MONITORING PROCESS OF THE RE-CONSTRUCTION OF AN ANCIENT STRUCTURE: THE BALUARTE DO CAVALEIRO

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The Baluarte do Cavaleiro is part of the stone masonry wall system existing in the city of Chaves of Portugal and it is a construction dated from the XVII century. The Baluarte do Cavaleiro is formed by three walls (North-East, NE; South-East, SE; South-West, SW) and by two junction elements (designated here by *cunhais*). The SE wall has suffered two collapses recently. The main objective of this research work is to describe the monitoring process adopted to control the stability of the Baluarte do Cavaleiro and the adjacent constructions that could be affected during the last rebuilding process of this wall. Taking into account that this rebuilding process included the total removal of this wall, it was also possible to identify the real geometry of the cross section of the wall, its building solution and the type of the sustained soil. It was also possible to contribute for a better understanding of the structural behaviour of this kind of stone masonry construction.

Keywords: monitoring, stone masonry wall, wall, maintenance, consolidation

1. Introduction

Portugal is a country that has a vast and a rich heritage of stone masonry constructions which are live witnesses of the historical past of a country and, therefore, must be preserved. There are

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examples of this type of construction in almost all regions of Portugal and can be castles, churches, bridges, walls and buildings constructions.

The Baluarte do Cavaleiro wall, built in the XVII century, is an example of this type of construction. It was built during the governance of the Earl of S. João Luís Alvarez de Távora (Chaves 2007) and it is located in the city of Chaves, Portugal. This wall has the following characteristics: supports soil; is located near the Tâmega river (where the ground-water level is high); the surrounding foundation soil has low resistance capacity. Furthermore, there are buildings attached to the wall.

The SE wall of the Baluarte do Cavaleiro suffered two partial collapses recently (March of 2001 and April of 2002) and, consequently, underwent two reconstruction processes. This work is related to the last reconstruction process which finished in February of 2007. This reconstruction process included the total demolition of the buildings that were attached to the SE wall, almost the total demolition of that wall (by stages), the cut of a 12.5 m thick layer of soil and the reinforcement of the foundation of the wall. Because these working stages could put in risk the stability of the above constructions it was necessary to monitoring them.

The main goal of this research work is to describe the adopted monitoring process to control the stability of the wall and all the constructions attached to it, which could be affected during the last reconstruction process. Taking into account the scale of the problem (i.e. big size constructions, several constructions to be monitored), the available means and the location, the following monitoring process was adopted: to control the displacement of key-points by using the traditional surveying techniques. This process was complemented by controlling the crack opening of the existing cracks using appropriate monitoring equipment. Considering that this reconstruction process took two years to complete and the average number of records was two per week, it was possible to obtain detailed data that allowed to analyze the influence of each rebuilding stage on the structural behaviour of each construction related to this monitoring process.

2. The Baluarte do Cavaleiro Wall

Figure 1 shows Chaves city in the XVII century and the set of walls that formed its fortification system. From this set of walls the Baluarte do Cavaleiro wall stands out. The development and expansion of the city culminated in the destruction of substantial parts of this fortification system. Nowadays, there only exist some of those walls and some remains (visible in the backyards of some of the buildings of the Cadeia street) (Silva and Gomes).

Baluarte do Cavaleiro
Wall

Figure 1. Chaves (XVII century)

Figure 2 illustrates the location of the Baluarte do Cavaleiro. It is visible that it is located in the centre of the city, near the Tâmega river. Through this figure, it is also possible to realize that the Baluarte do Cavaleiro is formed by three walls. These walls correspond to the NE, SE and SW walls, with the length of 12 m, 30 m and 40 m, respectively. In 2005, there were buildings attached to the SW wall, there was a building attached to the NE wall and there were two buildings attached to the SE wall. These attached buildings to the walls have been used as housing states and/or commerce, they were built later (from XIX to XX centuries) than the wall but still have the same constructive technique (stone masonry). These buildings contact directly to the Baluarte do Cavaleiro through their stone masonry walls and, in general the Baluarte do Cavaleiro works as the back wall of these buildings.

Figure 2. Location of the Baluarte do Cavaleiro wall

The Baluarte do Cavaleiro is a typical stone masonry wall. The real geometry and dimensions of its cross section is shown in Figure 3. The building technique detail adopted in the construction of the wall that consists of using large granite stone pieces in the inner and the outer faces and filling the gap between them using small and irregularly shaped granite stone pieces is also illustrated in Figure 3.

Figure 3. Cross-section of the Baluarte do Cavaleiro wall (December 2005)

The connection between walls is materialized by junction element which is designated here by *cunhal*, Figure 4(a). These elements were built up using dry cut stone masonry. On the other hand, the walls have filled joints, Figure 4(a).

(a)   (b)
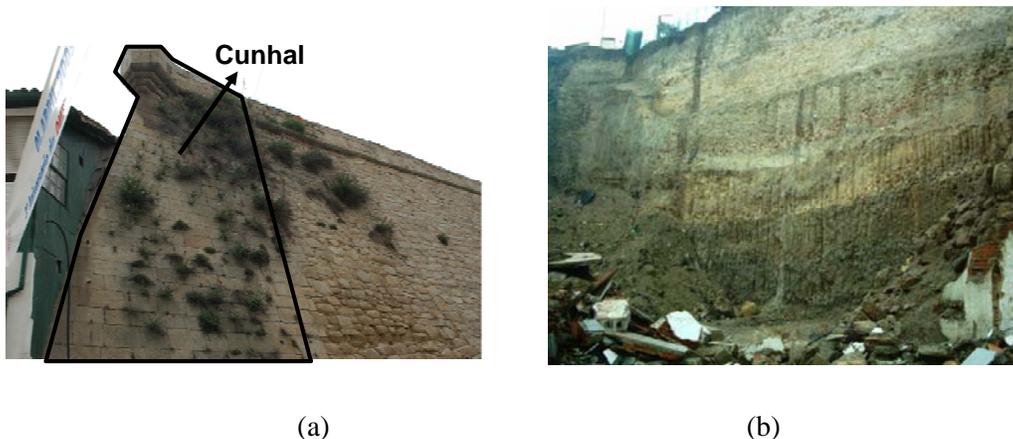
Figure 4. a) Cunhal that connects the SE and SW walls; b) Soil profile supported by the wall (December 2005)

