Suggested Methodology for Rehabilitation of Ancient Masonry Castles and Forts on Rock Hills

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Abstract. Forts, including in this designation military castles, present high complexity due to their nature. Methodologies followed in the rehabilitation of forts are briefly presented, with the emphasis on characterization of materials and rock masses and on tests and numerical models developed for ancient forts. Studies concerning forts with Portuguese legacy are presented. The first case is related with rehabilitation of foundations and walls of the Guimarães Castle, Portugal. The causes of the appearance of holes or torn threads in the exposed face of the wall and the tower of the extreme southwest of the castle were assessed. The intervention performed was focused on the stabilization of the rock mass and careful sealing of discontinuities in the high strength rock mass and consolidation of the most weathered fractured rock mass. The second case is related to forts existing at Muscat, Oman. The protection of the Jalali Fort is studied in detail. During 2007, cyclone Gonu caused substantial damage to the seawall adjacent to the fort. The study addresses the redesign of the seawall.

Keywords: masonry forts, rehabilitation, rock mechanics, Guimarães Castle, Jalali Fort.

1. Introduction

The analysis of historical masonry forts is a complex task. Relatively limited resources have been allocated to the study of the mechanical behavior of masonry, which includes nondestructive *in situ* testing, adequate laboratory experimental testing and development of reliable numerical tools. Despite this, significant contributions have been made in these research fields. The difficulties in using the existing knowledge are inherent to the analysis of historical structures.

Conservation and restoration of historical monuments and their surrounding areas, both urban and rural, are disciplines that require specific training and a multidisciplinary approach. The continuous changes in materials and construction techniques, and the challenging technical and scientific developments, make new possibilities available for the preservation of the architectural heritage, and are key aspects in the division between the science of construction and the art of restoration. These aspects add an intrinsic dimension and character to the field and it seems extremely difficult to appreciate historical buildings without a broad knowledge. The necessary knowledge includes a wide variety of non-traditional fields that are usually not covered by most university curricula in civil engineering and architecture.

Forts, including in this designation military castles, are among these monuments that are high complexity due to their frequent location in high hills. Each fort has distinctive engineering and architectural features that make its study a challenge. This paper deals with the methodologies for the rehabilitation of ancient forts with focus on forts with Portuguese legacy. These forts are frequently on high elevated natural rock that hinders their access, which adds a dimension of difficulty to their study. An example of the foundations for a medieval fort is indicated in Fig. 1. Forts with Portuguese legacy are disseminated in all the continents. Several good examples are forts in Oman such as the Muttrah Fort constructed in the 17th Century (Fig. 2), and the Hormuz Fort in Iran, as represented in Fig. 3. These forts are made by sectioned walls built over rock outcrops overlapping the walls that tend to adapt to these erratic weathered profiles sweetening the foundations to these geologies.

In this paper, the methodologies in the field of rock mechanics studies and investigations on forts are briefly presented in section 2, with emphasis placed on the charac-

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Figure 1 - Foundations of the medieval Algozo Fort.

Figure 2 - Muttrah Fort, Oman.

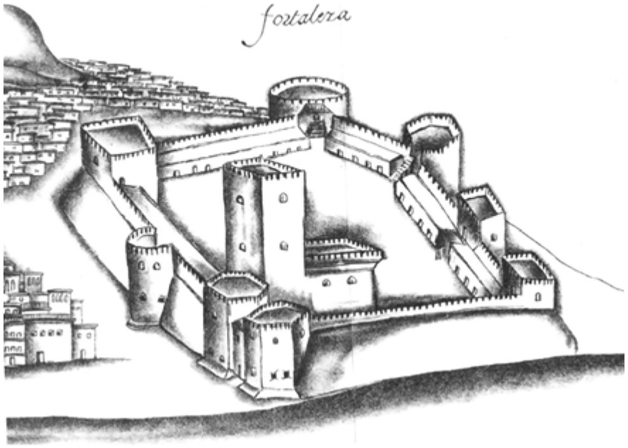


Figure 3 - Fort of Hormuz: drawing of Gaspar Correia (16th Century) (Couto & Loureiro, 2008).

terization of materials and rock masses in section 3 and on tests and numerical models developed for ancient forts in section 4. The paper also presents specific studies concerning forts with Portuguese legacy. The first case is related to the rehabilitation of foundations and walls of the Guimarães Castle in Portugal in section 5, where the intervention consisted of stabilizing the foundation by the careful sealing of discontinuities in the high strength rock mass, and consolidation of the most weathered and fractured rock mass. The second case is presented in section 6 and is related to forts existing at Muscat, Oman. The protection of the Jalali Fort is studied in detail. During 2007, Cyclone Gonu caused substantial damage to the seawall adjacent to the fort, and the study addresses the redesign of the seawall. Finally, section 7 ends with conclusions.

2. Rock Mechanics Activities

The analysis of ancient structures is faced with several challenges that include the complexity of the geometry and construction details, the variability of the properties of the materials and rock masses of the foundations, and the pathologies induced over time. Thus, one of the major difficulties encountered when attempting to simulate of these structures is related to a detailed characterization of the properties of the materials and the rock masses involved. These studies have particular interest when they are located in areas of high probability of occurrence of earthquakes. A great effort has been made to gain a better knowledge of the behavior of structures to seismic action and how this affects the type of damages, especially when dealing with ancient masonry structures, which exhibit complex and unpredictable behavior when subjected to dynamic loads. Finally, important Rock Mechanics activities are related with the characterization of the masonry materials and of the foundation geotechnical formations, normally rock formations.

The methodologies for the rehabilitation of ancient forts requires a detailed analysis of the behaviour of these structures, comprising of several rock mechanics activities, numerical modelling and monitoring of the structures during the rehabilitation process.

The analysis of ancient forts must not be made without careful consideration to the historical changes that have occurred during the lifetime of the forts, and this has to be included in any structural analysis (Betti *et al.*, 2006). The genesis of the geological materials that make up the foundations on which the forts are built is also a very important factor. The fracture patterns are greatly influenced by tectonics, stratigraphy, hydrology, rock formations, weathering, and faults, filling material of discontinuities, shear surfaces and heterogeneities. In order to map the rock mass beneath and around the forts, digital photogrammetry can be adopted using high quality digital cameras in different systems. These cameras are simple to use and have a high degree of performance and automation that make it accessible (Birch, 2006; Pötsch & Gaich, 2007).

The use of appropriate in situ and laboratory tests are described in detail in the next section. For the calibration of numerical models it is essential to perform tests for geometrical identification, evaluation of deformability and strength characterization.

In general, the activities involve the following phases:

- Knowledge phase – In this phase, information on the structure is collected. This information includes, but is not limited to geologic, geotechnical, construction history and the evolution of the structural transformations.
- Analysis phase – In this phase, the structure is modeled using appropriate tools and models. The modelling should consider: type of model (limit analysis, finite element models and discontinuity models using discrete element models); and type of analysis (static linear, static non-linear, dynamic, and 2D and 3D modelling).
- Rehabilitation phase – In this phase, the design and implementation of rehabilitation works is performed. This should include proper monitoring of the rehabilitation works, which includes human supervision, and monitoring systems.

The flowchart of Fig. 4 summarizes the methodologies that should be followed for the rehabilitation of ancient masonry forts on rock hills indicating the need to assess to historical documentation and the existing information, and to have a detailed site characterization of the fort and its foundations.

3. Characterization of Materials and Rock Masses

The characterization of structural materials and rock masses that form the foundations of such ancient structures through in situ experimentation is one of the fundamental steps in any rehabilitation process. The methodologies that should be implemented for rock mass and masonry characterization are summarized in Figs. 5 and 6, respectively.

