Geogr. Fis. Dinam. Quat.
31 (2008), 99-105, 8 figg.

HERMANN BONNICI (*), NORBERT GATT (*), STEPHEN C. SPITERI (*) & JOHN VALENTINO (**)

VILHENA PALACE AND UNDERLYING BASTIONS (MDINA, MALTA) - A MULTI-DISCIPLINARY APPROACH IN DEFINING A CONSOLIDATION INTERVENTION

ABSTRACT: BONNICI H., GATT N., SPITERI S. & VALENTINO J., *Vilhena Palace and underlying bastions (Mdina, Malta) - A multi-disciplinary approach in defining a consolidation intervention*. (IT ISSN 0391-9838, 2008).

Foundation problems under Vilhena Palace and the underlying bastions have long been recorded dating back to when the citadel was being constructed. In the past a number of attempts to address these movements have been undertaken without much success. This paper investigates recent study campaign carried out by an interdisciplinary team of experts that included photogrammetry, ground and structural monitoring, structural and geotechnical investigation and laboratory testing, and finite element modelling. Finally a geotechnical and structural solution to the problem is proposed.

KEY WORDS: Photogrammetry, Geotechnical site investigations, Consolidation, Mdina, Malta.

INTRODUCTION

Mdina, Malta's medieval capital, can trace its origins back more than 4000 years.

From the mid-9th century to the mid-13th century, during Arab domination, for defence reasons the higher plateau was encircled with a fortified belt, creating the actual citadel of Medina. The city, one of Europe's finest examples of an ancient walled city, lies on a geologically sensitive area. In fact, many of its historic buildings and bastion walls, lying on the outer perimeter of the town, have serious structural problems. One such building is the Vilhena Palace, situated on the north-eastern tip Mdina.

The foundation problems of the area have long been recorded, and in the past various attempts to resolve this delicate situation were undertaken. The paper will discuss the most recent study campaign carried out by an interdisciplinary team of experts. Surveys included photogrammetric, meteorological, topographical and structural monitoring, corroborated by a number of laboratory tests to determine the material properties of the superstructure and underlying strata. A two dimensional computer model using a dedicated finite element program PLAXIS of the area below Council Square, where the largest movements were observed, was made using the material and geometric data obtained. Restraints in the form of secant piles and anchor rods where introduced in the model to arrest movement. The results of the computer model formed the basis of a design proposal below Council Square.

The paper concludes by having a look at a number of different proposals made during the years. All the different proposals have been based on some scientific judgment, be it hydrological, geotechnical or structural, and each one has its own merit, deficiency and financial repercussions. It is hoped that this paper raises an awareness of the problem so that the most feasible solution be adopted.

A HISTORICAL OVERVIEW

One of the most imposing buildings in Mdina, after the Baroque Cathedral, must surely be the Magisterial Palace. This monumental building erected by Grand Master Manoel de Vilhena as part of his programme to rekindle Mdina in the early 18th century is considered to be among the most beautiful, elegant and refined examples of baroque palatial architecture to be found in the Maltese islands. Vilhena's magisterial palace is located near the main entrance into the old city, just behind the main monumental gate (fig. 1).

It was built in 1724 (De Lucca, 1993) to the design of the Order's French resident military engineer, Charles

(*) *Restoration Unit, Works Division, Project House, Floriana, CMR 02, Malta.*
(**) *Building and Engineering Department, Works Division, Project House, Floriana, CMR 02, Malta.*

FIG. 1 - Aerial photo showing location of Vilhena Palace.

Francois de Mondion. The palace was conceived as part of a wider replanning scheme involving the main entrance area into Baroque style architecture, following damage caused by the 1693 earthquake. This town was, until then, still a largely medieval city.

The origins of the palace as a magisterial residence go back to the first Grand Master, Jacques Villiers de L'Isle Adam who had taken up residence there mainly to establish his sovereignty over the island's capital when the Order took over the Maltese islands in 1530. In antiquity the same site had served as part of a medieval castle, which itself may have first taken root as a Byzantine fortress. The medieval castle was partially dismantled in the mid-15th century but its outer walls continued to remain incorporated into the old city's outer ramparts.

