The seismic behaviour of the “Aqueduto da Amoreira” in Elvas using distinct element modelling

Alberto Drei
Polythecnic University of Milan, Structural Engineering Department, Milan, Italy

Carlos Sousa Oliveira
Instituto Superior Técnico, DECivil, Lisbon, Portugal

ABSTRACT: The aim of this research is to provide a model for the seismic behaviour of the XVI century stone masonry “Aqueduto da Amoreira” of Elvas, in Portugal.
A part of the structure with one, two or three pillars was modelled using a discrete element code. A quite large number of rigid elements were used to catch a plausible representation of the stone texture of the structure.

In the model the stone connections are responsible for dissipating the seismic energy, in a similar form as in a real stone masonry structure.
The seismic action considered was a synthetic accelerogram obtained following the Portuguese code indication for the zone of Elvas, and a recorded Italian accelerogram that has a PGA value about two times the previous artificial input. The latter one was chosen to test the collapse condition of the structure.

The obtained results indicate the importance of assessing the mechanical characteristics of the real material, which can be obtained only by mean of a specific experimental campaign.

1 INTRODUCTION

Ancient arch aqueducts are a quite common characteristic of the Portuguese landscape. Probably Portugal is the country of Europe with the largest number of these monumental structures, which can be found in all its regions, from north to south.

The principal monumental aqueducts classified and protected by Portuguese law are by now about twenty. Apart from a few remains of roman age, most of them were erected from XIV to XVIII century, indicating the care of the governments of those times for a civil public architecture.

In many cases these structures are used also nowadays as aqueducts, the most important example is that of “Aqueduto das Águas Livres” in Lisbon. Therefore their maintenance involves also an utility problem, in addition to the important aspect of restoration and protection of the historical architectural heritage.

For the old monuments in general, and certainly for this kind of typology, one of the most important problem is the prevention of the decreasing of the bearing capacity due to aging and misuse, nevertheless these aspects of the protection of the structure are not considered in this paper. This study is focused mainly on the global resistance of the structure when subjected to seismic actions.

The seismicity of continental Portugal in not quite high, if the exposition to the effects of strong earthquakes originating in the oceanic crust is not taken into account. Generally these are strong but far earthquakes, with a large presumptive return period (Lisbon 1755 Earthquake).

The earthquakes with epicenter in the country have generally a small-medium magnitude, but they can cause large damage. In order to estimate their effects, it is important to know what is the built heritage of the region, and to know a plausible seismic behaviour of the structures. For the historical architectonic heritage, this information is extremely important, as also minor damages should be avoided.


Figures 1 - 2 : Tallest part of “Aqueduto da Amoreira”, in Elvas

2 DESCRIPTION OF THE AQUEDUCT

The “Aqueduto da Amoreira” in Elvas is one of the most important historical aqueducts of Portugal, for its dimensions it is immediately after the “Aqueduto das Águas Livres” in Lisbon.

It runs on a system of 833 arcades, which in the tallest parts are made by a system of four arches at different levels between the pillars. The maximum height reached is 31 m. The global length of the Aqueduct is 7.054 m from the spring to the city wall of Elvas, then it continues for other 450 m to the “fonte da Misericórdia”. Less then one third of the structure in on arches, the aqueduct runs in part in an underground gallery (1367 m) and for the most part in a channel at the ground level (4049 m).

Quadrangular big pillars are the bearing structure of the aqueduct; they are reinforced at each side by large semi-circular buttresses, as it can be seen in the photographs alleged.

There is not a regular geometrical shape for the pillars. Their dimensions are different and the buttresses have different height and section; sometimes they are not present.

The works for the construction of the aqueduct lasted for a lot of time, and were performed in different periods. They began in 1498, on the project of Francisco de Arruda, and were continued, with some interruptions, by other architects (Alfonso Àlvares, Diogo Marques, Pero Vaz Pereira) until 1622, when the work was concluded.

Francisco de Arruda was the architect responsible also for the project and for the construction works of “Aqueduto da Prata” in Évora, whose architectural style is quite different. Probably it depends from the different “size” of the building: “Aqueduto da Amoreira” is higher (in some parts almost three times) with respect to “Aqueduto da Prata”.