Foundations of ancient forts, which are frequently in rock masses, are first characterized using standard rock mechanics procedures (Wyllie, 1992; Hudson & Harrison, 1997; Wyllie & Mah, 2004). Natural cavities are detected using seismic techniques such as high resolution seismic reflection, by boreholes in the areas where major cavities are expected. If necessary, P and S waves seismic cross-hole (CH) techniques, complemented with tomographic (RT) refraction, can also be used, giving tomographic images that can show to a very good resolution the spatial distribution of VS, which in turn indicates the presence of weak zones where attention may be addressed (Carvalho *et al.*, 2008). Logging of the core should be when possible done during all drilling operations and digital photographs of the core as each box is filled up. The selection of the cores for laboratory tests can be done at the core storage area. Sonic logging and/or televiewer scanning is often better, faster and cheaper than recovery of oriented core (Sousa, 2009). Finally, for the selection of the optimal position of boreholes appropriate virtual Bayesian preposterior analysis should be used (Sousa, 2010; Einstein & Sousa, 2012).

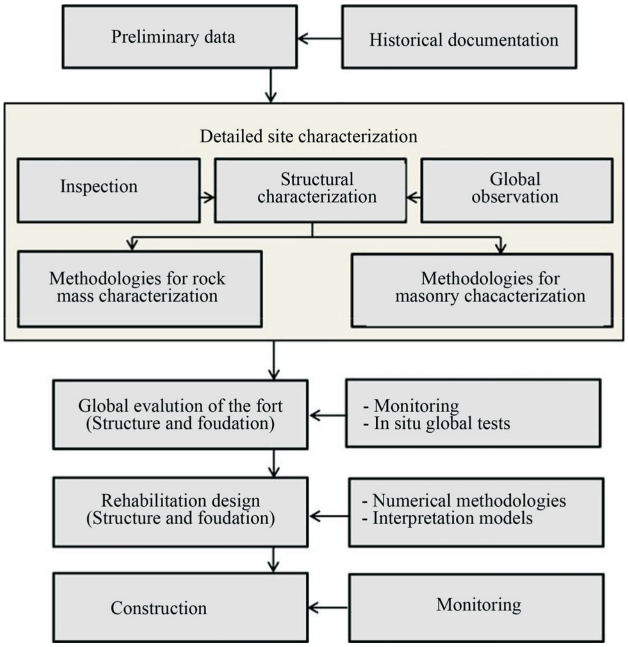


Figure 4 - Flowchart for rehabilitation of ancient masonry forts.

The materials that make up forts masonry are normally rocky, with few cases existing in some countries where masonry is made of ceramic or earth materials. There are several tools, procedures and techniques that enable the qualitative and the quantitative characterization of these materials. Such techniques include the use of sonic wave propagation tests and flat jack tests at the location of the site, followed by broader characterization techniques, such as load tests and identification dynamics tests (Guedes *et al.*, 2010). In addition, classical rock mechanics tests can also be used to characterize the masonry.

A laboratory prototype for discontinuity shear behavior was developed at University of Porto to perform tests on stone masonry joints as illustrated at Fig. 7. The shear box is 200 x 200 x 150 mm^3 with a capacity of 500 kN in normal and shear loads. Shear displacement is mechanically imposed up to a maximum 25 mm/hour rate. Normal displacements are measured for dilatancy characterization. The

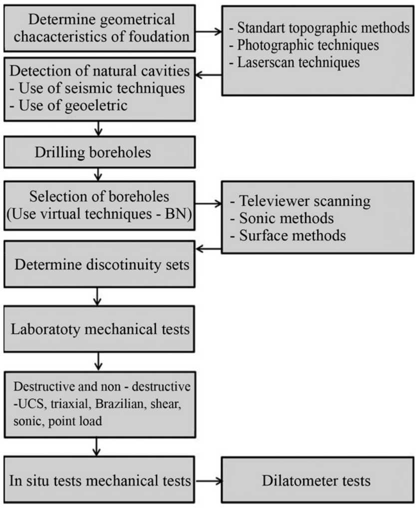


Figure 5 - Methodologies for rock mass characterization.

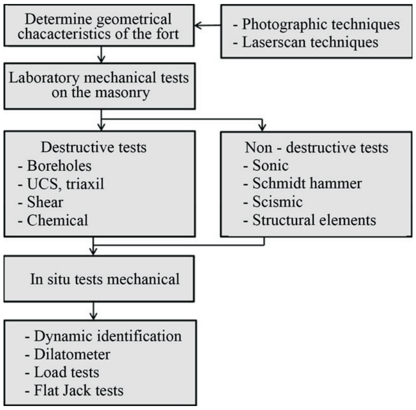


Figure 6 - Methodologies for masonry characterization.

Figure 7 - Discontinuity shear tests.

equipment also allows cyclic testing of joints for residual shear strength determination. Masonry samples are specially cut to fit the shear box volume with the mean joint plane at 75 mm from base. When mortar is used in masonry its thickness is included in the 150 mm sample height. If a shear test of rock over soil (tout-venant) is performed, the upper half of joint sample is always of rock. An example of studies performed using this equipment is described in Costa *et al.* (2012) for the bulwark of Chaves.

Local sonic wave tests are non-destructive techniques that can be applied in situ and measure the velocity of propagation of a sonic wave between two points, which depends on the characteristics of the medium the wave is travelling though (Guedes *et al.*, 2010; Lopes *et al.*, 2010).

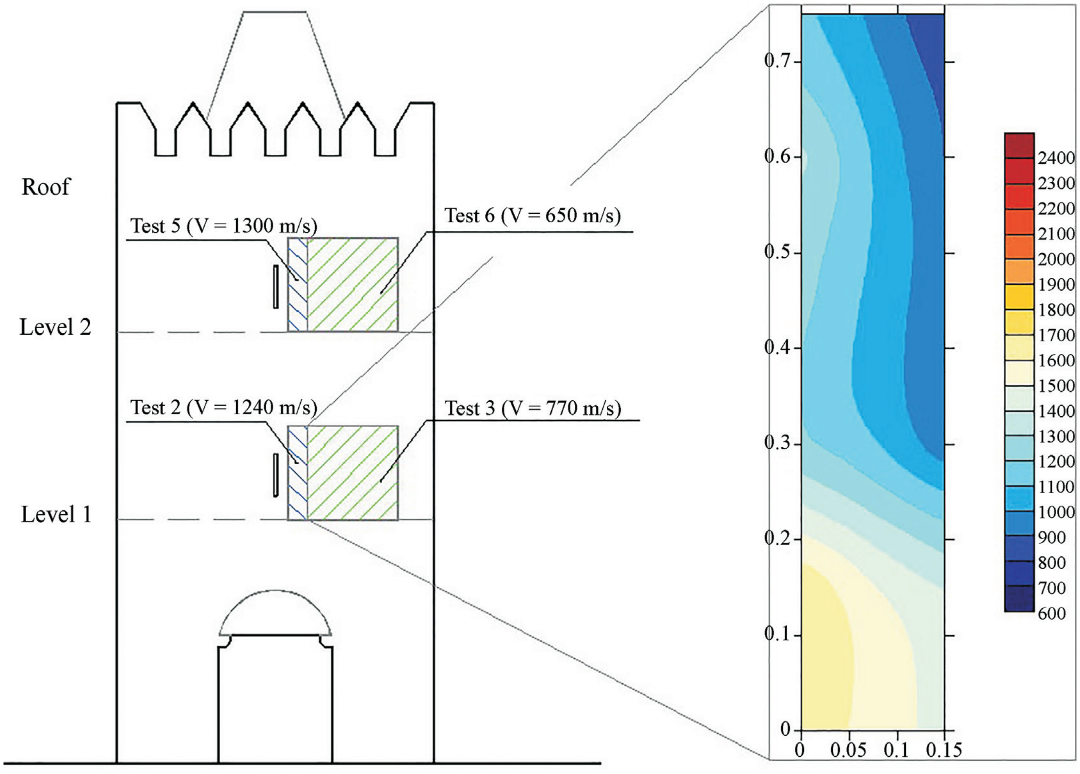
In ancient masonry structures this technique can be applied to determine the mechanical properties of the materials that make up walls for example. In Fig. 8 results of application of this sonic technology to the Caminha tower are presented (Silva *et al.*, 2009).

Another local non-destructive technique to evaluate mechanical properties of a masonry wall is using flat jacks. This is a common technique in rock mechanics that allows one to evaluate the in situ state of stress as well as the deformability of the rock mass materials. Testing procedures for stone masonry structures are standardized in ASTM and RILEM. In particular, these standards define the dimensions of the jacks in function of the main stone elements and define the minimal dimensions of the jacks. This implies to use adapted jacks to the different types of masonry.