The palace which Grand Master Vilhena established onsite appears to have occupied much of the original footprint of the medieval castle. The eighteenth century edifice which replaced the magisterial residence was built during the reign of Grand Master Antoine Manuel de Vilhena. Eventually, it became the Council House of the Mdina Community. In the early 20th century the palace was converted into a hospital through the generous funding of HRH the Duke of Connaught, King Edward VII. A National Museum of Natural History was set up in the palace in 1973.

GEOLOGY OF THE AREA

The old Capital of Mdina is located on the northeast margin of the Rabat-Dingli Limestone Plateau at about 180 m above sea level (Scerri, 2005). The fortifications and marginal structures of Mdina such as Vilhena Palace are founded on this Limestone.

The rocks exposed on the slopes of the plateau comprise (fig. 2):

– Upper Globigerina Limestone Member at the base
– Blue Clay Formation
– Greensand Formation
– Upper Coralline Limestone Formation, at the top.

Upper Globigerina Limestone is an approximately 18 m thick unit composed of two yellow medium grained moderately weak foraminiferal limestone beds with a 5m bluish grey marl interbed. The rock unit is overlain by the Blue Clay Formation – blue plastic caolinitic clay with up to 25% carbonate content. This unit is about 30 m thick beneath Mdina and forms the slopes of the Rabat – Dingli Plateau. The Greensand Formation overlies the Blue Clay and is about 2 m thick and consists of medium grained friable orange glauconitic sand. The Upper Coralline Limestone on which the city is founded is a cap about 3-6 m thick and is composed of moderately weak to moderately strong limestone exposed in vertical cliff sections on the margin of the plateau, overlying the Greensand.

Over the years the fortifications and adjoining structures have suffered severe structural damages due to undermining of the underlying friable sand and plastic clay causing the overlying limestone to shear accompanied by settlement and toppling of columnar limestone blocks (gravity toppling and creep toppling).

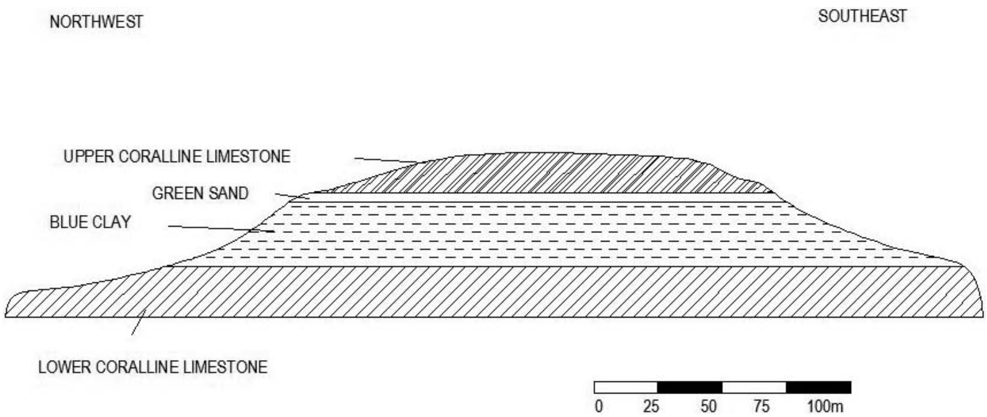

FIG. 2 - Schematic geological cross-section across Mdina.

In order to remedy the precarious geological conditions a number of site investigations were undertaken (De Beaufort, 1967). These were concentrated on the bastions and area surrounding Vilhena Palace, Council Square and St Paul's Bastion. The most exhaustive geological site investigation and laboratory testing was undertaken by the Works Division in collaboration with the University of Bologna in 2000-2002. Besides a number of vertical and inclined borings with continuous coring and installation of piezometers it also included a radar survey and a seismic survey. In situ tests included SPT, recovery of undisturbed and disturbed samples. Clinometers and leveling points were also set up and were monitored to establish the modality of the subsidence.

