the three Euler angles, $\mathbf{A_F}$ - $\mathbf{M_q}$ - $\mathbf{B_c}$ are derived by means of Lagrange equations and are function of the Euler angles and the three inertia moments of the block, $\mathbf{F}$ and $\mathbf{Q}$ collect the contact forces and the related moments, $\mathbf{f}$ is the vector of external forces applied to center of mass. In the case of earthquake forces only f $= [mg - ma_{g,x}(t), -ma_{g,x}(t)]^T$. The axes are aligned with the principal reference system (Fig. 11).
The equations of motion can be cast in a single vector equation. Besides, it is convenient to use a state space form in order to apply numerical integration procedures. In this work, the Runge-Kutta scheme is adopted.
In [12] the soil is modelled alternatively by means of concentrated springs and dampers at the corners in contact with the ground, or by a Winkler model with distributed springs and dampers. The analysis of the impacts can also be treated by means of the conservation of angular momentum [13], even if in real cases the actual non complete rigidity of the impact zones should be taken into account. For the sake of this initial study, according to [12], the parameters are chosen in order to characterize a

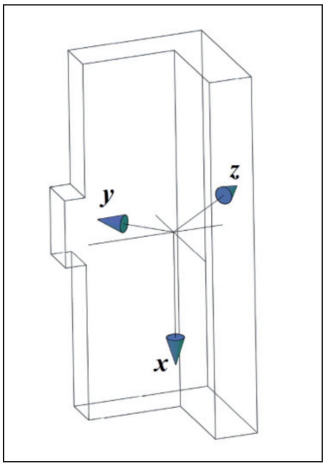

FIGURE 11 Rocking model and principal axes
Source: ENEA

soil with elastic modulus of 1.0 GPa. For the friction coefficient the value 0.8 has been assumed. An exact estimation of parameters would require an experimental characterization of the soil. The results are presented in Fig. 12.
In the first case (Fig. 12), the acceleration of Fig. 9 has been considered, whereas in the second one (Fig. 12) the acceleration has been amplified by a factor 4. In the former, the system is clearly stable, whereas displacements becomes relevant in the second case, even if the stability is maintained. Thus, a failure for rocking motion of the whole structure seems unlikely to occur, whereas the structure could be unsafe for sliding of some part.

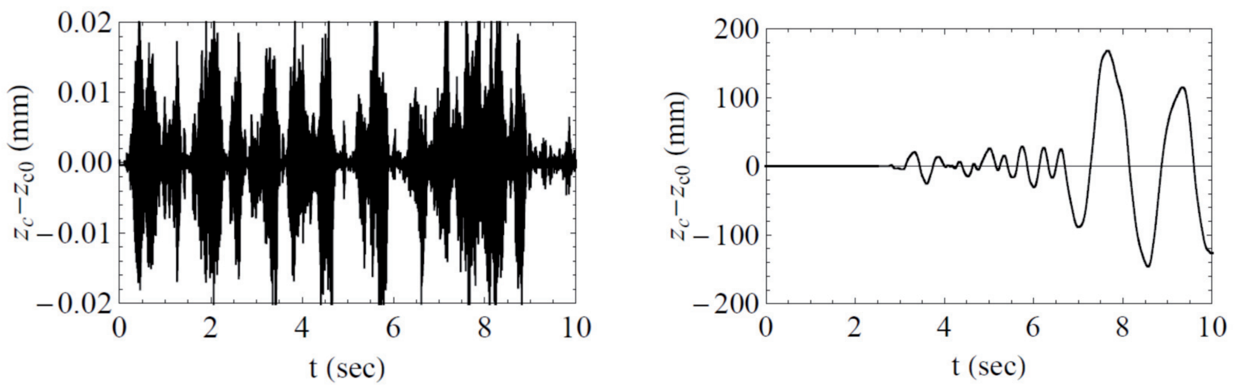

FIGURE 12 Horizontal displacement of the centre of gravity due to: a) Seismic acceleration following the Italian code; b) Seismic acceleration amplified by a factor 4
Source: ENEA

Conclusions

The first analysis of the Pompeii archaeological area, here reported, pointed out the high vulnerability of such kind of structures to seismic actions. In view of its historical importance and the daily massive influx of tourists, the seismic rehabilitation of the archaeological site of Pompeii is quite delicate, having to account for the protection of both human life and cultural heritage. For this reason, all these efforts should pursue a suitable equilibrium between the two essential requirements, i.e. safety and conservation, in order to obtain an effective seismic improvement, preserving the original cultural meaning and value.

References

[1] Maiuri A. (1942), *L'ultima fase edilizia di Pompei.* Istituto di Studi Romani, Roma.

[2] Adam J.P. (1989), *Osservazioni tecniche sugli effetti del terremoto di Pompei del 62 d.C.* In Guidoboni E. (Ed.) I terremoti prima del Mille in Italia e nell'area mediterranea. SGA,

[3] Locati M., Camassi R., Stucchi M. (Eds.) (2011), *DBMI11, the 2011 version of the Italian Macroseismic Database.* Milano, Bologna, http://emidius.mi.ingv.it/DBMI11.

[4] Proietti G. (Ed.) (1994), *Dopo la polvere – Rilevazione degli interventi di recupero post-sismico del patrimonio archeologico, architettonico e artistico delle regioni Campania e Basilicata danneggiato dal terremoto del 23 novembre 1980*, 1, Ministero per i Beni Culturali e Ambientali, Roma.

[5] Adam J.P. (1988), *L'arte di costruire presso i Romani: materiali e tecniche.* Longanesi, Milano.

[6] Lugli G. (1957), *La tecnica edilizia romana.* 2 Voll., Giovanni Bardi ed., Roma.

[7] Lancaster L. (2008), *Roman Engineering and Construction.* In Oleson J.P. (Ed.) The Oxford Handbook of Engineering and Technology in the Classical World, Oxford University Press.

[8] Giuffrè A. (1991a), *Letture sulla meccanica delle murature storiche.* Kappa ed., Roma.

[9] Giuffrè A. (1996), *A Mechanical Model for Statics and Dynamics of Historical Masonry Buildings.* In Petrini V., Save M. (Eds.) Protection of the Architectural Heritage against Earthquake. Wien, Springer.

[10] Bergamasco I., Carpani B., Clemente P., Papaccio V. (2012). *Seismic Preservation of archeological sites: the case of Pompeii.* Proc. 8th Int. Conf. on Structural Analysis of Historical Constructions, SAHC 2012 (Wroclaw, 15-17 Oct.).

[11] Shenton, H. (1996), *Criteria for initiation of slide, rock and slide-rock rigid-body modes.* Journal of Engineering Mechanics, 122(7), 690–693.

[12] Chatzis M.N., Smyth A.W. (2012), *Modeling of the 3D rocking problem.* International Journal of Non-Linear Mechanics, 47, 85-98.

[13] Zulli D., Contento A., Di Egidio A. (2012), *3D model of rigid block with a rectangular base subject to pulse-type excitation.* International Journal of Non-Linear Mechanics, 47, 679-687.