The technique of flat jacks, when applied to walls, allows one to perform two types of tests for different purposes; simple test and double test. These two procedures turn out to be complementary. The simple test uses one horizontal slot and one flat jack and can be considered as the first phase of a double test (Fig. 9a). The test permits one to evaluate the state of stress on the wall, which in turn allows one to determine the existing loads on the wall. Since this value can be estimated by considering the various elements discharging on the structure, comparison between the estimated value and the value determined by tests can be made. The eventual difference between values may indicate the existence of anomalies (Miranda *et al.*, 2010). Figure 10 illustrates results of a single flat jack test.

After a single test is performed, and with the flat jack still positioned in the slot, a second slot is made, above and parallel to the first one (Fig. 9b). After it is placed, displacement measuring apparatus between the two flat jacks, often four vertically and one horizontally, is installed. The flat jacks are supplied from the same pump, so that they convey the same pressure. The double test may be considered as an in situ compression test performed on a stretch of the wall that lies within the area bounded by the two flat jacks. Figure 9b illustrates the double flat jack test.

To calibrate numerical models of ancient forts, it is essential to perform dynamic tests which identify the dynamic behavior of the structure (frequencies and shape modes). An example of this for the Caminha tower is in Silva *et al.* (2009). The tower that dates from the thirteenth



Facade South

Test 2:
$V_{average}$ = 1240 m/s

Test	Thickness (m)	Nº of points	$V_{average}$ (m/s)
2	1.2	12	1222 - 1249
3	2.0	36	765
5	1.2	12	1297
6	2.0	12	646

Figure 8 - Results of a sonic test for the walls of Caminha tower (Silva *et al.*, 2009).

Century is what remains of a medieval castle, with three levels and a regular plan (Fig. 11a). The study involved a geometric, exterior and interior, survey using the laser scanner technique, and the mechanical characterization of the stone masonry using dynamic identification and sonic wave tests. Figure 11b shows the detail of a laser scan image, the control points and the positioning of the accelerometers for the vibration tests (Figs. 11c and d), and the hammer for the sonic tests (Fig. 11e). Details of the dynamic identification of the tower are analysed in Lopes *et al.* (2010).

The position of the accelerometers shown in Fig. 11c was chosen to identify a large number of possible modes. The analysis of the testing results showed 28 peaks (Fig. 12). However, not all correspond to vibration modes of the tower, and out of these, 10 were associated with the tower vibration. The remaining peaks are local modes associated with the structure that exists on top of the tower to sustain the tower bell. The main dynamic identification modes are illustrated at Fig. 13 (Lopes *et al.*, 2010).

In seismically prone areas, it is important to study the response of ancient monuments during earthquakes, particularly during the process of rehabilitation. Figure 14 illustrates shaking table tests of a model simulating the fort that was severely damaged during the earthquake at Abruzzo, in 2009, after being strengthened (Miranda *et al.*, 2010).

Other tests in the laboratory can be performed for masonry using samples of rock and of joints (UCS, triaxial tests, Brazilian tests, shear tests, etc.). Load tests at the laboratory can also be conducted on models or panels of ancient monuments (Costa *et al.*, 2010). In situ tests, like ultrasound surveys or dilatometer tests can also be performed (Costa *et al.*, 2010; Paupério *et al.*, 2010).

4. The Role of Numerical Modeling

Numerical modeling forms an essential part of the study of ancient forts and structures. A practical numerical analysis implies great simplifications and assumptions and must evaluate what is important and what can be neglected in the analysis. Geometric idealizations can and should be

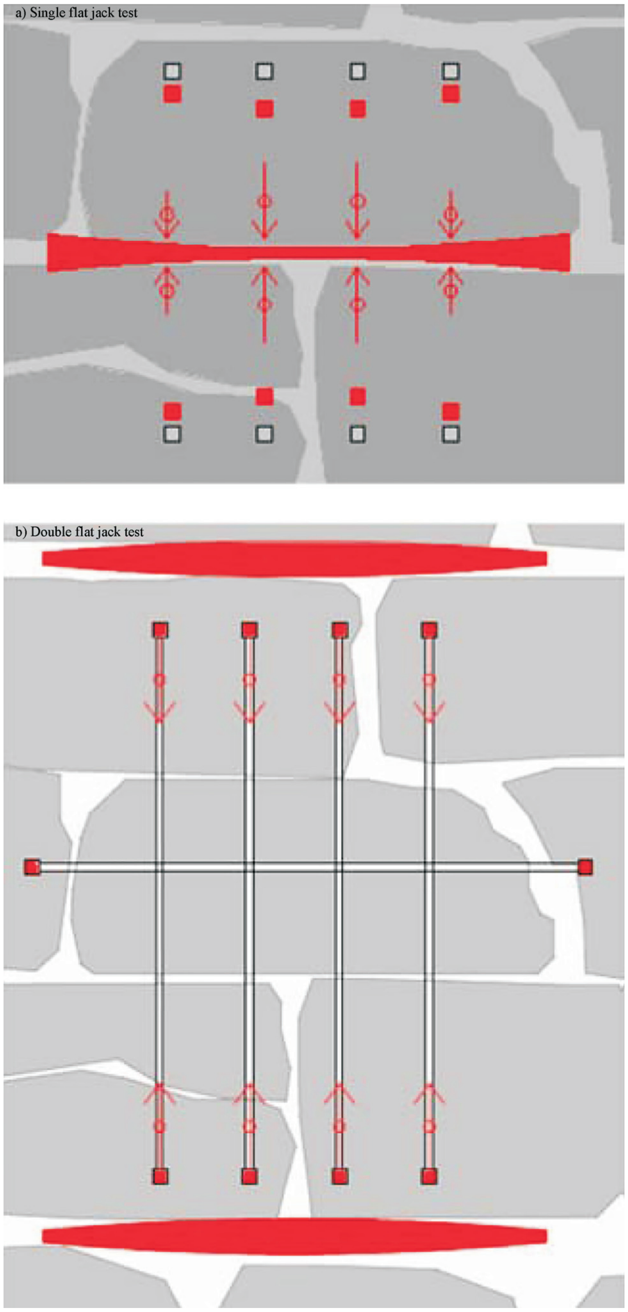


Figure 9 - Type of flat jack tests: single and double test (Miranda *et al.*, 2010). a) Single flat jack test. b) Double flat jack test.

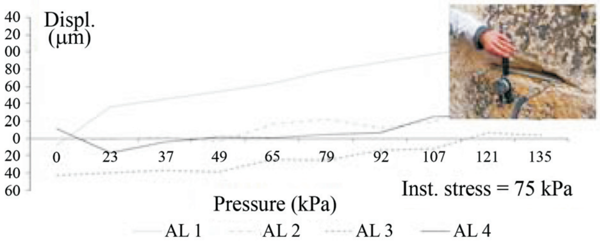


Figure 10 - Results of a single flat jack test (Guedes *et al.*, 2010).

kept as simple as possible, while still being appropriate to solve the problem. While technological and scientific advances allow increasing complexity in numerical models, often the increase in size and detail of a model may yield too much information that can complicate the analysis and make it difficult to interpret the behavior of the structure.

Figure 15 summarizes different types of numerical models that can be used for the numerical modeling of ancient forts in masonry.

The Finite Element Method (FEM) is one of the most frequently used models in numerical analysis of structures (Silva *et al.*, 2010). The modelling can be done at the micro level, considering the material batch, or at the macro level. Hybrid models can also be created when modelling a specific structural element within in a more complex structure.

Some studies have used strategies with micro simplified modeling characterized by the combination or omission of certain constituents, allowing for a drastic reduction in computation time without significant loss of accuracy. For example, Lourenço (2001) considers joints and filling as a single material with characteristics equivalent to their individual components. Other studies have used macro models, also known as continuous or homogeneous models, in which all the elements of an assembly of materials are incorporated into a continuous medium, and a relationship between extensions and average stresses of masonry is established. Damage models with distributed scalar cracking are often used in modeling macro masonry. Such models, in which damage is defined at each point by a scalar value that defines the level of degradation of the material, are commonly used in modeling of reinforced concrete structures (Silva *et al.*, 2009).