MONITORING CAMPAIGNS AND INTERVENTION PROPOSALS

Site surveys

Documentation constitutes an important phase in the monitoring programme devised for Vilhena Palace (Baratin & *alii*, 2001). The surveying techniques adopted for this purposes were chosen in the light of the multidisciplinary nature of the project and were designed to address the current situation on three levels, primarily:

1. the production of a detailed numerical cartography in a scale of 1:500 designed primarily for the analysis of the urban texture;
2. the setting up of an altimetric grid network throughout the medieval city of Mdina, and in particular in the proximity of Palazzo Vilhena;
3. the preparation of detailed architectural surveys making use of various surveying methods and classical and simplified photogrammetric techniques.

Numerical Cartography in 1:500 Scale

A detailed numerical cartographic base of Mdina, in 1:500 nominal scale, was prepared to serve as the basis for the documentation (fig. 3). The advantages of such detailed numerical cartographic base over the conventional smaller scale aerial surveys included the possibility of representing the building volumes more accurately, enabling a better understanding of the relationship of Palazzo Vilhena with the fortifications and nearby buildings as well as permitting a more precise mapping of the geological outcrops influencing the structural behaviour of the palace and its immediate neighbourhood. More important, this detailed numeric cartographic base provided a more accurate geo-referenced base for a GIS setup.

Furthermore, the extensive amount of information contained within this 3-Dimensional product permitted the integration of terrestrial, photographic and photogrammetric surveys to produce a single reference frame for a complete representation of Vilhena Palace within its urban context.

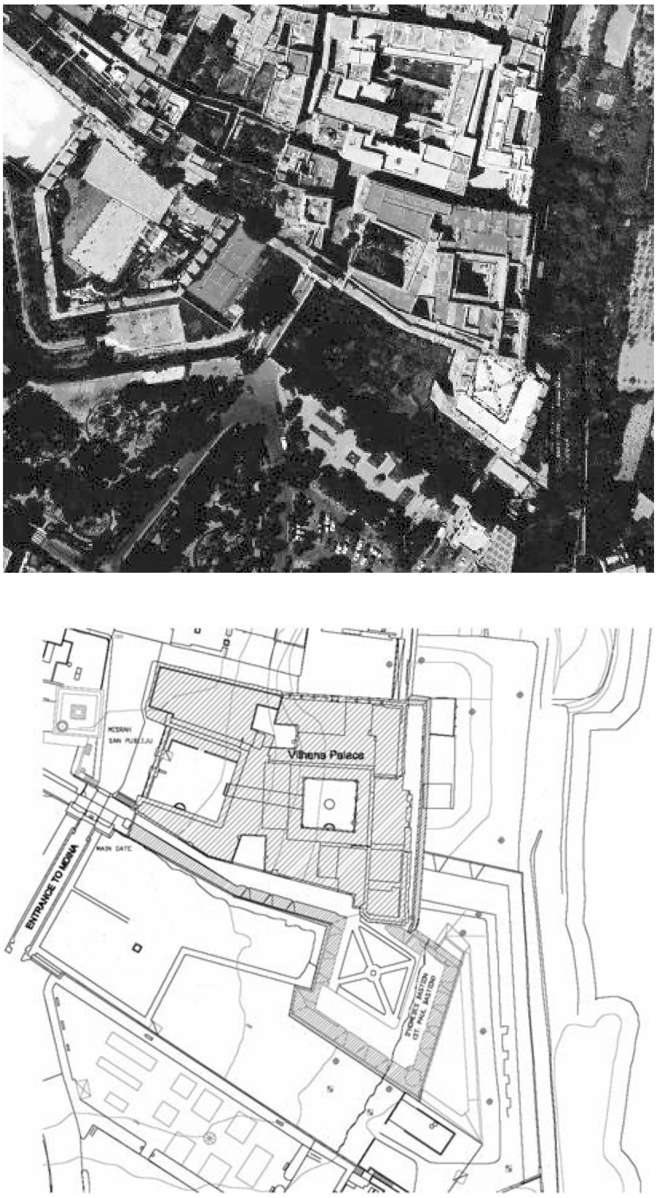

FIG. 3 - Detail of an aerial photograph of Vilhena Palace, and the corresponding restituted plan.

Altimetric Grid network

The evaluation of the structural stability of Vilhena Palace was not treated as a local phenomena, and a very precise altimetric grid network was set up to quantify differential movements throughout the medieval city.

