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A Case History: Seismic Analysis of the Retaining Wall of the "Sacro Convento" in Assisi (Italy)

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ABSTRACT

The aim of the present work is to analyse the seismic behaviour of the retaining wall of the square in front of the Basilica di San Francesco at Assisi that during a long seismic crisis occurred in September 1997 suffered some damage. Static, pseudo-static and dynamic analyses have been carried out on four significant sections of the wall. The data for the analysis derive from the geometric survey of the structures, the survey of the state of the damage, the measurement of the rotation movements of the wall, the collection of stratigraphic and geotechnical data, as well as the accelerometric recordings of the seismic events using instruments that had been in operation on the structures of the «Sacro Convento» since 1995.
Built during the first half of the 16th century, the wall is made of stone masonry, is about 93 m long, 4 m thick, and supports an embankment, the height of which varies between 9.0 m and 12.5 m. The wall is approximately 18 m high, and is under the ground also in the front part; it has a rectangular transversal section in the lower part and a T-shaped section in the upper part. It is built on calcareous rock, and supports a covered portico that is about 3.5 m high.
In practice, the recorded accelerometric history coincides with the one at the base of the wall. Numerous seismic events were recorded from 4/9/1997 to 6/10/1997, three of which had a PGA exceeding 0.15g. The most evident movement suffered by the wall was a rigid rotation that caused a movement at the top of the wall greater than 20 cm.

THE SO-CALLED «SOSTRUZIONE» WALL OF THE «SACRO CONVENTO» OF ASSISI

Outline of history and geometry

The monumental complex of the Basilica of San Francesco at Assisi rises at the top of a hill known as Paradise Hill, the morphology of which has been profoundly modified compared to its natural state (Photo 1 and Figure 1).
The Basilica, the construction of which began in 1228, two years after the death of San Francesco, consists of two superimposed churches. The lower church, containing the crypt that houses the mortal remains of San Francesco, materially and ideally supports the upper church. During the second big seismic shock, that took place at 11h.40' on 26 September 1997, the collapse of the vault of the upper church frescoed by Giotto occurred, in the course of a direct television broadcast. There were very serious consequences in terms of both the loss of human life (two victims) and the damage to humanity's cultural artistic heritage.
The conformation and slope of the ground prevented construction of two superimposed façades. In fact, entrance to the lower church is through a lateral portal built in 1271. The natural morphology of Paradise Hill had a convex form with a considerable slope in a N-S direction and a sinuous form in an E-W direction. The first arrangement of the square in front of the upper church dates to 1275. In that period, churchgoers could enter only the upper church. During the 15th and 16th centuries, several works on the space in front of the lower church were carried out. The present-day morphology of Paradise Hill, in a NS direction, is terraced, with two gravity-supported walls founded in the natural rocky soil. At the beginning of the 15th century, the lower retaining wall, that supports a grassy embankment with garden land, was already present. Instead, the upper wall, known as «sostruzione» wall, was begun in 1509, with the aim of creating a large paved square at the level of the lower church. The buried remains of a retaining wall were recently discovered approximately in correspondence with the middle line of the square, in a longitudinal direction to it. It was much smaller than the present «sostruzione» wall, and probably delimited a smaller square that was at a lower altitude than the present one. Lastly, in 1744, the double staircase that connects the squares in front of both churches was realised.