The Discrete Element Method (DEM) of modeling is important for modeling the discrete behavior of discontinuous rock masses (Lemos, 2012). DEM is also useful in modeling materials such as masonry. Applications of DEM to stone masonry structures are based on rigid or deformable blocks. Models based on deformable blocks can be used in a finite element mesh based on contact conditions in which the deformations are obtained from the relative displacement between blocks, taking into account normal and tangential stiffness. This type of contact model allows a slight overlap of blocks in compression, and uses explicit solutions for the resolution of static and dynamic problems.

Other models can be formulated as presented by Silva *et al.* (2010). This is the case for volume models (Fig. 15), which allow one to reproduce in a more realistic way the areas of intersection of elements. When using volume models it is possible to evaluate the stresses in the thickness of a wall. However, the models must be used with more than one element to discretize the thickness, otherwise errors may be high.

An example of the application of numerical models is for Caminha tower, which was analysed using FEM. The mesh developed using the software Cast3M is illustrated in

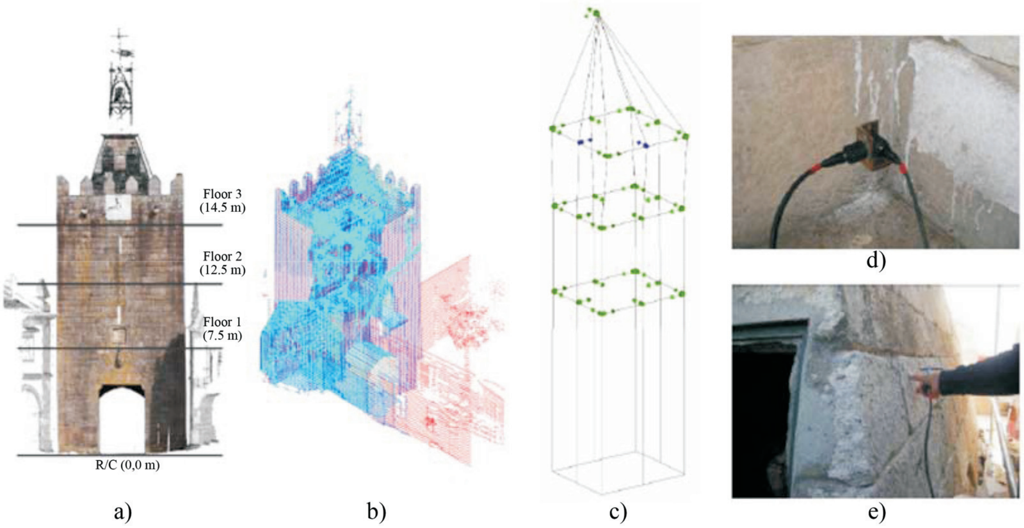


Figure 11 - Studies for the Caminha tower (Silva *et al.*, 2009). a) image of tower; b) laser scanning; c) points for vibration tests; d) colocation of accelerometers; e) hammer.

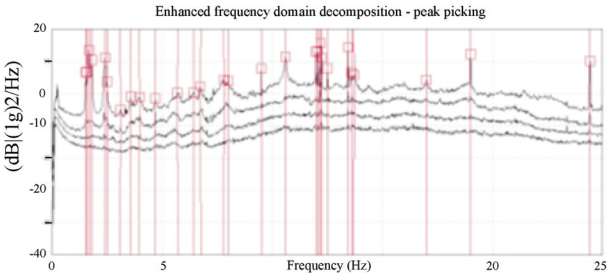


Figure 12 - Frequency peaks of the identified vibration modes for the Caminha tower (Lopes *et al.*, 2010).

Fig. 16 (Lopes *et al.*, 2010). Since the tower is connected with several buildings, these connections were taken into consideration. The calibration of the mechanical properties was done using the results of dynamic tests, to adjust the values of the modal frequencies and the obtained modal deformations using a parameter MAC (Lopes *et al.*, 1982). The deformability moduli obtained were: masonry of the tower – E = 1.4 GPa; masonry of the neighbor walls – E = 2.0 GPa. These values can be considered within the expected range for this type of fort.

5. Rehabilitation of Foundations and Walls of Guimarães Castle

The Guimarães Castle was founded in the 10th Century (Fig. 17). In the last gothic phase, the southwest corner of the fence was reviewed, advancing on the walls of the village. The castle was rebuilt between 1265 and 1318. In the last century, starting in 1936, several restoration works on the monument were made. The works consisted of consolidation of the walls, restoration of the main door, re-

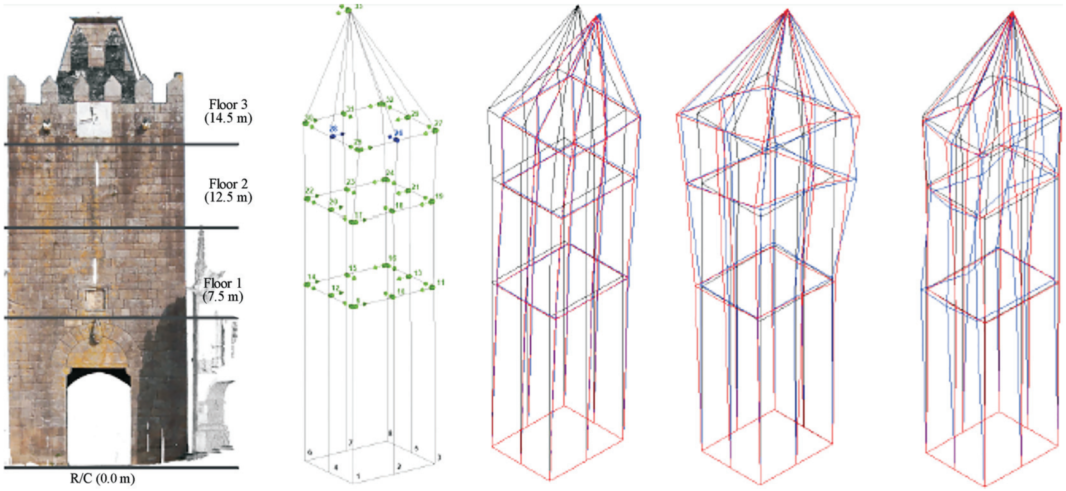


Figure 13 - Mode shapes identified from dynamic tests on Caminha tower (Lopes *et al.*, 2010).

Figure 14 - Shaking table tests in a masonry model reinforced using injections (Modena *et al.*, 2010).

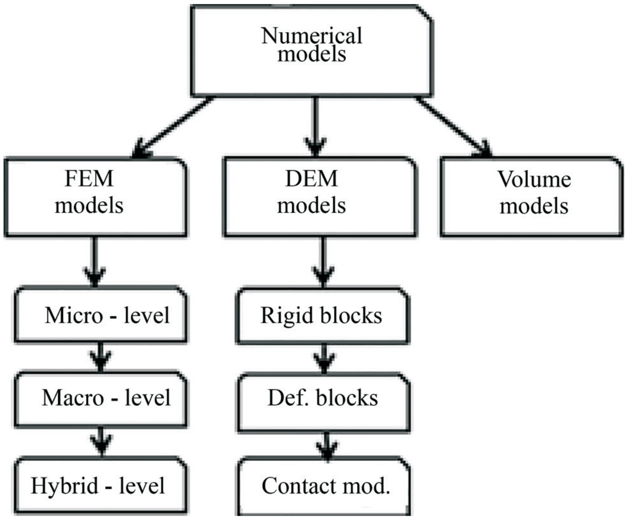


Figure 15 - Numerical models for masonry forts.

placement of masonry, demolition of elements 'newly built', and the reconstruction of the battlement stairs, parapets and battlements, reconstruction of wall panels, etc. These operations ended in 1971.