Topographic surveying using high precision geometric levelling was considered as the most suited technique for this scope as it enables the monitoring of large areas with millimetric accuracy. A number of benchmarks were installed in strategic locations of the area being studied, and periodically levelled. The precision of this system is dependent upon the effective distribution of the benchmarks. For this reason, around eighty benchmarks were anchored in strategic locations to ensure reliable monitoring of the whole city. Around twelve of these benchmarks specifically address the monitoring of the subsidence at Palazzo Vilhena.

In an effort to ensure the maximum possible accuracy, the grid network established in Mdina is made up of a series of closed traverses. The first readings where taken in July 2001. High precision levelling instruments with calibrated invar mounting rods were used, and an average accuracy of one millimetre was obtained. The levelling exercise is repeated every twelve months.

Photogrammetry for documentation

The documentation of the palace was carried out using a combination of surveying and photogrammetric techniques. An extensive topographic survey of the palace was carried out. The aim of this survey was to establish a local reference system for the direct survey of the complex accomplished by an elaborate system of triangulations, as well as to obtain an altimetric record of the palace. Different controls were carried out to ensure an elevated degree of precision.

Various close-range photogrammetric techniques were adopted for the documentation of the architectural elements of the palace. The methods used were decided upon after the building characteristics, the scope and desired precision of the surveys were evaluated. Metric and semimetric, medium format negative cameras, as well as digital cameras were used. The restitution was in large part carried out using digital instrumentation. A number of control points were set up and their coordinates related to the vertices of the main network. Digital rectification, using Rollei MSR software was used for the documentation of simple facades having no elaborate ornamentation. More elaborate elements were documented using pairs of orthophotos. The orientation process for the 3-D plotting as well as the plotting of 3D lines and polylines was accomplished by Stereo View software (fig. 4).

Site investigations and proposed interventions

The structural problems of the Mdina bastions, in particular to the area underlying Vilhena Palace, have long been recorded, and in the past various attempts to resolve this delicate situation were undertaken. Several reports have been drawn up in the recent past, but none to date have led to any direct intervention. The following is a brief overview of the main proposals of interventions.

UNESCO report (1966)

In 1966 UNESCO was commissioned to prepare a technical report on the interventions necessary to arrest the movements in Vilhena Palace (De Beaufort, 1967). This study was commissioned after significant movements were reportedly noticed following the Second World War. Field investigations with borings were made to determine the underlying strata and the material properties of the clay. The laboratory results confirmed that the clay had good properties of plasticity, was rather dense and impervious, and that the shear strength was rather good. The conclusions of the report are based on geotechnical engineering judgment and these highlight the importance of the hydrogeology of the area. A rise in the water table and in the pore pressures sometimes has disastrous results for the stability of the area. The report also looks at previous reports that had suggested ground water control using ground dewatering by electro-osmosis and pumping from bored wells however these have not been recommended. The recommendations are to line the wells to avoid leakages of water, to remove the concrete block wall intervention built after the Second World War, and to underpin the bastions with bored piles.

Thesis Study «Palazzo Vilhena, Mdina Malta - Progetto di Restauro»

The study analyses the structural deformations of the building, and in the context of the existing historical and geological scenario outlines a hypothetical failure mechanism (Gatt & De Schryver, 1996). This leads to a proposed intervention from inside Vilhena Palace, by underpinning the bastion wall with the tip of a propped cantilevers supported on micro-piles driven to the underlying rock (fig 5). The far ends of the cantilevers are restrained under the internal walls.