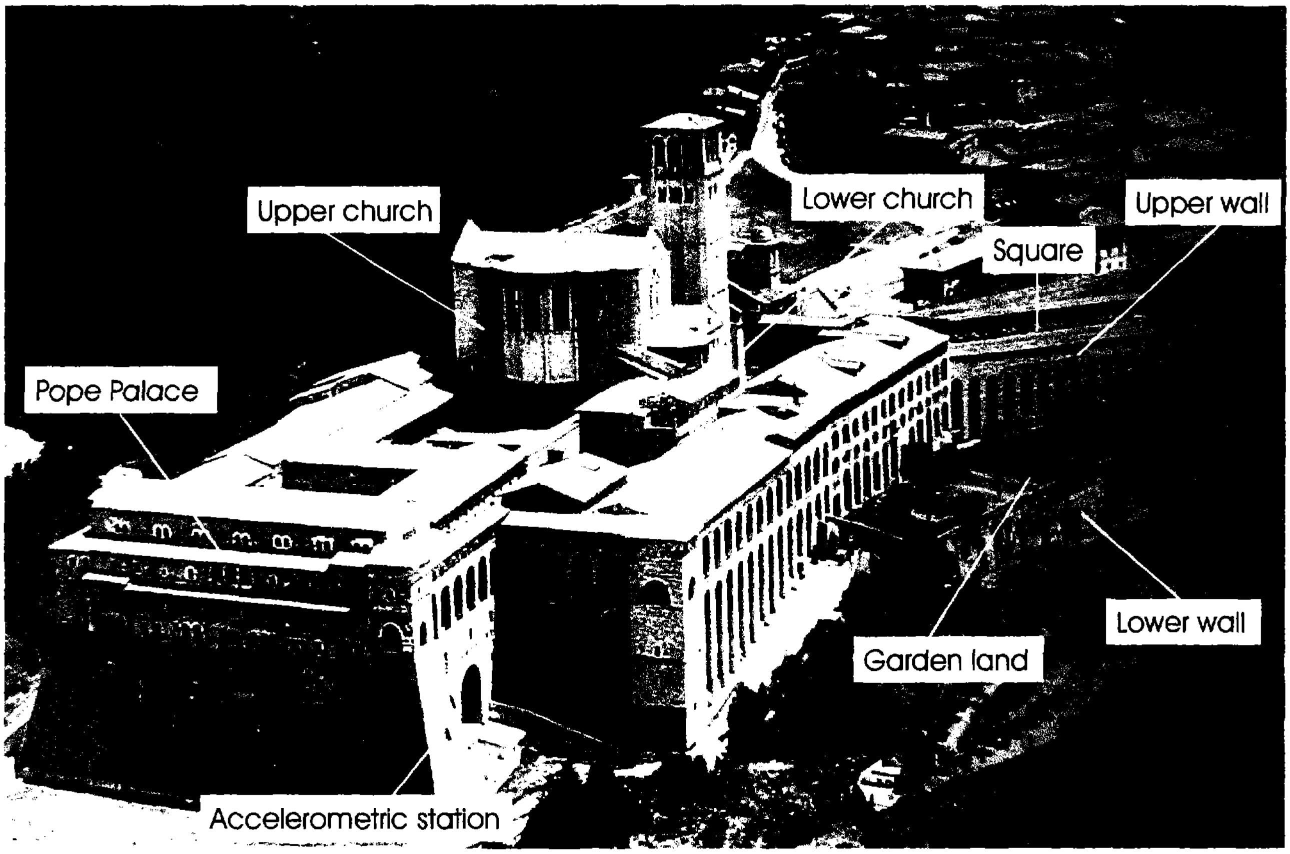


Photo 1. General view of the monumental complex of the «Sacro Convento» in Assisi.

The seismic history of the «sostruzione» wall, which is the subject of the present note, thus began in 1509. From the catalogue of strong Italian earthquakes from 461 B.C. to 1990, edited by the Italian 'Istituto Nazionale di Geofisica' (http://www.ingrm.it), it can be inferred that there have been three earthquakes (1751, 1832 and 1984) felt with greatest local intensity (from 7 to 8) in Assisi during the considered period. In the historical documents and reports, in which the damage caused by earthquakes is described, among which that of the «Sacro Convento», there is no mention of movements in the «sostruzione» wall.

The aforesaid wall is a gravity-supported work made of stone masonry. It has a thickness of 4 m, is rectilinear, about 93 m long, and a total variable height that is not completely known, but probably included between 10 m and 20 m. The height of the part above ground is between 9 m and 12.5 m.

The wall, made of stone masonry, has constant thickness from the foundation level to ground level of the garden land , while in the upper part it has a ribbed, box-shaped structure, with pylons and arches that repeat themselves every about 4.8 m (Figure 1). On the top of the wall, at the height of the square of the lower church, there is a loggia decorated with cross vaults, closed from the valley side by a 0.7-m-thick wall and delimited by a colonnade on the side overlooking the square. The loggia continues also beyond the «sostruzione» wall, delimiting the square of the lower church on three sides.

Stratigraphic and geotechnical conditions

The stratigraphic and geotechnical conditions below the square were investigated by means of 12 boreholes with continuous drilling, extended to depths varying between 5 m and 22 m from the road level and, in any case, as far as they penetrated into the rocky substrate for at least two metres. Two borings were performed inclined and adjacent to the wall, for the purpose of verifying its thickness and foundation level.