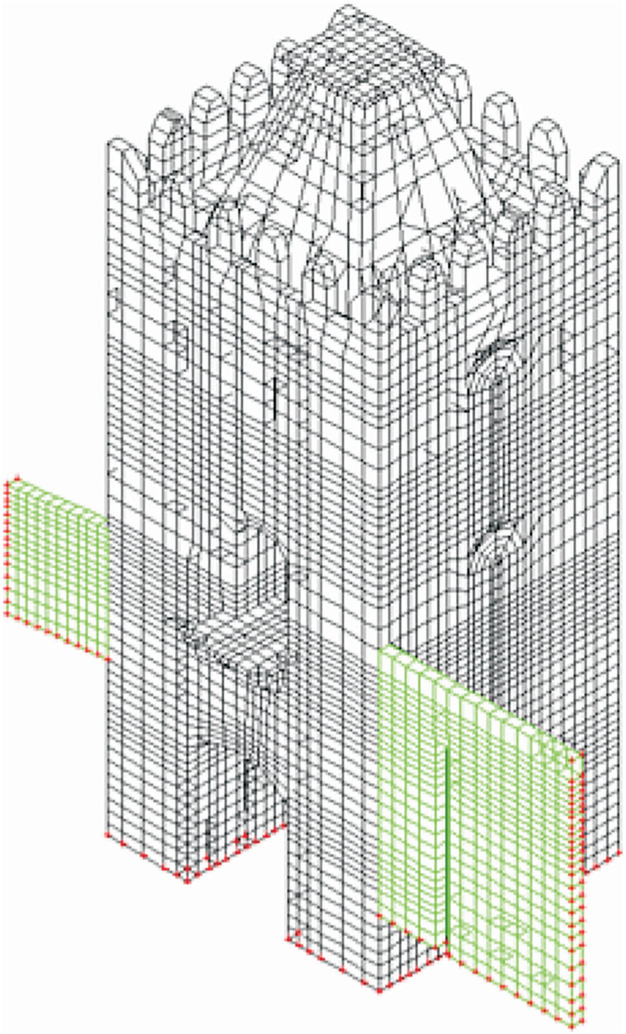


Figure 16 - Numerical discretization of Caminha tower using volume elements (Lopes *et al.*, 2010).

Figure 17 - A general view of the medieval Guimarães Castle.

In November 2008, an intervention was commissioned to evaluate the causes of the development of fissures and fractures in the exposed in face of the main wall and tower in the Southeast of the castle. A solution for these problems should be arisen from it, namely for the contention of these damages (Fig. 18). The tower presents an opening of the joints with a development in the vertice on the base of the wedge, reflecting a rotation in the base. On the North face, together with the opening of the joint, a singular fracture was observed with some losses of stone masonry indiciating a crashing by compression, as a consequence of the increase in stress resulting from the rotation of the wedge.

The foundation of the wall, and specifically of this wedge, is a rocky system with an outcrop of around 3.5 m above the surface and presents a clear fracturing system and a high degree of weathering, more intense in the base. The position and orientation of the discontinuity sets explains fairly well the orientation of the fissuring in the masonry, especially along vertical joints in the North side of the fort, as illustrated in Fig. 19. Therefore, from the performed analysis, where the geological-geotechnical studies have played an important role for the understanding of the structural mechanisms, it was concluded that an early cutting of the rock outcrops, executed in the decade starting on 1940, to enlarge the view of the fortified masonry in a urbanistic arrangement, might have been responsible for the instability verified in some of these outcrops. (Viana da Fonseca *et al.*, 2006).

The presence of granite blocks is related to geological structures such as fractures, foliation or faults, where water can easily flow into and through, accelerating chemical weathering processes. They can be reasonable determined when a careful and rigorous geological-geotechnical site investigation campaign, involving the all excavated volume, is carried out into the boreholes net, in order to construct a reliable geological-geotechnical model.

The study area is characterized by granite formations, whose matrix corresponds to a calcalkaline granite two-mica biotite with predominant porphyritic texture. An emphasis is due to the importance of masses of rounded blocks, consisting of granites low weathering levels (W2), included in sound granitic masses.

The characterization of discontinuities contained in the unstable blocks was first made in a field survey and drilled cores. Table 1 presents the characteristics of the discontinuity sets at the foundation. Three sets were obtained, being F2 subdivided in two (F2A and F2B with a small variation in the orientation), using the software DIPS from Rocscience (Fig. 20). FT and LT represents the average planes of the main families.

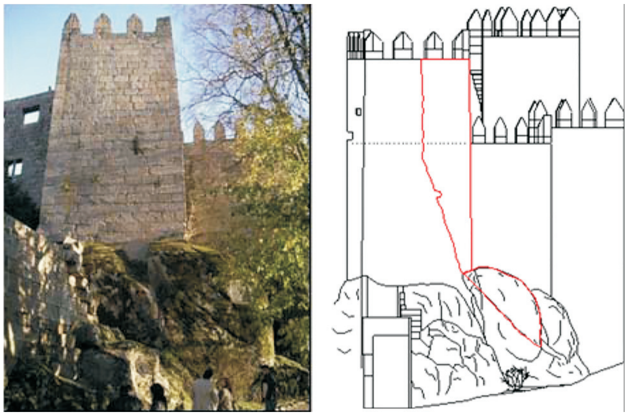


Figure 18 - Perspective of the instabilized foundations.

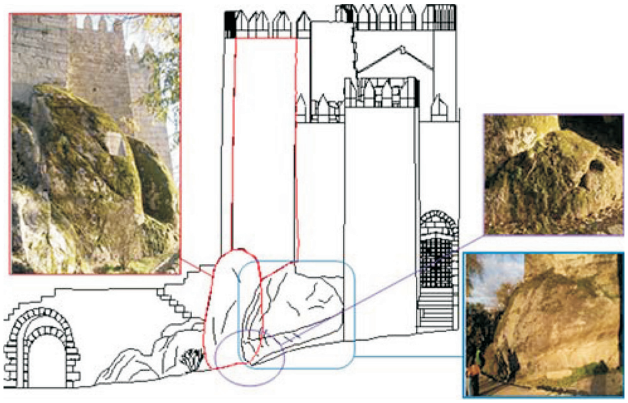


Figure 19 - Perspective of the granite massif that supports the foundation of the tower.

Strength parameters were evaluated through discontinuity shear tests or through the combination of tilt tests and the use of Schmidt hammer (Rocha, 1971; Barton & Choubey, 1977). In Table 2 are represented the obtained results with tilt and Schmidt hammer tests, where D1 and D2 are addressed, respectively, to the higher and lower values. The value of r varies between 25 to 35, R equal to 46, JRC equal to 11 and JCS between 40 to 60 MPa. The friction angles calculated varies (Barton, 1976; Hoek, 2007): basic (φ_b) 35-45°; peak (φ_p) 55-65°; and residual (φ_r) 34-36°.

After the geological-geotechnical characterization, it became evident the need for adopting measures to stabilize the large block that supports the foundation of the tower, in particular the west corner, dominated by an inclind facture with an unfavorable tilt angle, and where, apparently, there had been a very recent movement that evolved to the foundation of that part of the structure which leaned partially. Figure 21 outlines the most likely mechanism of instability, and illustrates photos of areas of weakness.

Table 1 - Characteristics of the discontinuities at the foundation.