Figures 3 - 4 : Parts of “Aqueduto da Amoreira” in the plain near Elvas

3 BUILDING TECHNOLOGY

The building technology used was the common technique applied at that time for large structural elements: an external wall of good material, or at least with a good texture of bricks and stones, and an inner part filled with weak and heterogeneous material. The global quality of the construction was not particularly good, considering that historical information reports significant damage suffered by the aqueduct due to large rains, during a period when the construction work was interrupted.

The external parts of the pillars are generally of stone masonry with mortar, but there are parts of full brick masonry, mainly the arches.

In the last decades of 1800 the monument underwent large works of restoration a reconstruction, particularly of the arches, involving almost all the building. The structure worked as an aqueduct only in some periods of its life. A photographic documentation taken in 1939 shows the collapse of many arches and the bad structural conditions of some pillars. Nevertheless the available historical information does’t give indications about seismic damage, probably the damages suffered by the structure were due to misuse and the lack of maintenance.

In the last 40 years the aqueduct was reinforced and restored to the present state, by means of a series of interventions: some arches were rebuilt, the cracks were closed, the channel on the top was practically rebuilt, etc.

4 NUMERICAL MODELLING

The modelled section of the aqueduct is taken in the tallest part. The considered pillars are 31 m high, and have a longitudinal width of 6 m. They are connected at different height by four arches of 6 m open span between them. The longitudinal seismic load was applied on a two pillars element, in some cases the analysis was performed also with a three-pillar model.

A single pillar with buttresses was considered for the seismic loading in transversal direction.

The assumed geometric features correspond to reality only in small sections of the aqueduct, but they seem enough representative for an estimation of the global seismic behaviour.

The analysis was performed using a synthetic accelerogram obtained according to the Portuguese Seismic Code, considering a seismic action type 1 for the ground characteristics (stiff soil) of the site of Elvas. The town is in Seismic Zone B, but the reduction seismic coefficient provided by the code α=0.7 was not used.

This seismic action corresponds to a 10 seconds shake from a shallow close earthquake, which have the most part of the energy at higher frequencies, in an interval in which are probably contained also the natural frequencies of aqueduct.

In order to verify also the collapse conditions, the model was subjected also to the accelerogram of a quite strong shallow Italian earthquake, Irpinia earthquake, recorded at the Sturno Station.

Table 1 Irpinia earthquake data

Date: 11 November 1980	Sturno record
Time: 18h-34m-52s	Sturno - epicentre distance ≈30 km
Epicenter co-ordinates: lat. 40.76 lon. 15.30	WE component PGA = 3.265 m/s^2
Depth: 11-19 km	NS component PGA = 2.076 m/s^2
ML 6.5	UP component PGA = 2.204 m/s^2
Epicenter Intensity MCS = 9/10	

The horizontal component EW used is the modelling, is reported in figure 5. It has a PGA about double than that of the synthetic accelerogram, moreover its duration is 30 seconds. In some modelling also the UP component record was applied.