Figure 4(b) shows the soil that has been supported by the wall (December 2005). This soil has the following constitution: 1.0 m thick organic soil as the first layer; 11.5 m thick of embankment type of soil as the second layer. This soil is extremely consolidated because it allowed an almost vertical cut, Figure 4(b). Exploration drilling tests were done in the downstream side of the SE wall in order to identify the foundation soil. The results of these tests concluded that the foundation soil has the following typology (see Figure 5): the first layer is a 1.0 m thick of silt; the second layer is a 2.0 m thick of thin sand; the third layer goes down to until the bedrock and is formed by saturated sand which varies in terms of granulometry from thin to thick. The bedrock depth is around 5.4 m near the cunhal that connects the SE and SW walls (test S1), 10.8 m in the middle span of the SE wall (test S2) and 7.4 m near the cunhal that connects the SE and NE walls (test S3).
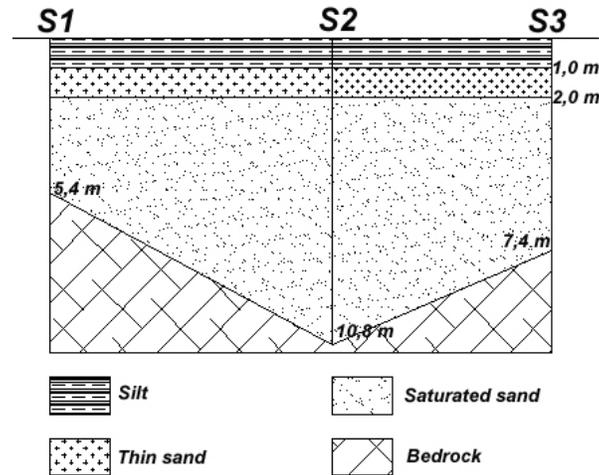
Figure 5. Results of the exploration drilling tests done in the downstream side of the SE wall (Tested by Material and Soils Laboratory of UTAD)

The SE wall has suffered two partial collapses recently. The first one occurred in March 2001 and the second one occurred in April 2002. Until March 2001, existed buildings attached to the SE wall all over its length, as can be seen in Figure 6.

Figure 6. SE wall of the Baluarte do Cavaleiro and the existing attached buildings before March 2001

The first collapse culminated in the loss of a substantial part of SE wall and also in the loss of some of the attached building, Figure 7(a). From this figure and from Figure 3 it is noticeable that parts (related to the contact area of wall and attached buildings) of the outer face of this wall had cement coat and in the other ones there was vegetation. These facts prove that the wall did not have a regular maintenance process and had faced changes in its original drainage system. Some structural instability signals gave evidence of occurrence of the first collapse. These signals were an impressive crack that was formed in the top of the soil that was supported by the SE wall and a significant slope of the front façade of the buildings that collapsed.

After the first collapse, the SE wall was rebuilt and this reconstruction process took about 1 year to finalise. The attached buildings that had suffered partial or total collapse were completely demolished, Figure 7(a). Just after the conclusion of the above reconstruction process (April 2002), the SE wall faced the second collapse which resulted in a smaller scale of destruction, Figure 7(b). This situation required another reconstruction process of the SE wall of the Baluarte do Cavaleiro that ended in February 2007. The monitoring process described in this work is related to this last reconstruction process.

| (a) | (b) |

Figure 7. Scale of destruction of the SE wall of the Baluarte do Cavaleiro after the two collapses: a) First collapse (March 2001); b) Second collapse (April 2002)

3. Adopted Monitoring Process

After the second collapse, the reconstruction process of the SE wall included the almost total demolition of this wall. The temporary removal of this structural element generated some doubts about the stability of the others structural elements of the wall (i.e. *cunhais*, the others walls (NE and SW) and the attached buildings). This fact led to monitoring the above structural elements throughout the period of time required for the second reconstruction process. In general, a monitoring process consists of getting data about certain parameters (Arêde and Costa 2006) such as: displacements; crack opening; levelling; verticality; temperature gradients; soil settling; ground-water level gradient. The process of getting the data can be periodic or continuous. The criteria to choose for this process may be the following: complexity of the construction; historical value of the construction; available time to do the task; facilities; type of parameter to measure. The analyse of the structural behaviour of a construction based on controlling the displacements or the rotations (or verticality) can be done by using specific instruments or by defining adequate key-points (Arêde and Costa 2006).

The experimental measurement of the displacements can be done by using mechanical transducers, linear voltage differential transducers (LVDT), wire transducers or transducers that are based on the gradient of the hydrostatic pressure in a communicating vessels system (Félix et al. 2003). Besides the first type of instruments, the others ones allow a continuous data

registration and are more precise. On the other hand, the inclinometers are the instruments more adequate to control the rotation (or displacement).

Taking into account the type of constructions to monitor (masonry wall), their dimensions, the number of constructions (12 buildings, SW wall, NE wall, cunhal NE/SE and cunhal SE/SW), the fact that it is an external control and the fact that these constructions are located in the centre of Chaves (pedestrian zone), we have chose to define a set of key-points strategically located on the constructions and to measure their coordinates periodically (using the traditional surveying technique) as a monitoring process which seemed to be most suitable in this context.