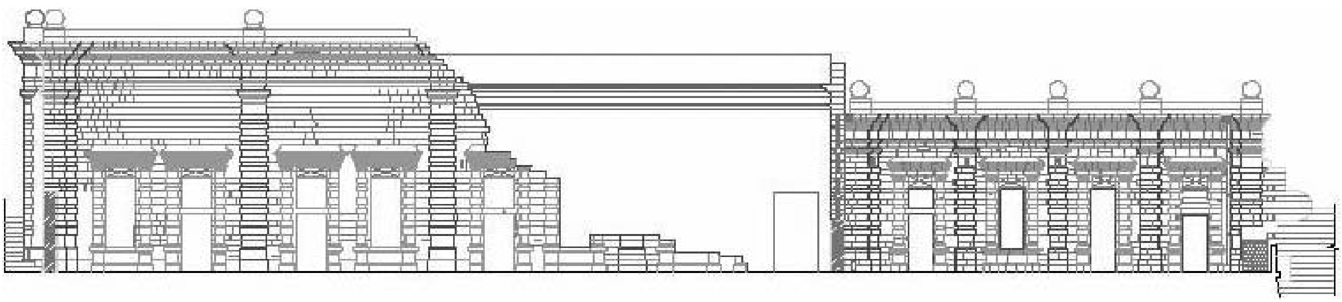

FIG. 4 - Restituted back façade.

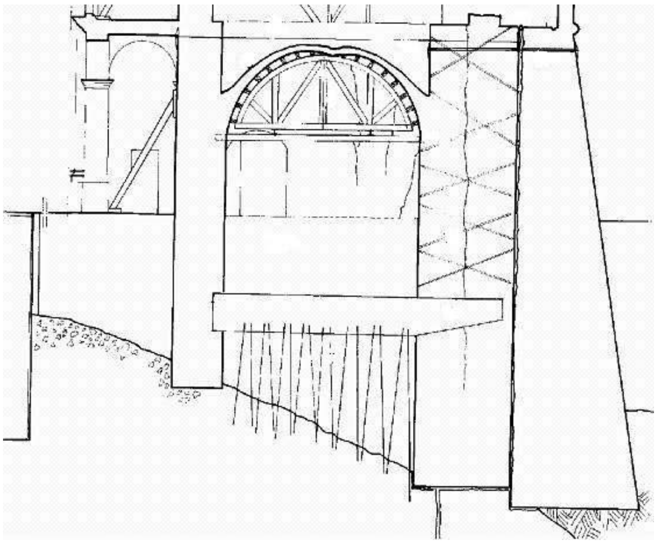

FIG. 5 - Detail of proposed consolidation intervention (Gatt & De Schryver, 1996).

University of Bologna Report

In 2001 a Study was commissioned by the Maltese Government for an in-depth geotechnical investigation of the perimeter Xara Palace, Council Square, Vilhena Palace and the of St. Peter and St. Paul bastions (Cuppini & *alii*, 2003).

Site Investigation and Monitoring

A weather station was set up in the area to record the temperature, humidity and rainfall. Structural and geotechnical investigations and monitoring were also carried out in the area. All the data gathered from the monitoring was fed to a data logger.

The structural investigations on Vilhena Palace were made to determine the material properties of the building fabric and to assess the solidity of the structure by checking for any weakness or cavities. Cores were extracted from the structure to determine the physical properties such as strength, absorption and density of the limestone. Video endoscope, ultrasonic methods and surface penetrating radar were employed on site to detect for any flaws, discontinuities, internal cracks or cavities in the masonry. Also in-situ tests using flat plat jacks were carried out to determine the actual stresses in the structure. These tests all indicated that the structural fabric was solid and the stresses moderately low.

Structural Monitoring on Vilhena Palace, Council Square, Xara Palace and St. Paul's Bastion was carried out over a period of 15 months commencing in October 2001 to determine any horizontal, vertical and rotational movement (Falci, 2004). This monitoring was done using strain gauges, potentiometers and biangular inclinometers. These data were correlated with climatic data and it resulted that the movements were due to seasonal variations, with the movement occurring primarily during the dry season between June-September, and being rather static during the rest of the season (fig. 6). The movement was most pronounced in the area of Council Square and Xara palace. In the other regions the movement was very minimal and even reversible.