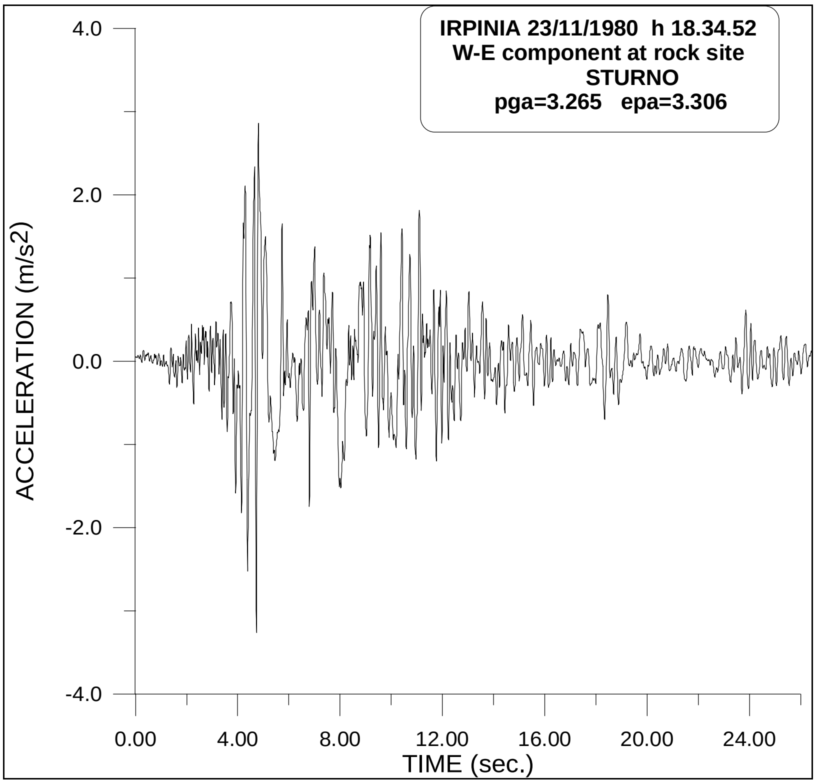


Figure 5: Irpinia Earthquake, WE component accelerogram recorded at Sturno

The numerical modelling of a block masonry structure should take into account this building technology, which influences its static and dynamic behaviour. A realistic modelling can be obtained by means of a distinct element code, in this case UDEC2D, which can simulate the dynamic behaviour of the blocks up to the complete collapse of the structure.

In the analysis performed, the seismic action was considered completely sustained by the joints among the stone blocks of the structure, assumed as rigid blocks. This model can be considered realistic, if the number of the blocks is similar to that of the stone elements in the structure. In this bidimensional modelling, this condition was fulfilled assuming block dimensions similar to those of the real stones (50-60 cm).

The mechanical characteristics set for the joints are plausible values, as there is no direct experimental information available. (Cohesion values from 0 to 0.5 MPa, friction angles 25-30°, and small or null joint resistance in traction). Therefore the study performed represents a general indication of the global seismic behaviour of the aqueduct, considering also that the obtained results suggest a strong influence of the regularity of the texture of the blocks and of the global geometric shape on the final collapse of the structure.

A critical point in the analysis is the value of the damping to assume in the block model.

Previous studies on this topic performed by different authors, suggest the use of quite low values of a mass proportional Raleigh damping, to avoid excessive damping affecting the structure behaviour at the collapse, and for problems related to a suitable time step value in order to have acceptable computation times.

The mechanical behaviour of the three constituent materials, whose mass was set to 1900, 2000, 2300 kg/m^3 respectively for the inner weak material, for the arch masonry and for the external walls of the pillars) was simulated assigning different values to the joint properties.

A preliminary analysis yielded the first natural frequencies of the modelled parts, about 2 Hz in transverse direction (1 pillar model), and about 2.6 Hz in longitudinal direction (2 pillars model).

5 RESULTS - LONGITUDINAL LOADING

Figures 6 and 7 refer to the synthetic accelerogram corresponding to a seismic load type 1 of the Portuguese code, applied in longitudinal direction. In Fig. 7 joint mechanical properties are weaker. The light lines in figures indicate the fracture of the joints, as expected in the weak inner material, but there is not the collapse of the structure.

A damage condition with the collapse of the arches can be obtained applying the EW component of the Sturno record. The addition of the UP component gave a further significant damage and failure in the pillars, with almost all the joints fractured. Similar results are obtained also with lower values of the joint properties (e. g. cohesion 20% less, 25° instead of 30° friction angle) and considering non resisting in traction joints.

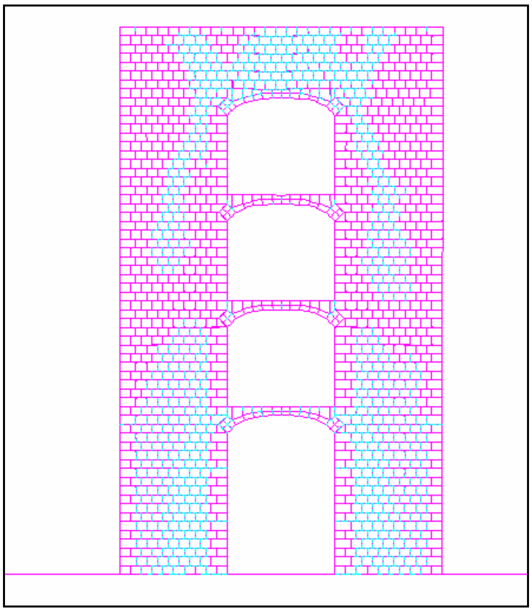
Figure 8 represents the failure pattern of a weak model at 15 seconds, but at the end of the shake the configuration remains almost the same.