Based upon what was described above, the selected methodology to guaranty the stability of the constructions that could be directly or indirectly affected by the reconstruction process of the SE wall of the Baluarte do Cavaleiro, consisted of controlling the displacements and the verticality of those constructions. This control was carried out during the whole of the reconstruction process (2 years). In this context, a set of key points were defined in which reflectors were glued to. The criteria adopted to select those points were: points of the construction which were more likely to deform; a set of points able to model adequately the global deformed shape of a construction; points that allowed to stick on a reflector (i.e. points that were not inaccessible by an obstacle such as a building) or points that did not have obstacles in its field of view; the minimum number of points by construction being equal to two.

(a)   (b)

(c)   (d)

Figure 8. Key-points location and controlled buildings: a) Plan view; b) NE wall, Manas stair; c) SE wall, 25 de Abril road; d) SO wall and attached buildings (from A to K), Sol road

The location of the defined set of key-points (identified from 1 to 36) and the adopted notation for the controlled building (identified from A to L) can be seen in Figure 8. The coordinates of these points were measured using a pulse laser station NIKON-302 (Nikon 2007) and according to the traditional surveying techniques. Those coordinates were initially measured in a global coordinate system (x, y, z). In order to simplify the analysis of the results those coordinates were then converted in a local referential (x`- direction perpendicular to the construction, y`- direction parallel to the construction, z, vertical), as represented in Figure 9.
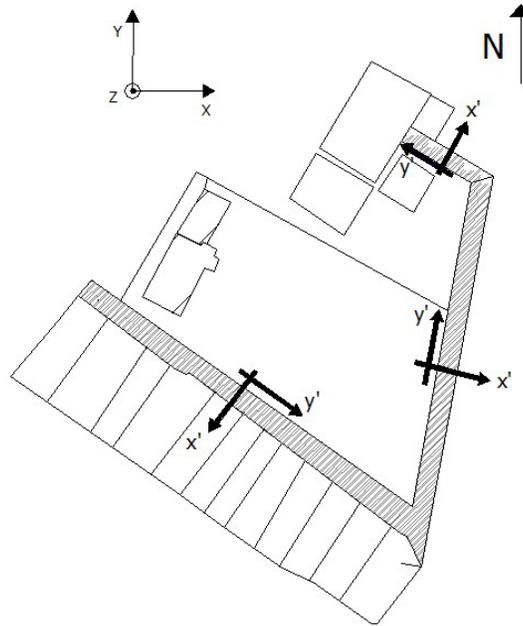
Figure 9. Global coordinate system (x, y, z) and local coordinate system (x`, y`, z`)

The difference between the coordinates of a point measured in different dates gives the displacement of that point occurred during the period of time defined by those dates. Knowing the displacement of the key-points defined for a construction gives an approach of its global deformation which may be an instability indicator.

It was assumed that the average value of the first five coordinate measurements of a key-point would be the reference value for the identification of the displacement evolution of that key-point throughout the time of duration required for the reconstruction process. It is important to stress that those five coordinates were measured before any work related to the reconstruction process of the SE wall was done (t_0). These measurements were done during April 2005. In this way, the difference between the value of the coordinates of a key-point in a certain time (t_i) and the average value of the first five coordinate measurements of that point represents its displacement occurred from t_0 to t_i. On the other hand, the slope evolution of the façade ($\Delta tg\alpha$) of a construction could be evaluated based on these coordinates and taking into account the fact that at

least two aligned key-points were defined for each façade, Figure 8 and that alignment has an angle α with the vertical direction. The slope evolution of a façade allows the control of its verticality during the reconstruction process.

As it was done for the displacement quantification of a key-point, a reference slope for each façade was quantified which was based on the first five coordinate measurements for the key-points defined for that façade. The verticality control of that façade, in a certain time t_i, was related to the slope variation occurred between t_0 and t_i. An increasing slope evolution (i.e. similar to a global rotation of the façade) results on the loss of the verticality of a façade which is an instability evidence of the construction. Parameters like the temperature, the atmospheric pressure, the relative humidity and the wind speed can affect the measurement precision of the key-points coordinates. Thus, these physical parameters were also measured, taking into account that the weather conditions in Chaves city change sharply between winter and summer. For simplicity this measurements are not presented in this paper. On the other hand, measurements of parameters related to the environmental noise vibration were not was not considered in this work, because they may influence significantly the results. Even if the construction is located in the city centre, the traffic in this zone in quit and the robustness of the construction allows to consider that the influence of the environmental noise vibrations are inexpressive in the structural response. Furthermore, this analysis is focused on the measurement of static relative displacements evolution, for very slow deformation variations, using technologies and equipment for static measurements. Therefore, the dynamic response measurements were not considered in the context of this study. In order to assure that other instability signals (i.e. the appearance of new wall cracks or soil cracks) were not emerging, a visual inspection was also done in each visit to the building site.

Each attached building to the NE and SW walls, Figures 8(a) and 8(d), was subjected to a detailed characterization process which included an exhaustive identification of the all existing pathologies in that building, before the beginning of any work related to the reconstruction of the SE wall. This process was done between March and April 2005 and consisted of creating a building characterization record. This building characterization record included the following data: location of the building; utilisation type; structural solution, information about any rehabilitation/reinforcement process done; description of the existing pathologies. In addition, a detailed characterization of the pathologies identified in each building was done. This characterization pathology record included the following data: its identification; its location; pathology type; a description of it; photographic support. The pathology types identified were: cracks; humidity; localised falling over coat; painting deterioration; constructive element showing high deflection.