The soil underlying the «sostruzione» wall is a marly calcareous rock, densely stratified and fractured, which belongs to the geological formation of the «Scaglia Rossa» outcropping in the zone. The soil on the sides of the wall, both upstream and downstream, even if with different thickness, is a cohesionless and very heterogeneous man made fill. Stone elements and fragments of bricks of varying dimensions are immersed in a sandy and loose silty matrix. The thickness of the filling soil is very variable, especially in a direction transversal to the square and to the wall. This is because, as we have said, the natural morphology is very uneven and steep. In particular, in correspondence with the middle line of the square, the thickness is of about 4-6 metres, while at times it reaches a thickness of 20 metres in correspondence with the «sostruzione» wall. In view of the cohesionless nature of the filling soil, it was not possible to take undisturbed samples: the estimate of the shear strength was, in fact, based on the results of 10 SPT. The measured N_{SPT} values were high but dispersed, and in the

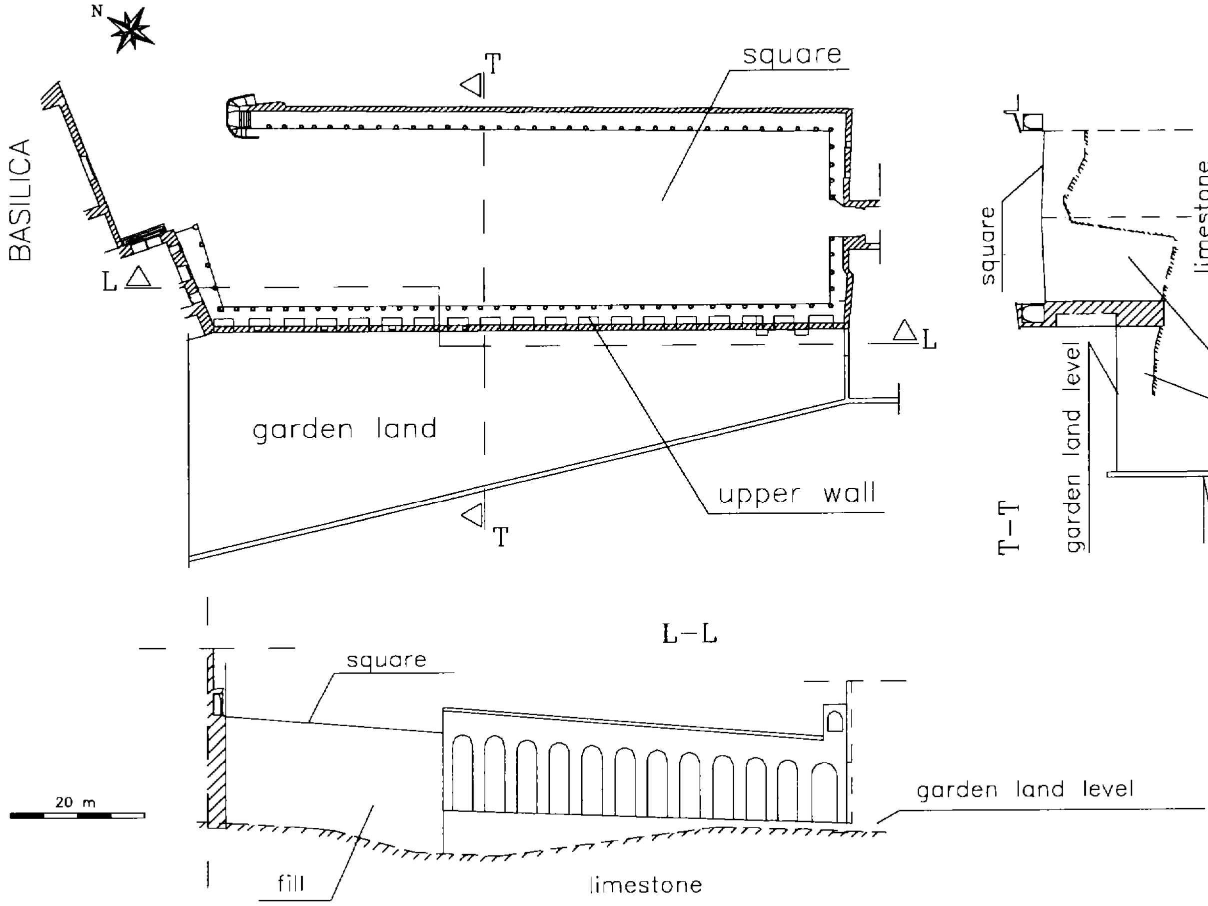


Figure 1. Plan at the square level; transversal and longitudinal sections.

analysis the design value $\phi' = 33°$ was assumed for the angle of shear resistance. Both upstream and downstream from the wall, ground water table is not present and the soil can be considered dry.