Discontinuity set	Average dip/direction	JRC
FT	90/070	10-12
LT	90/320	10-12
F1	71/333	10-12
F2A	30/250	10-12
F2B	10/250	10-12
F3	30/140	1-12

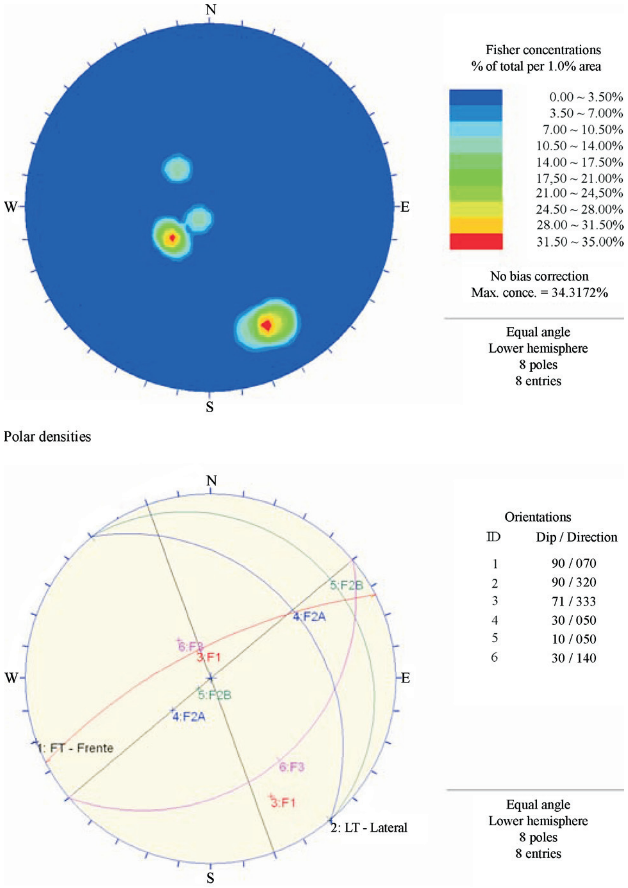


Figure 20 - General aspects of the discontinuities (Mota Engil, 2009).

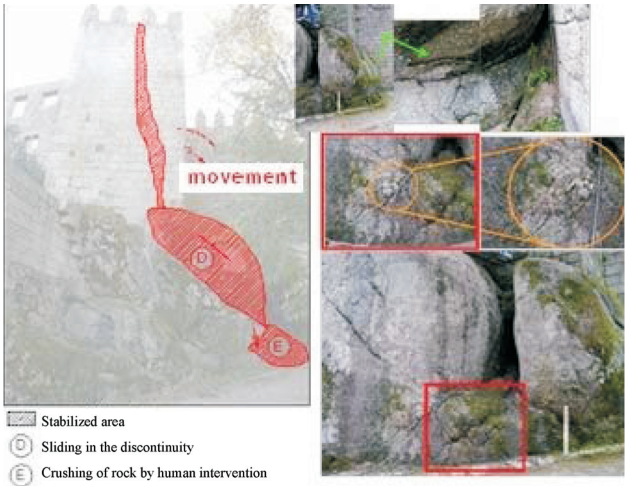


Figure 21 - Instability mechanism explaining the observed damage.

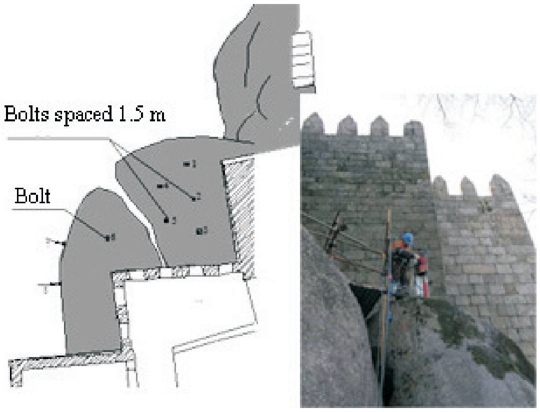


Figure 22 - Plan of nailing positioning and drilling.

The stabilization measures were intended, as a principle, to "sew" the two sides of the block and prevent future relative movements. Figure 22 presents a scheme of stabilization - absolutely indicative and preliminary.

After studying various solutions that could be implemented in this case and taking into account the constraints of the site, a set of stabilization measures were proposed that, at first glance, would ensure the stabilization of the rock mass above the large fractured block by bolting the passive feature. These high resistance steel bolts would be sealed with selective and repetitive injections in the area of fractures and faults, but also in the rest of the involved areas, looking to fill other discontinuities which would be identified in drilling process for installation of the bolts. To this end the drilling procedure that has been prescribed would have to enable an integral sampling for characterization and classification of the underlying rock mass, in particular the foundation of the wall itself. The integral rotary technique that was used to execute the holes for the inclusion of the steel bars had the advantage of not transmitting significant vibrations to the structure. This drilling was extended deep enough so that the lengths of sealing guaranteed a safe embeddedness in the sound rock (W2 to W3). This was complemented with enough drilling extend to assure the nailing of the contiguous block, to ensure its attachment to the base, and finally, the mass sealed with microcement underlying the two major granite balls (identified in Fig. 21 as zone E). The space between the two blocks would still be filled with structural material cemented due to capping of the original stone material. Finally a thorough monitoring system was installed to evaluate a possible structural reinforcement of the tower and adjacent walls.

Table 2 - Results with tilt test and Schmidt hammer.

Sample	φ_b	UCS (MPa)	
	(°)	Average	σ^2
Not weathered	-	123.5	39.3
D1	40	64.0	22.9
D2	35	41.4	24.7

It is considered that bolts subject to cutting forces should be introduced through the upper surface of the block, near the area of the foundation close to the walls, and that drilling openings should be spaced at 1.5 m from the edge line, looking for a layout that was as orthogonal as possible to the gap plane (diagram in Fig. 22). The bolting elements to be adopted should consist of steel bars of high resistance so that they could establish the safety levels imposed by design criteria an in number compatible with the available space. The injection procedure and inspection criteria are described below.

The design model used a limit equilibrium analysis with the following expression for the safety factor (Viana da Fonseca & Cruz, 2010):

$$FS = \frac{\left[(1 \pm k_v)W_n - V - k_h W \sin(\alpha)\right]\tan(\delta) + T}{W_t + U + K_n W \cos(\alpha)} \qquad (1)$$

where W_n and W_t are, respectively, the normal and tangential projection at the failure surface of the weight of the block; V and U uplift forces that are equal to zero in this situation; T force applied by bolts; δ friction angle of the failure surface; k_v and k_h the seismic coefficients that were not relevant in this case. The strength capacity of the bolts is given by:

$$T = \frac{0.9 t f_{yd} A_S}{2} \qquad (2)$$

The value of fyd was equal to 913 MPa for a bolt with a diameter of 45 mm, being the strength capacity of the bolts equal to 653 kN (Viana da Fonseca & Cruz, 2010).

The solution proposed required continuous monitoring, needed to adjust the solution in terms of length of the bars, arrangement and number depending on the recognition of the solid and weathered rock zones. Figure 23 shows a monitoring scheme with clinometers for tower T1 (Arêde *et al.*, 2010).

The construction phases are illustrated in Fig. 24. The work should be started from injection upwards defining two injection steps: a first run by gravity purge tube up to the mouth; the second - performed immediately - by injection under pressure with the volume control (accompanied by a careful check upwelling). Two different types' injections should be considered: injections in rock masses of good quality and injections in rock masses very weathered and soils. The injections were performed with cement grout to achieve the pressures defined in paragraph below, which ensured the consolidation of land and good sealing of the armor. The first hole injection would be used to assess the type of solution to be used and method of implementation of the injections. In the treatment of mass for the foundations and in the presence of soils areas and highly weathered rock masses, selective and repetitive injections would be necessary in some specific sections.

Finally, all the mouths of the holes were closed with cores that were cut with a diameter of 200 mm and that had been removed on the starting of the execution of the holes.