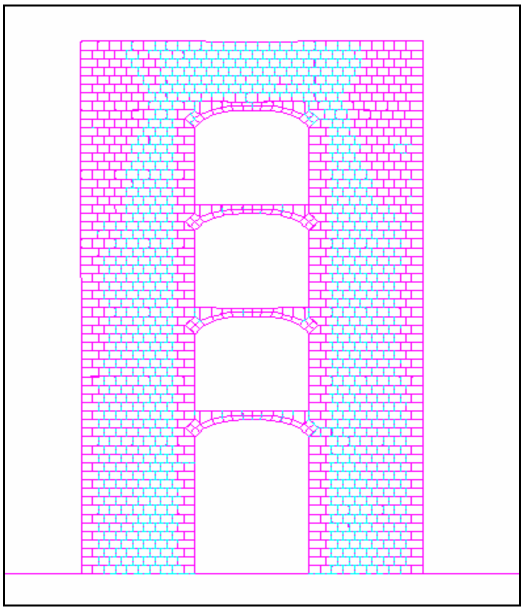
The simple analysis performed gives a significant global resistance of the structure, which probably depends on the regularity of the geometry and of the block texture. The real behaviour surely is affected by the irregular shape of the blocks and by the local presence of fractures and of weak elements. In case of seismic loading these items can result in a triggering system of the collapse.

This situation was modelled adding only a few inclined cracks in the pillars, involving the width of one or two blocks, at the base of the arches.

The results of the analysis remained quite similar to those obtained without the small initial damage simulation. Only the strong dynamic loading induces a certain increase of the damage and of the falling down in the pillars (fig. 9 and fig. 10). But after the falling down of the arches, the "skeleton" of the pillars, probably due to the large longitudinal dimensions, even damaged and with opened cracks, remains steady.

In order to avoid the effect of the fallen blocks of the arches, which could restrain the structure at the base, during the computation part of these blocks were eliminated.





Figures 6 - 7 : Type 1 transverse seismic loading

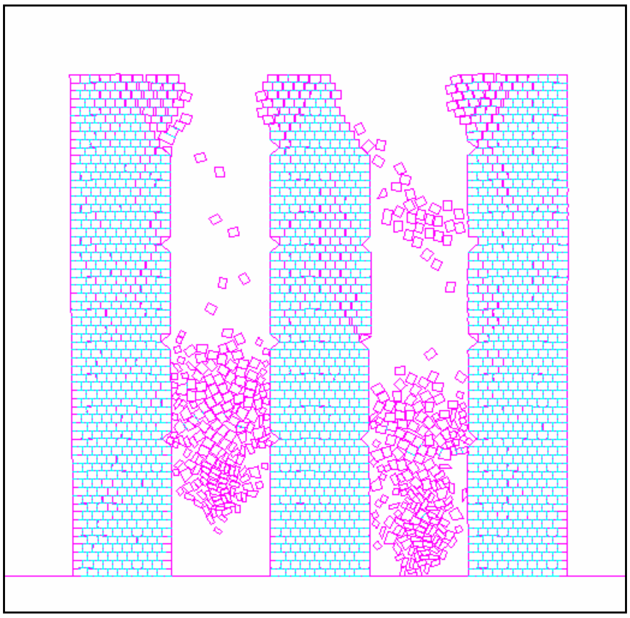
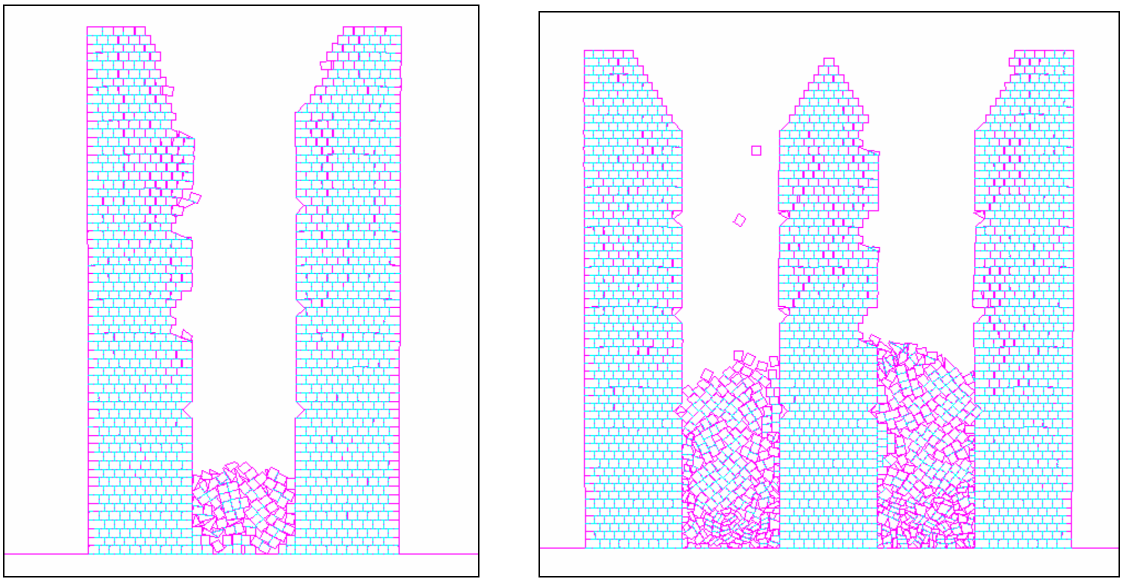