Cracks existing in the over coat of the interior walls of the buildings were the type of pathology which was under an intensive monitoring process. Because of the fact that most of the buildings had a high number of cracks, a crack selection process was required in order to choose which crack should be instrumented (reference crack) per building. The adopted ranging criteria were: existence of a crack in a structural element; a pronounced crack in a high cracked constructive element (for example: masonry wall); a crack located in the connection between building and wall of the Baluarte do Cavaleiro. In order to evaluate the opening crack evolution throughout the duration of the reconstruction process several techniques were used such as plaster coupon, mechanical transducers, rulers and scale microscopy.

4. Main Results and Discussion

Figure 10 shows a graphical representation of the evolution of the tasks related to the reconstruction process of the SE wall of the Baluarte do Cavaleiro. The task related to the demolition of the SE wall and the excavation/removal of the embankment soil, identified in Figure 10 by Task 1, was considered the most critical in terms of the monitoring process. At the same time, this task was the one that required more time to finish because there were several periods of time in which the works were suspended. This delay was related to the land and compensation costs matter and to the fact that the design of the reconstruction of the SE wall was changed. Figure 10 also gives the date (month and year) of each coordinate measurement. This information is very important because allows to analysis of the influence of some factors such as the climate conditions (i.e. dry or wet month, cold or hot month) and the task in course on the values of the measured coordinates of each key point and, consequently, on the global stability of the constructions. For simplification, only the displacement evolution of the key-points defined for the NE wall, SW wall and for the cunhais is discussed in this paper.

The displacement components evolution of the key-points of the NE wall (6, 7, 8 and 9) throughout the reconstruction process of the SE wall is shown in Figure 11. None of these points had an increasing displacement evolution. In fact, the evolution was an oscillatory function type, having in general maximum values less than 6.0 mm in terms of absolute value. The average value of the displacement components of these key points was in general less than 2.0 mm. Only the perpendicular displacement component of the key point 8 showed an average value of 2.7 mm. In fact, if the error associated to the surveying process was taken into account in the quantification of the coordinates of the key-points then the above displacement values could be assumed as being smaller. This error is a function of: (1) the instrument accuracy, which can be quantified using the expression presented next; (2) the precision of the measurement, associated to a human error; (3) the temperature correction.

Year	2005											
Month	1	2	3	4	5	6	7	8	9	10	11	12
Measurement	--	--	--	1 . . 5	6 . . 16	17 . . 24	25 . . 32	33 . . 40	41 . . 48	49 . . 56	57 . . 64	65 . . 70
Task 1												
Task 2												
Task 3												
Task 4												
Year	2006											
Month	1	2	3	4	5	6	7	8	9	10	11	12
Measurement	71 . . 79	80 . . 87	88 . . 96	97 . . 102	103 . . 111	112 . . 120	121 . . 129	130 . . 138	139 . . 146	147 . . 154	155 . . 163	164 . . 167
Task 1												
Task 2												
Task 3												
Task 4												
Year	2007											
Month	1	2	3	4	5	6	7	8	9	10	11	12
Measurement	168 . . 175	176 . . 183	--	--	--	--	--	--	--	--	--	--
Task 1												
Task 2												
Task 3												
Task 4												

Key: Task 1 – Demolition of the wall SE. Excavation and removal of the embankment soil; Task 2 – Reinforcement of the foundation; Task 3 – Execution of the drainage system; Task 4 – Rebuilding of the wall SE.

■ Task in course   ▦ Suspension of the task

Figure 10. Evolution of the tasks related to reconstruction process of the SE wall. Measurements of the coordinates of the key points

According to the technical specifications of the used surveying instrument (Nikon 2007), its accuracy can be measured using the expression $+/-(3+3ppm \times D)$ mm, in which: D is the distance (in km) from the surveying instrument to the reflector. Thus, the key-points of the NE wall had no expressive displacements during the reconstruction process of the SE wall, these displacements were mainly related to the normal behaviour of the NE wall as being a stone masonry wall structure. We may conclude that the tasks related to the reconstruction process did not affect the stability of the NE wall. In fact, as it was stated before, the key-point 8 was the one that had shown a higher value of displacement and, at the same time, it was the most far away from the rebuilding area, Figure 8(b).

Displacement (mm)

a) Key point 6

Displacement (mm)

b) Key point 7

Displacement (mm)