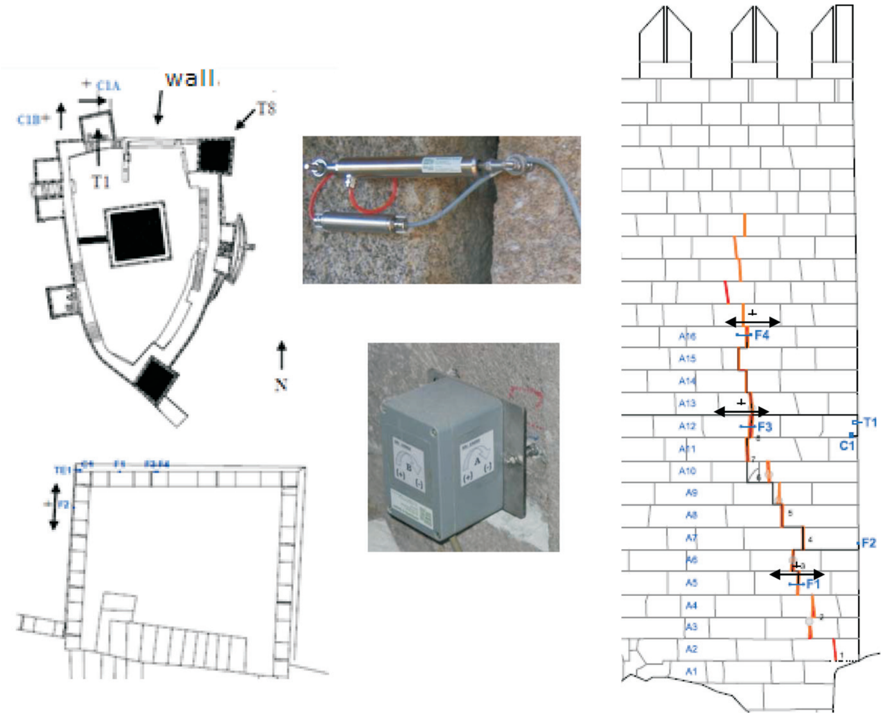


Figure 23 - Guiarães Castle. Instrumentation on tower T1 for structural monitoring with relative displacement (crackmeter) and rotation monitoring (tiltmeter) (Arêde *et al.*, 2010).

Figure 24 - Arrangement of nailings and consolidation zone with micro-cement.

The space in between was filled with cemented large stone blocks and a dry stone masonry similar to the wall was built faceting that fill. At the base of the second block, where consolidation had been made with very fluid mortar and micro-cement it was proceeded similarly (Fig. 25).

6. Forts in Muscat, Oman. Protection of the Jalali Fort

The fortifications in the region of Muscat with Portuguese legacy are very complex consisting of several forts and bastions arranged according to the nature of the mountainous terrain and were constructed to defend the bay. Figure 26 is a schematic of the fortification system from the 17th Century (Garcia, 2009). The Jalali and Mirani forts, which were built in the 16th Century, are the most famous forts and are located at the entrance of the Muscat Bay. The Jalali Fort in particular is the finest of Omans historical fortifications in the capital area and its environment (Fig. 27). The fort went through a series of transformations in design and fortification. The Mirani Fort was completed in 1587, and is located at the opposite side of the bay of the Jalali Fort. It currently overlooks the Sultan's Palace, in the old city of Muscat.

As part of a major rehabilitation and restoration program for forts around the Muscat area, the rocky slopes on which both the Jalali and Mirani forts are constructed were studied. For the Jalali Fort, a detailed geotechnical investigation was carried out including a topographic survey, plotting engineering geological data and collecting geotechnical information from the faces of the hill. Reference is made to the two watching towers protecting the entrance of the bay, as well as to the magnificent Mutrah Fort in a bay very near the Jalali and Mirani forts (Fig. 2). It is interesting to note that there is a small chapel located in one of the watching towers which is still preserved to this day. The Muttrah Fort lies on a rocky formation over the Sultan Qaboos harbour near the city of Muscat. The rocky slopes were studied in detail and a geological map was prepared. The topographic map was done by a total station where the geological structures were located. The cavities were also studied in detail and suitable measures were suggested for reducing their enlargement.

The geology of the old Muscat area is described in detail in a geotechnical report from Chaterjee (2007). The geology comprises mainly of dunite and peridotite (Hurzburgite). Therefore, the forts are founded on hard and tough ultra-basic rock stratum. The weathering effect of the rock masses, which is extensive, and the nature of the rocks have affected the strength of the rock masses, with the existence of significant discontinuities, sometimes with significant aperture, zones with marked heterogeneity, and the occurrence of natural cavities. Also relevant weak regions were identified which have important consequences on the stability of slopes upon which the forts are built. Figures 28 and 29 illustrate the occurrence of natural cavities, and dis-

Figure 25 - Stabilized situation of the castle.

Figure 26 - Forts around Muscat (Garcia, 2009).

Figure 27 - Jalali Fort.

continuities with significant aperture and major shear surfaces (Sousa, 2009).

In the Muttrah Fort area, the rock is mainly peridotite and in the Mirani Fort area mainly dunite. There is a profuse quantity of olivine intruded by serpentine veins and dykes which maintain parallelism with prevailing joints. The dykes vary in thickness from about 2 to 50 cm. The rocks may be described as greenish grey occasionally met with black spots. Under the microscope the rocks may be classified as indicated in Table 3, taking into consideration their mineralogical composition, grade of alteration and strength. Special mention is made to cavities and holes and their influence in the stability of the forts.

A detailed structural analysis of the joint systems has been carried out by plotting several types of diagrams. From the analysis of these diagrams, five predominant sets of joints were established (Chaterjee, 2007): 1) dipping northerly; 2) dipping towards N 30° E; 3) dipping towards S 20° E; 4) dipping towards S 30° W; and 5) dipping towards westerly. Only 3 sets were considered vulnerable, namely sets 1, 2 and 5. Geological structures like fault/shear zones,

Table 3 - Microscopic study of rocks below Forts Muttrah and Mirani (Chaterjee, 2007).

Rock	Main minerals	Texture	Texture	Texture
Peridotite Muttrah Fort	Olivine (55%) Orthopyroxene (40%) Chromites (5%)	Interlocking texture with jacketed look due to alteration to serpentine	Massive more than 75% of olivine are altered to serpentine as well as iddingsite (brown)	Very strong, crystalline
Dunite Mirani Fort	Olivine (95%) Phlogopite(2%) Chromites (2%) Carbonates(1%)	Interlocking texture with vigorous ([> 75%) alteration of olivine along fractures to serpentine produces a jacketed look	Massive with increased porosity, highly fractured (regular and irregular)	Crystalline, weakened by fracturing and increased porosity
Dunite Mirani Fort	Olivine ([> 90%) Clinopyroxene (5%) Phlogopite (3) Chromites (2%)	Interlocking texture with vigorous alteration of olivine produces a jacketed look	Massive with increased porosity	Crystalline, weakened by recrystallization, increased content of secondary mineral and porosity

disposition of different joint planes and other features were evaluated.

The initial phase of the protection and rehabilitation works on the fortifications comprised of protecting the entire rocky hill and surrounding area from further erosion from the action of sea waves. Protection works started with Jalali Fort (Karam, 2007) while rehabilitation works for the foundations were only performed until now for the Muttrah Fort.

The eastern side of the Jalali Fort is particularly prone to large waves caused by high winds, and this is especially the case during cyclones that occasionally hit the Muscat coast. The eastern side of the fort is open to the Indian Ocean, and is characterized by a very steep sea bed. On 6 June, 2007, cyclone Gonu hit the coastline of Oman causing extensive damage to many coastal areas including the cities of Muscat, Sur and Ras al Hadd at the easternmost point of the Omani mainland. The cyclone killed 49 people, with 27 reported missing. Around 20,000 people were affected and damage in the country was estimated at around $4 billion, ranking it as the worst natural disaster on record in Oman.

Figure 28 - Rock mass in the vicinity of Jalali Fort.

Figure 29 - Discontinuities in the rock mass.

In Muscat, Cyclone Gonu caused significant damage to the 300 m long seawall protecting the Jalali Fort (Fig. 30). The damage included destruction of 200 m of the Shed concrete armor units, collapse of numerous 160 ton concrete crest blocks and failure of the slope (Bentika *et al.*, 2010). It was therefore necessary to redesign the existing seawall for protection against the occurrence of cyclones as the first step in protecting these historically significant structures.

As an initial assessment of the impact of the Gonu cyclone on the seawall, track and wind speed information was reviewed and used to model the storm as it crossed the Indian ocean and approached the site using the 3rd generation SWAN wave model driven by moving wind fields as boundary conditions (Bentika *et al.*, 2010).

The seawall was originally constructed in 1980, and was about 265 m long. The armor was provided by Dolos units in two layers with total thickness of 2.6 m at a slope of 1:1.5 (V:H) laid on stone. The potential causes of failure included armor unit structural failure, toe failure and loss of underlayer leading to undermining of the units. Figure 31 shows a view of the fort during construction of the new seawall.