The geotechnical investigations consisted of radar scans of the ground and vertical and inclined bores with core recovery to determine the underlying strata. Piezometers were installed to record the interstitial pressures and

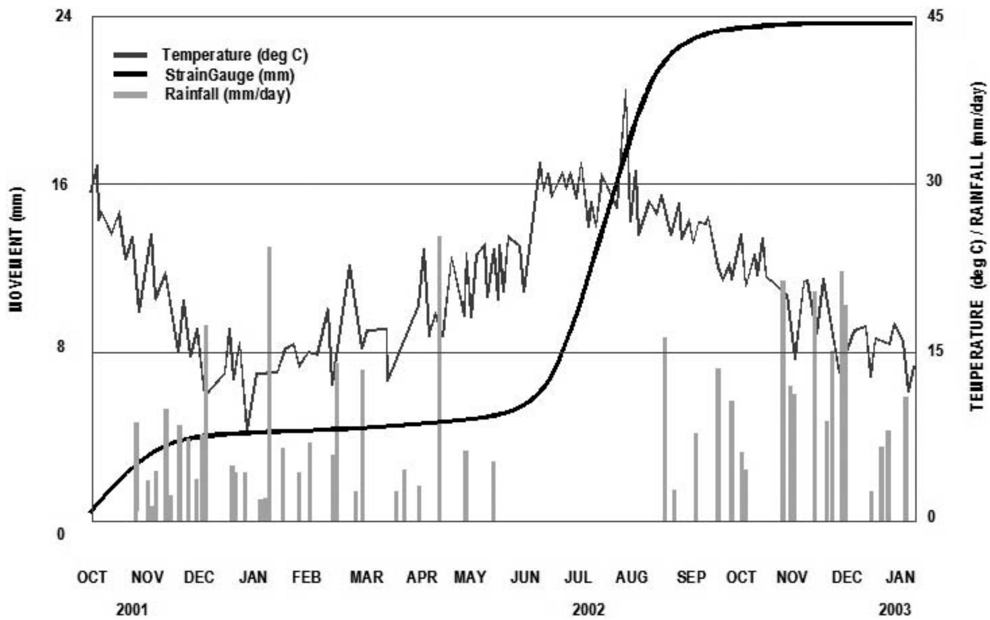

FIG. 6 - Strain gauges measurement at Xara Palace with temperature and rainfall (Cuppini & *alii*, 2003).

to observe the levels of the water table and inclinometers were driven in the ground to determine any underlying ground movement. Laboratory tests were carried out on the recovered samples to determine the physical properties of the underlying strata. The inclinometers indicated that ground movement was generally in the area of Council Square, however the values were not significant to induce any ground slippage (fig. 7).

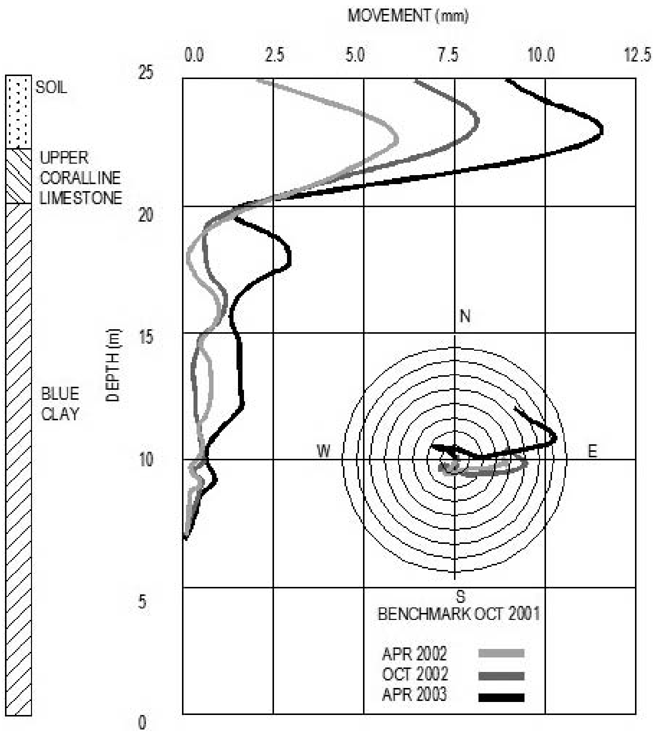

FIG. 7 - Inclinometer readings under Council Square (Cuppini & *alii*, 2003).