c) Key point 8

Displacement (mm)
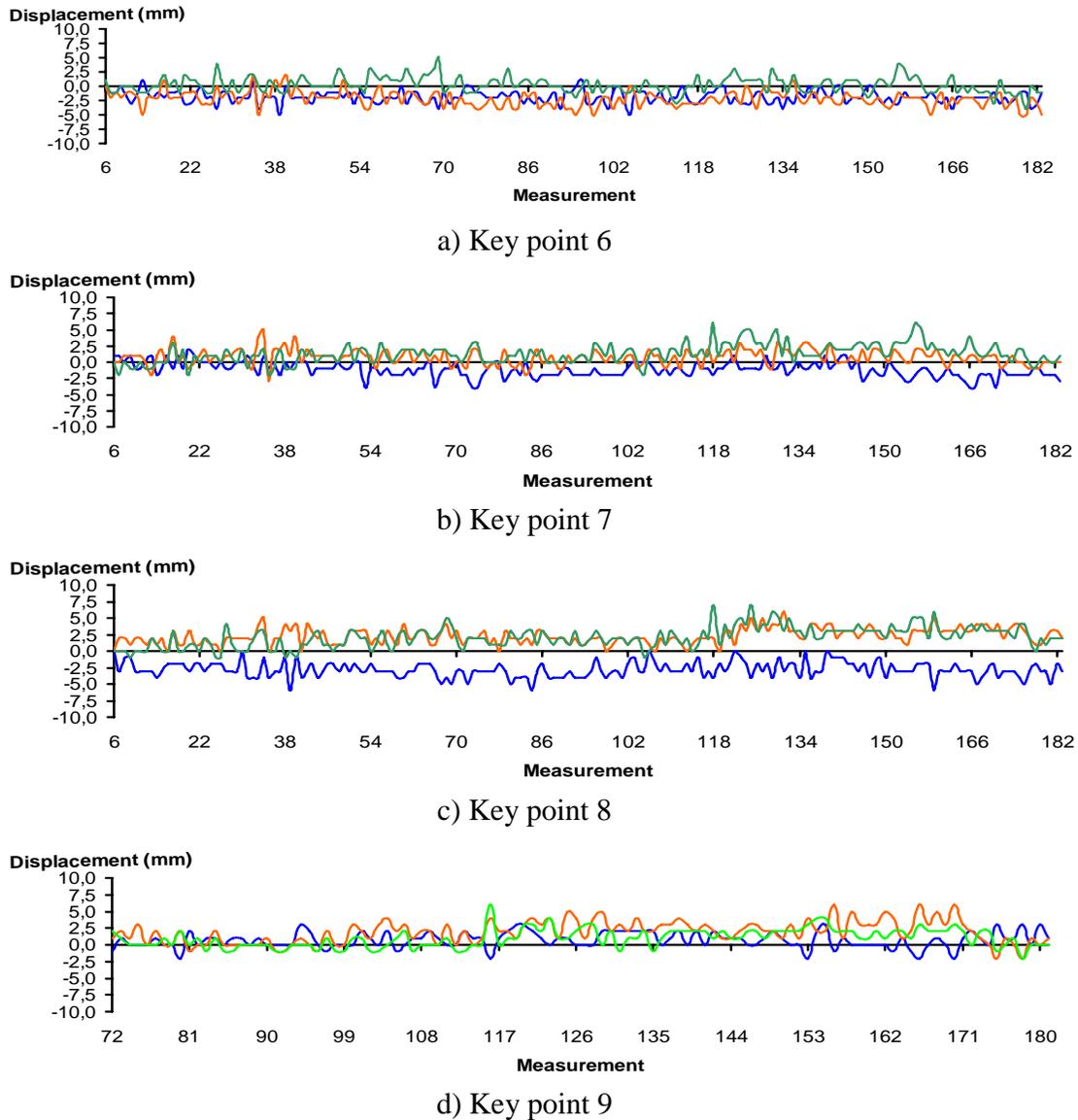
d) Key point 9

Where:

Perpendicular Evolution   Parallel Evolution   Vertical Evolution

Figure 11. Displacement evolution of the key points of the NE wall (6, 7, 8 and 9)

Figure 11(d) only includes the displacement evolution of the key-point 9 from the 72nd measurement because the reflector (that materialised this key-point) fell down in December of 2005. It was only possible to define one key-point (key-point 37) in the SW wall of the wall because the attached buildings did not allow sticking other reflectors on this wall. This key-point was located approximately at the half length of this wall, Figure 8-d), and consequently a bit far from the zone affected by the demolition/reconstruction of the SE wall. The displacement evolution of the key-point 37 is illustrated in Figure 12 where we can realise that there was no significant displacement of this point throughout the reconstruction process of the SE wall. This

evolution was not increasing type and the displacement component that had shown higher average value (equal to 1.8 mm) was the vertical one.
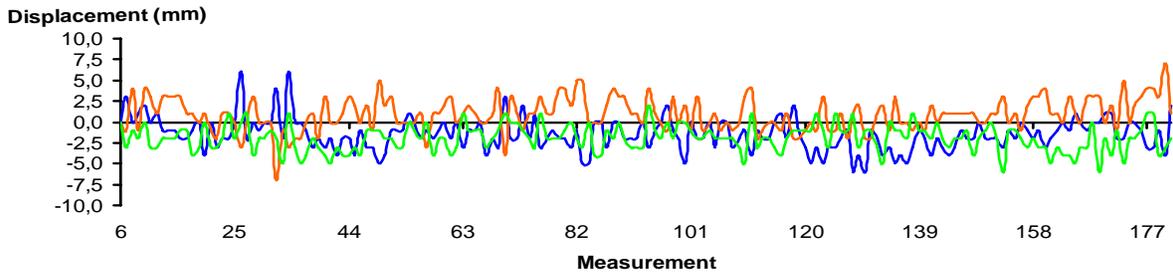
Displacement (mm)

Where:

——— Perpendicular Evolution ——— Parallel Evolution ——— Vertical Evolution

Figure 12. Displacement evolution of the key point 37 that was defined in the SW wall

The key-points 12 and 13, Figure 8(c), were defined to monitor the cunhal that connects the SW and SE walls. Their displacement evolution is shown in Figure 13. In this case, there was not a generalised increasing trend on the component displacement of these key-points either; the average value of these components was less than 2.0 mm. These facts indicate that this structural element was not affected by the reconstruction process of the SE wall.