Figure 8: Transversal and vertical seismic load; Sturno record

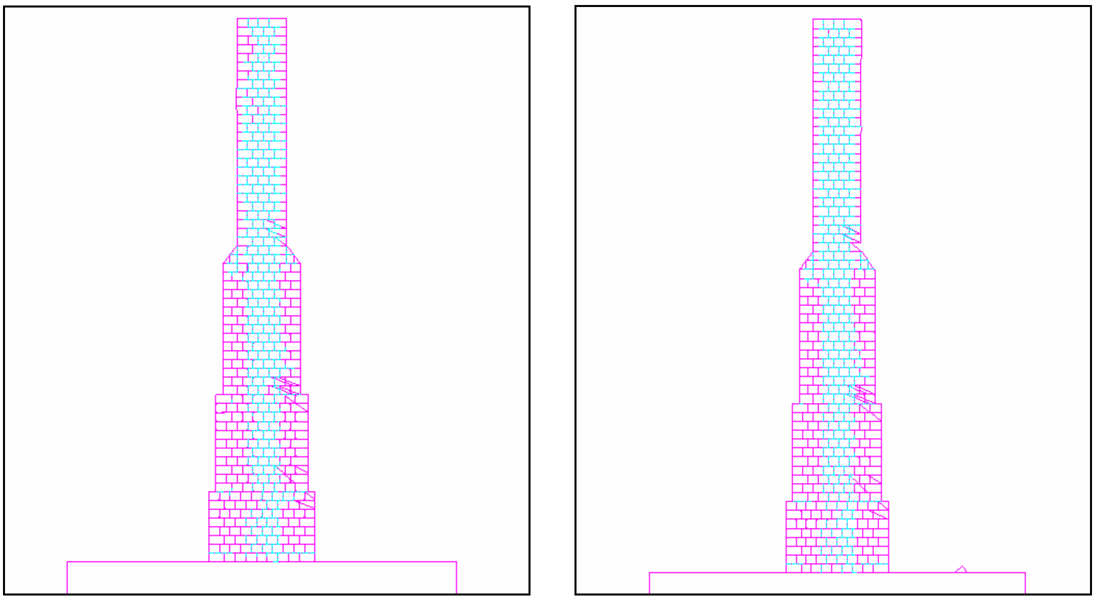


Figures 9 - 10: Aqueduct pillars with small initial damages; Sturno Record

6 RESULTS - TRANSVERSE LOADING

The earthquake effects in transversal direction were modelled considering only one pillar, with the two external walls in strong stone masonry, and a system of buttresses decreasing their width up to about half height (17 m) of the pillar.

The top slender part of the pillar is 2.8 m width; the dimension at the base is 6 m, the same in longitudinal direction.