The seawall was redesigned using appropriate hydraulic models for simulating the extreme conditions for the waves and scale tested in a random wave flumes to optimize the design. The new seawall is shown in Fig. 32, and the final configuration is shown in Fig. 33.

The construction works included dredging the debris field at the toe from the failed slopes of the old seawall; lifting the large, and oddly shaped 180 ton concrete crest units, splitting them into two 90 ton concrete blocks and then lifting them into position to form the new toe for economic

Figure 30 - Jalali Fort. Location of the new seawall.

Figure 31 - Jalali Fort during construction of the seawall.

Figure 33 - View of the new protection of Jalali Fort.

purposes; re-profiling the slope and laying the 2.4-4.8 ton underlayer rock; and placing over 900 16 m^3 AccropodeTM units on the slope. The 16 m^3 AccropodeTM units weigh about 40 tons each, and represent the largest sized 16 m^3 Accropode^{TM} units used in the Middle East, and are amongst the largest used in the world. The quantities of different materials used in the construction are shown in Table 4 (Karam, 2007).

The rocks were sourced from a quarry about 70 km from Muscat and were sorted and tested at the quarry prior to transporting to site. Standard rock tests included shape ratio tests, hardness, and abrasion tests, as well as others. The AccropodeTM units were cast at a batching plant located about 100 km away from site. While transportation costs would be higher since trailers can only carry a single AccropodeTM unit, the casting process could be better monitored and testing ensuring quality control. Geotextile was placed under toe blocks to create an impermeable membrane. A bedding layer was immediately placed to ensure that the membrane stays in place. To ensure the stability of the new toe, a series of boreholes were performed in order to identify the geotechnical formations. The surface layer to the depth of 2.5 to 4.0 m was identified as man-made ground with basalt origin; between 2.5 to 19.0 m, dense light grey clayey sand with occasional shell fragments; and at depths greater than 19.0 m, black fractured basalt. Slope stability analyses with shallow and deep rotational failure surfaces were performed with the geotechnical profile, and the revetment was found to be stable.

The newly constructed seawall successfully stood up to cyclone Phet, albeit it is noted that Phet was much milder than cyclone Gonu.

7. Conclusion

The analysis of historical masonry structures such us forts and castles on rock hills is a complex task, and the

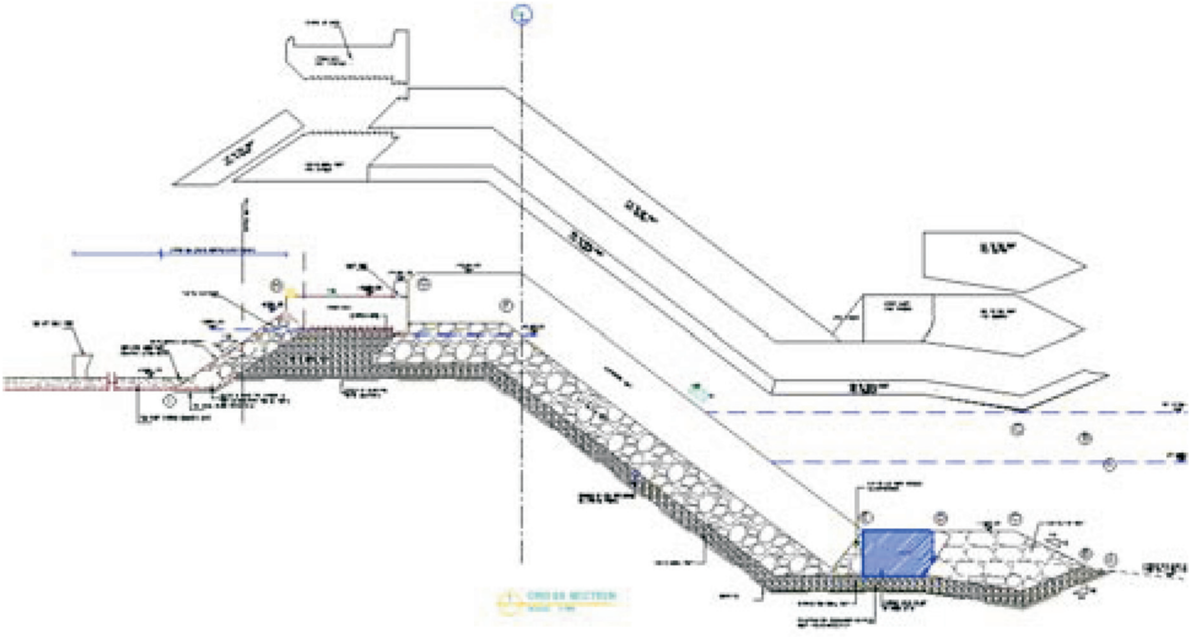


Figure 32 - Final design typical section.

Table 4 - Quantities in the new design of the revetment.

Item	Quantity
100-500 kg bedding rock	20,000 m^3
2.4-4.8 T underlayer rock	25,000 m^3
5-7 T scour rock	10,500 m^3
Total Rock	58,750 m^3
Crown wall concrete	4,250 m^3
Accropodes (901 x 16 m^3)	14,400 m^3
Total concrete	18,650 m^3
Geotextile	7,750 m^2

conservation and restoration of these monuments ant its rock foundations in historical areas are disciplines that require specific training. Each fort and castle has distinctive engineering and architectural features that make it a physical challenge.

Emphasis was made to the methodologies followed in studies and investigations on ancient forts and castles. A flowchart was presented that summarized the methodology that should be followed for the rehabilitation of ancient masonry forts on rock hills indicating the need to assess to historical documentation and the existing information, and to have a detailed site characterization of the fort and its foundations. Also the methodologies that should be implemented for rock mass characterization and masonry characterization were detailed. In situ and laboratory tests as well numerical modelling were discussed.

Difficulties in the analysis of historical forts are mainly related to missing information related to geometry, characterization of mechanical properties of materials, and the large variability of mechanical properties, the significant changes in the core and constitution of structural elements, and the unknown construction sequence and the existing damage in the structure.

The solution for the rehabilitation of foundations and walls of the Guimarães Castle is an excellent example of application of rock mechanics concepts for the stabilization of the foundation and of the walls. The empirical knowledge used was important in all the design process. The importance of the monitoring activities during the rehabilitation works has been also emphasized

The fortifications in the region of Muscat with Portuguese legacy are very complex consisting of several forts and bastions. The redesign and construction of a new seawall to protect the Jalali Fort and its surroundings constitutes a complete study combining issues regarding the influence of the occurrence of severe cyclones, and the geotechnical issues related to the needs of rock materials. The rehabilitation of the foundation of Jalali Fort has not yet started but the nature of the rocks, the existence of significant discontinuities and the occurrence of detected natural cavities imply to do that in the future.

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List of Symbols and Acronyms

δ: friction angle of the surface failure

ν: Poisson's ratio

φ_c: peak friction angle

φ_r: residual friction angle

ρ: density

A_s: area of the bolt transversal section

E: modulus of deformability

k_v, k_h: seismic coefficient in vertical and horizontal directions

r: Schmidt rebound number wet and weathered fracture surfaces

R: Schmidt rebound number on dry unweathered sawn surfaces

T: strength capacity of bolts

U and V: uplift forces

w_n and w_t: normal and tangential projections of the weight at failure surface
2D: two dimensional
3D: three dimensional
Accropode^{TM}: units for the protection revetment
ASTM: American Society for Testing and Materials
CH: P and S wave seismic cross-hole technique
DEM: Discrete Element Method
DRCN: North Regional Direction of Culture in Portugal
FEM: Finite Element Method
FS: Safety Factor
GSI: Geological Strength Index
IPPAR/IGESPAR: Institute for Buildings and Natural Monuments in Portugal
JCS: Joint wall Compressive Strength
JRC: Joint Roughness Coefficient
MAC: Correlation coefficient for modal vector analysis
RILEM: Reunion Internationale des Laboratoires et Experts des Materiaux
RMR: Rock Mass Rating
RT: Tomographic refraction
Q: Q system index volume
UCS: Uniaxial Compressive Strength
W: ISRM weathering level