Displacement (mm)
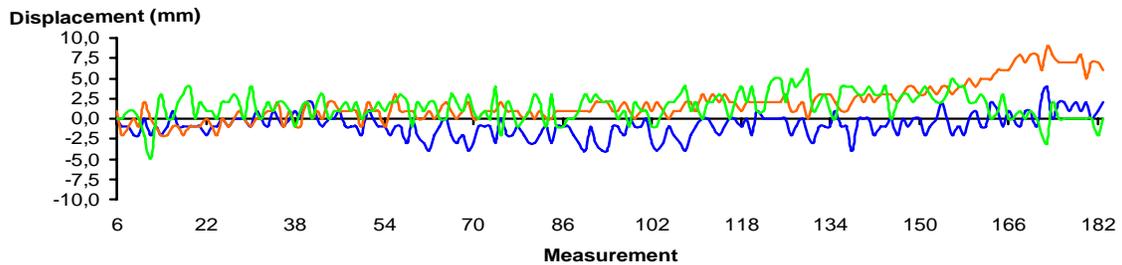
a) Key point 12
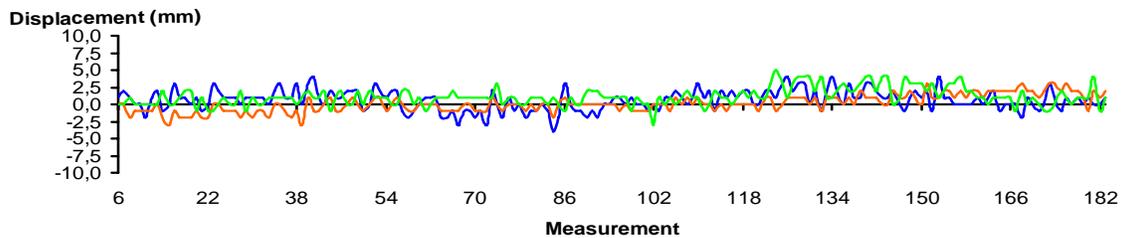
Displacement (mm)

b) Key point 13

Where:

——— Perpendicular Evolution ——— Parallel Evolution ——— Vertical Evolution

Figure 13. Displacement evolution of the key points 12 and 13 related to the cunhal that connects the SE and SW walls

However, it is noticed in Figure 13(a) that the parallel displacement component of the key-point 12 had suffered an increasing evolution between the measurements 141 and 167 (September and December 2006). This behaviour was related to the fact that this key-point had been defined in a piece of stone of the top course of stone (Figure 14) and this piece of stone had suffered movements resulting from the working process. This parallel displacement component evolution had stabilised from the measurement 167.

This is an example of an instability signal detected trough the proposed monitoring process in this work. In this particular case, it was possible to detect an instability signal (increasing evolution of a displacement component of a key point), to identify its cause (movement of a piece of stone resulted from the working process), to evaluate the scale of that instability signal (circumscribed to a piece of stone, the visual inspection did not find significant movements in the area surrounding that piece of stone, the key point 13 (near the key point 12) did not have an increasing displacement evolution during that period of time), to decide if the planned working process should continue (the working tasks related to the reconstruction process had run as planned because the instability signal did not give evidence indicating risk of collapse of the cunhal or other construction).

(a)   (b)
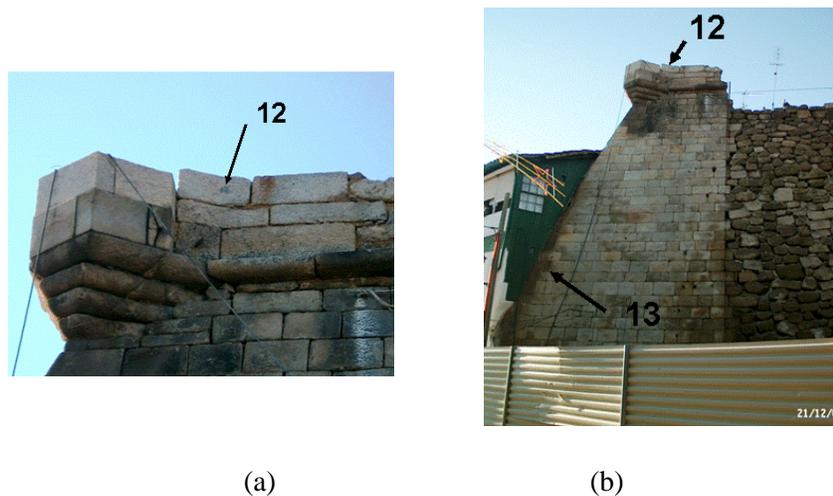
Figure 14. Key point 12: a) Location of the key point 12; b) Location of the key points and 13

A similar situation had happened for the cunhal that connects the SE and NE walls for which the related key points were 4 and 5, Figure 8(b). The displacement component evolution of these key points is described in Figure 15 where we can notice that until the 116th measurement (June 2006) there were not expressive value of displacement. However, from this measurement, the vertical component of displacement of both key points had increased which indicates that these key points went up. This evolution had inverted from the 158th measurement (November 2006) and the vertical component of displacement evolution converged to 0 mm, Figure 15.

Displacement (mm)