Figures 11 - 12: Transverse loading, seismic action Type 1

The results obtained repeat those of the longitudinal dynamic loading. The shake according to the Portuguese code does not give the collapse of the structure. Even applying both components WE and UP of the Sturno record, which have quite large PGA values, there is the fracture of the most part of the joints, but not the falling down of the model.

Then a limited local weakness, only in one side of the pillar, was simulated by means of a few inclined fractures in correspondence of the changing in section of the column, as in the case of transversal loading. However seismic action type 1 remains inadequate to get the collapse (figure 11) even with lower joint resistance (figure 12).

On the other hand, the assumed small triggering mechanism is quite effective with the strong earthquake record, inducing a general falling down of the structure. Figure 13 reports the stage of the failure process at 15 seconds, after the PGA value, at half of the shake time.

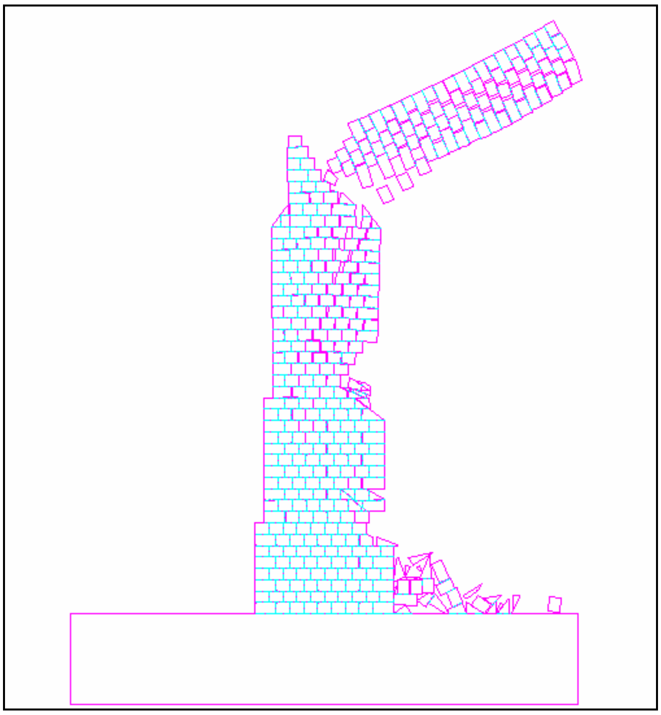


Figure 13 : Transverse failure process at 15 seconds; Sturno record

7 CONCLUSIONS

The modelling performed is only representative of the seismic behaviour of the aqueduct. The geometry is that of a small part only of the structure, and the mechanical properties assumed are plausible values.

The use of block elements similar to the real stone blocks, at least in part of the external shell of the structure, seems a realistic modelling of the structure, but some caution is necessary in using it for the evaluation of the collapse dynamic load, as an example for the assessment of a PGA value of collapse of the structure.

The resistance of the model appears due mainly to the regular texture of the blocks, and to the uniformity of the structure. The collapse obtained depends strongly on the presence of small localized weak elements, which behave as a triggering device of the failure.

The modelling performed gives in any case a confirmation of the importance in seismic reinforcing of masonry structures, of the elimination of local defects and damages, even the small ones.

The settlement of uniformity and of a regular texture, can result more effective than an improving of the mechanical characteristics of the material without removing local possible damage triggering elements.

ACKNOWLEDGEMENTS

The authors acknowledge the Direcção-Geral dos Edifícios e Monumentos Nacionais, for the information and the data about "Aqueduto da Amoreira".

The authors acknowledge also the Italian-Portuguese research agreement CNR/ICCTI year 2000, for the partial financing of this research.

REFERENCES

Itasca 2000. UDEC Universal Distinct Element Code, version 3.1 Minneapolis: Itasca Consulting Group Inc.

RSAEEP: Regulamento de Segurança e Acções em Estruturas de Edifícios e Pontes, *Dec. Lei nº 235/83 de 31 de Maio de 1983,* Lisbon

Sincraian, G. E. 2001. Seismic behaviour of block masonry structures - A discrete element method Approach. *Civil Engineering PhD Thesis*, Lisbon: Instituto Superior Técnico.