The bastion walls are founded on a fractured upper coralline limestone layer of thickness circa 2.7 metres, overlying a thin layer of 1.5 metres of orange sand and a thick layer of blue clay supported on rock. The top layer of the blue clay consists of an overlying layer of 1 metre of yellow clay. The slope consists of a thick layer of black soil with water flowing over the underlying clay.

Numerical Analysis and Computer Model

A numerical analysis was made to check the stability of the slope against rotational slippage using Bishop and Janbu's method (Marchi, 2004). This analysis indicated that the slope was stable with safety factors varying from 1.56 to 1.12.

A two dimensional computer model using a dedicated finite element program PLAXIS (PLAXIS Ver. 8.0, 2002, Delft University of Technology) of the area below council square was made using the material and geometric data gathered. Council square was chosen since the largest movements were observed in this area. Imposed loads in the form of lateral water pressures and seismic loads together with self weight of the structures were introduced. Restraints in the form of secant piles and anchor rods where introduced in the model to arrest the movement. The results of the computer model formed the basis of a design proposal.

The primary mode of failure was rigid body rotation about the toe of the foundation wall with toppling at the top due to yielding of the underlying clay strata. It has been inferred that movement is aggravated by the variation in the water content of the clay and the rotation is assisted by weathering of the underlying upper coralline strata.

Intervention

The intervention is phased in three phases near Xara Palace and Council Square, Vilhena Palace, and the perimeter of the bastion wall of St. Paul. The design proposal (fig. 8) consists of boring a double row of 100 cm diameter concrete piles to a depth of 16 metres in the ground supporting a continuous reinforced concrete underground pile-cap beam of cross sectional area of circa 6 m^2. The beam is in turn tied to the bastion walls and the underlying strata with 30 in No 12 or 16 m 32 mm diameter threaded bars and 5 in number 26 m strand anchors for every 10 m length of wall. The inner row of piles are spaced every 2 metres and the outer row every 4 metres. The area under the foundation walls is reinforced by grout injections up to a depth of 10 metres to reduce the permeability and to increase the allowable bearing pressures.

The interventions proposed aim to arrest the rotation and movement of the bastions walls by:

1. limiting the plasticization of the clay due to excessive bearing pressures;
2. confining the clay under the structures;
3. tying together the fractured upper coralline limestone;
4. reducing the erosion of substrata composed of orange sand, yellow and blue clay;
5. increasing the allowable bearing pressures and reducing settlement by geotechnical interventions.

CONCLUSION

The analysis of interaction between ground and building has always proven to be an issue of difficult understanding. Old buildings such as the Vilhena Palace, which have undergone several mutations throughout their existence, further highlight this complexity. A technically viable and economically feasible solution can be achieved through a system of integrated monitoring techniques coupled with interdisciplinary expertise.