a) Key point 4

Displacement (mm)
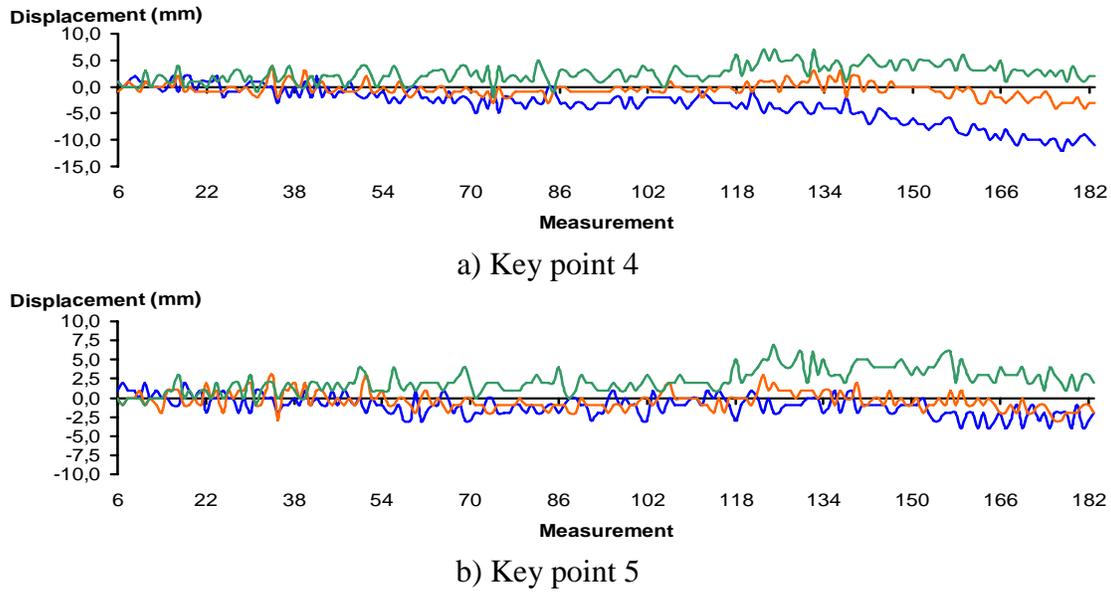
b) Key point 5

Where:

——— Perpendicular Evolution   ——— Parallel Evolution   ——— Vertical Evolution

Figure 15. Displacement evolution of the key points 4 and 5 related to the cunhal that connects the SE and NE walls

Through Figure 10, it is possible to realize that the 116th measurement was done when the demolition of the SE wall was taking place and, more precisely, this demolition task (Task 1, Figure 10) was taking place next to the cunhais. Simultaneously, the work task related to the excavation for the execution of the drainage system (Task 2, Figure 10) was also in progress by that time. Based upon these facts, the ascendant displacement of the key points 4 and 5 may be related to the above work tasks. As the reconstruction process was progressing (after the 116th measurement) the key points 4 and 5 had shown a displacement components evolution trend similar to the initial one (before the 116th measurement).

The key points 12 and 13 also had shown a similar displacement evolution trend, Figure 14, as the one described for the key points 4 and 5 being though less expressive. Figure 15 also shows that the key-point 4 of the NE wall had had an increasing evolution of the perpendicular displacement component that started from the 138th measurement. By the time in which the 138th measurement was done the reconstruction process of the SE wall was in progress. Since the values of this displacement component were negative, the piece of stone on which the reflector (that materialized the key point 4) was glued had moved in the direction of the embankment.

(a)   (b)

(c)   (d)
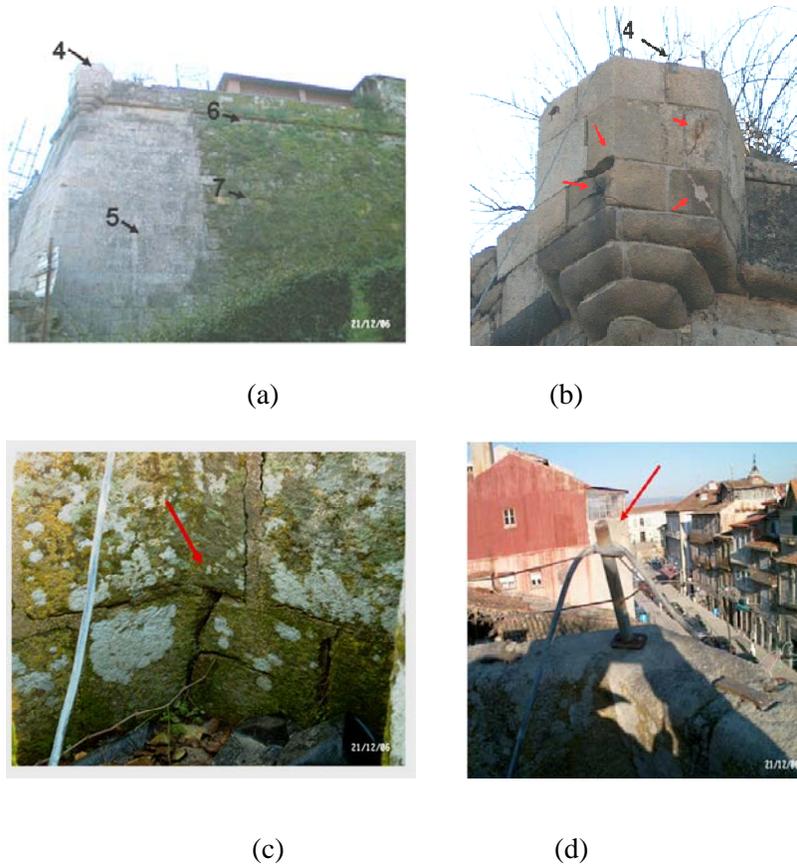
Figure 16. Key point 4: Some pathologies existing around the key point 4 and resulted from the working tasks related to the reconstruction process: a) Location of the key points 4, 5, 6 and 7; b) Existing pathologies surrounding the key point 4; c) Existing pathologies surrounding the key point 4; d) Existing steel bar next to the key point 4

As it was described for the key-point 12, the cause of the above displacement evolution of key point 4 was related to the working task that was in progress by the time in which the measurement 138th was taken. Figures 16(b) and 16(c) illustrate that some pieces of stone located near the key point 4 had cracks. Meanwhile, Figure 16(d) shows the existence of a steel bar fixed to the wall and also near the key point 4. This steel bar had been under an action, resulted from the working tasks of the reconstruction process, which resulted in a permanent deformed shape of this bar in the direction of the embankment.

This is another example case that validates the applicability of the adopted monitoring process described in this work. At the same time, graphs that describe the evolution of the angle α throughout the reconstruction process of the SE wall of the Baluarte do Cavaleiro were also defined in order to control the verticality of the constructions under the monitoring process. Figure 17 illustrates, as an example, the evolution of α for the alignment defined by the key-points 6 and 7 related to the NE wall. As it can be seen, the area of the wall surrounding this

alignment had kept the same slope (i.e. α remained almost constant) throughout the reconstruction process and this is another indication that the reconstruction process did not affect the stability of the NE wall.

Angle α (degrees)

Measurement
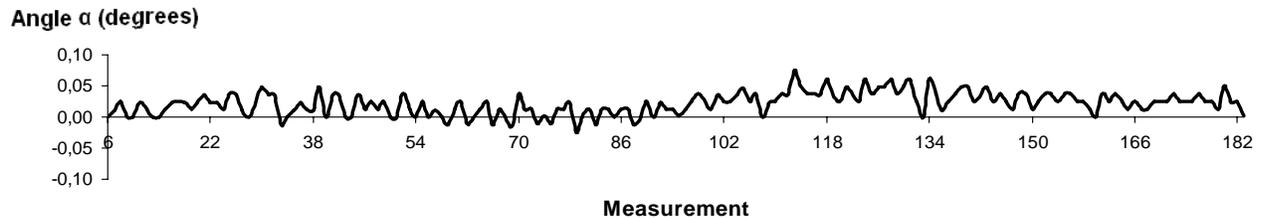
Figure 17. Evolution of α for the alignment defined by the key points 6 and 7 of the NE wall

Similar results were obtained for all the other defined alignments. In contrast to other type of structural materials, as steel, reinforced concrete, timber, a stone masonry wall is an heterogeneous structural system, with very complex local relative deformation mechanisms. The traditional construction procedures, associated to the properties of this natural material, to the irregular dimensions of the stone pieces, and to the irregular distribution of mortar in the joints justifies it. All these aspects contribute for the complex local behaviour and response inherent to this type of wall structural systems. This complex behaviour can lead, in certain situations, to significant differences in the displacement measured between adjacent stone blocks. However, in the selection of the monitoring key-points this fact was considered. In fact, the selected key-points are representative of the global behaviour of the wall. But, it was verified for all the key-points that the linkage of their supporting stones to the rest of the wall is good, diminishing the local movement influence in the measurements. Even if, in certain cases, the displacement of a single key-point may not model perfectly the global movement (point displacement) of the wall, the rotation evolution of the alignment defined by at least two key-points do it with an acceptable accuracy.

The opening crack evolution was studied during the reconstruction process. Those cracks did not have an expressive opening crack evolution. In general, the quantified opening crack evolution was the expected and resulted from the normal temperature changing through the year. Figure 18 illustrates the opening crack evolution graph of the crack D-1-36 (i.e. localized in the building D (Figures 8(a) and 8(d)), in the 1st floor and is the 36th pathology identified in that building) as an example. As it can be noticed from Figure 18, the crack opening evolution at this point is almost constant having the maximum value of 1.0 mm. This small oscillation of values was related to the normal temperature variation during the year even taking into account that all the cracks that were controlled were inside of a building.

Opening crack (mm)

Measurement
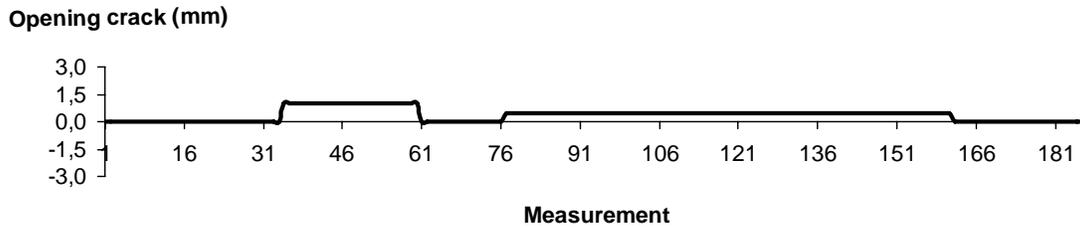
Figure 18. Opening crack evolution of the crack D-1-36

5. Conclusions and Final Comments

The fact that the Baluarte do Cavaleiro wall had been under a recent reconstruction process allowed the characterisation of its real cross section, the observation of its constitution in terms of a stone masonry wall and the identification of the soil that has been sustained by the wall. The natural ageing of the wall, the fact that it had been affected by the attached constructions and the lack of a regular maintenance contributed to the deterioration of the natural draining system of the wall. This seems to be one of the causes of the partial collapse that the Baluarte do Cavaleiro suffered in March of 2001.

During the reconstruction process of the SE wall of the Baluarte do Cavaleiro, the soil that was sustained by the wall proved to be extremely consolidated because it allowed for a vertical-like cut of a layer of 12.5 m high. This embankment kept stable during a period of time higher than one year without any stabilization structure. This fact sustains the above conclusion.

The measurement results indicate that the constructions observed practically does not present significant deformations, during the two years period of monitoring associated to the reconstruction process of the SE wall. The measured displacements were very small, with magnitude values approximately of the level of accuracy of the measurement process adopted to monitoring the movements of the key-points.

The current state of the sustained soil cohesive/consolidated does not generate significant impulses on the wall curtain. The stability of the lateral walls (NE and SW) was not highly affected when the transversal wall (SE) was almost totally demolished. All this structural elements including the *cunhais* have normally a monolithic behaviour. However, the contribution of the *cunhais* for the stability and structural behaviour of the whole masonry system is very important, particularly influencing the connection between elements and stabilization of the all system. From this analysis, it was concluded also that the hydrostatic impulses are one of the key factors in the behaviour of the wall structure.

The monitoring process adopted in this work proved to be adequate because it allowed to control a vast number of constructions in an almost continuous, simple and accurate way during the

period of time required for the reconstruction of the SE wall. Thus, the stability of all the constructions (directly and/or indirectly) related to the above reconstruction process was always controlled and all the planned works could proceed normally.

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