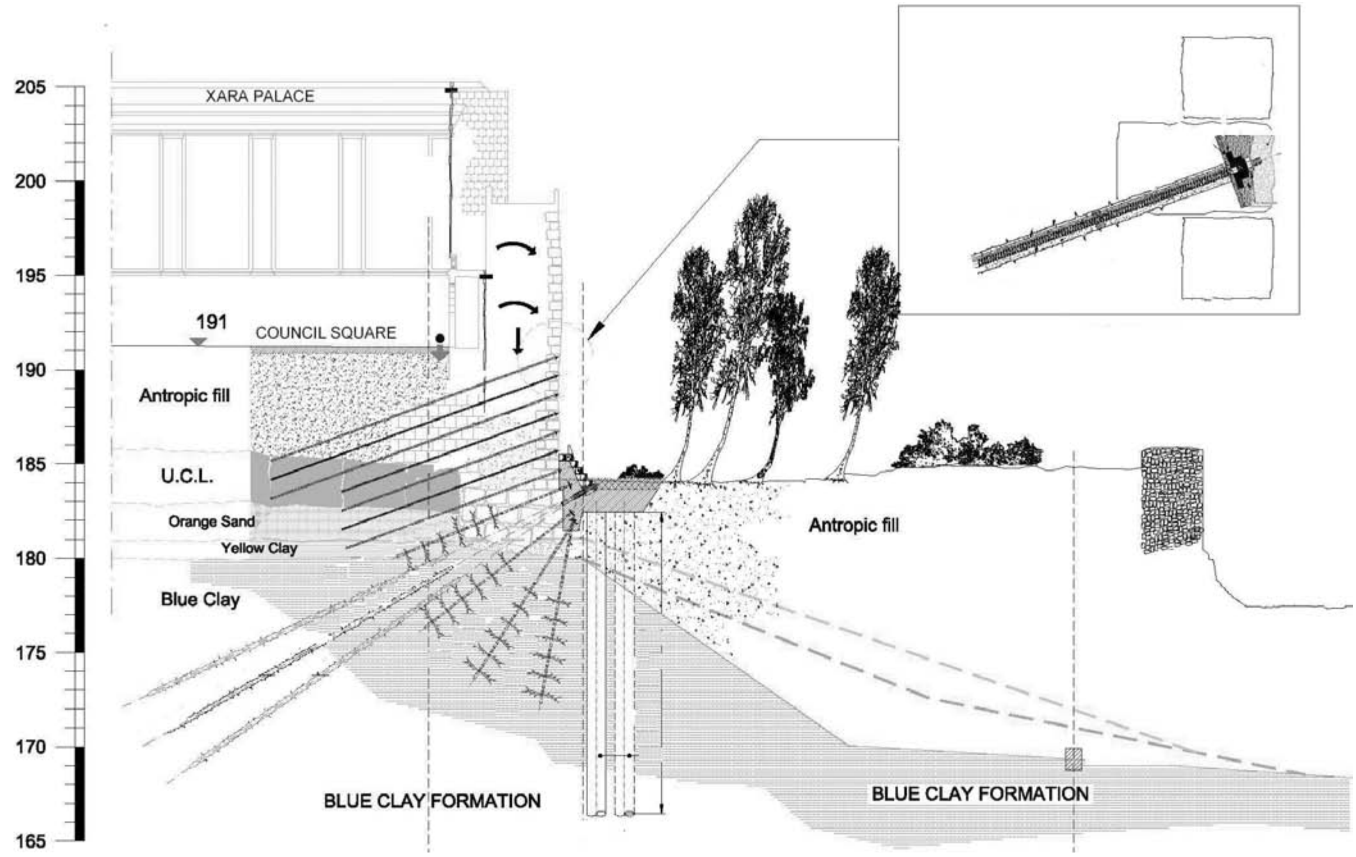

FIG. 8 - Detail of proposed consolidation intervention (Cuppini & *alii*, 2003).

REFERENCES

BARATIN L., BITELLI G., BONNICI H., UNGUENDOLI M. & ZANUTTA A. (2001) - *Traditional and Modern Methods of Surveying Architectural Heritage: A few examples in the fortified Island of Malta.* Proceedings of XVIII th International Symposium of CIPA, Potsdam, 529 pp.

CUPPINI G, BARATIN L., MARCHI G., SAMORI L. & RAGAZZINI A. (2003) - *Consolidamento del Palazzo Vilhena, Mdina, Malta - Osservazioni sullo stato di avanzamento delle indagini a del monitoraggio*. Alma Mater Studiorum, Università degli Studi di Bologna. Unpublished report.

DE BEAUFORT C. (1967) - *Malta - the preservation of Vilhena Palace, the Gran Castello and Fort St. Angelo.* Unpublished report.

DE LUCCA D. (1993) - *Architectural Interventions in Mdina following the Earthquake of 1693*. In: C.J. Azzopordi (Ed.), «Mdina and the Earthquake of 1693». Heritage Books, Malta, 49 pp.

FALCI M. (2004) - *La campagna di indagini e i monitoraggi geognostico e strutturale.* La fabbrica delle mura, Malta, 147 pp.

GATT N. & DE SCHRYVER S. (1996) - *Palazzo Vilhena, Mdina Malta - Progetto di Restauro.* Università degli Studi di Roma La Sapienza. Unpublished thesis.

MARCHI G. (2004) - *Indagini e monitoraggio finalizzati al recupero*. La fabbrica delle mura, Malta, 134 pp.

SCERRI S. (2005) - *Mdina - Subsurface Geological Site investigation.* Unpublished report.

(Ms. presented 30 April 2007; accepted 30 August 2008)