Estimate of the permanent movements of the wall during the earthquake

As a result of the September-October 1997 earthquake, four large cracks (Figure 2) were manifested in the pavement of the large square behind the «sostruzione» wall. The cracks, with a length of between 3 and 26 metres, formed a system that planimetrically delimited a flat arch in the end zone of the wall, where its height is greatest. The arch has a rise of 11 metres and a chord of about 60 metres.

Verticality measurements (out of plumb) of the downstream face of the wall pointed out the rotation of the wall towards the outside, with maximum values in the section corresponding to the top of the arch detected by the system of cracks in the pavement of the square. In short, a three-dimensional active earth pressure wedge, delimited by an arch in the horizontal level of the square, was well defined. The extremities of the arch corresponded on the one side with the terminal corner - and therefore constrained - zone of the wall and, on the other, with a zone in which the height of the wall is considerably less. In correspondence with the four sections A, B, C, and D, indicated in the plan of Figure 2, the out of plumb from the level of the square to the level of the garden land, or for the height of wall above ground, was 14, 22, 20, and 3 cm, respectively. By supposing a rigid rotation movement of the wall around the outside edge of its foundation, the corresponding rotation angles are 0.65°, 1.06°, 1.03°, and 0.19°. As the value of the out of plumb of the wall before the 1997 earthquake is not known, it was not possible to learn the rota-

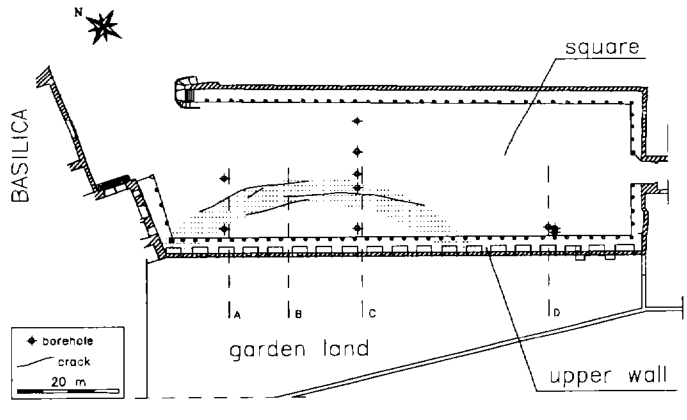


Figure 2. Plan at the square level with the position of the main cracks, the stratigraphic boreholes and the four analysed sections.

tion that occurred during that event. The estimated rotation values are its upper limit, since they also include the movement cumulated during the life of the structure, i.e. since 1509.

THE ACCELEROMETRIC STATION AT THE «SACRO CONVENTO» AND THE RECORDED MOTIONS OF SEPTEMBER-OCTOBER 1997

In 1995 the Italian National Seismic Service had a system of static and dynamic monitoring installed for a part of the «Sacro Convento» of Assisi, to study the behaviour of the structure in consequence of earthquakes of small and medium intensity. The control instrumentation was concentrated in the zone of the Papal Palace, where the signs of static instability were more evident. The monitoring system included a series of digital accelerometric stations, that were naturally activated during the seismic sequence of September-October 1997. Earthquake motions recorded at the station called Assisi Stallone, were selected for the dynamic analysis of the «sostruzione» wall. The reasons for this choice were the following: 1. the foundations of the Sacro Convento and of the «sostruzione» wall are on the same rocky formation; 2. the accelerometric station is located at the same level as the foundation of the wall, and is placed in the external boundary masonry of the Papal Palace, that is made of stone and is very thick.

Seven seismic events were recorded during the period from 4/9/1997 to 6/10/1997 by the Assisi Stallone accelerometric station. The instrumental data were corrected in order to eliminate the instrumental errors and the errors at high and low frequency, and to correct the base line. Three of the seismic events recorded had a peak ground acceleration greater than PGA = 0.15g in at least one of the horizontal components. The main characteristics of these events are indicated in Table 1.

Table 1. Main parameters of the three earthquake motions selected for the analysis

Time [dd.mm.yy] [hh.mm.ss]	Comp.	PGA [g]	I_A [cm/s]	T_o [s]	D_B [s]	D_T [s]
26.09.97	NS	0.11	5.75	0.248	1.40	4.28
02.33.44	WE	0.16	10.83	0.253	2.31	3.64
26.09.97	NS	0.18	23.17	0.339	4.44	4.21
09.40.58	WE	0.16	27.91	0.181.	4.47	4.34
06.10.97	NS	0.11	6.60	0.253	2.29	3.88
23.25.20	WE	0.20	14.57	0.248	2.66	3.41

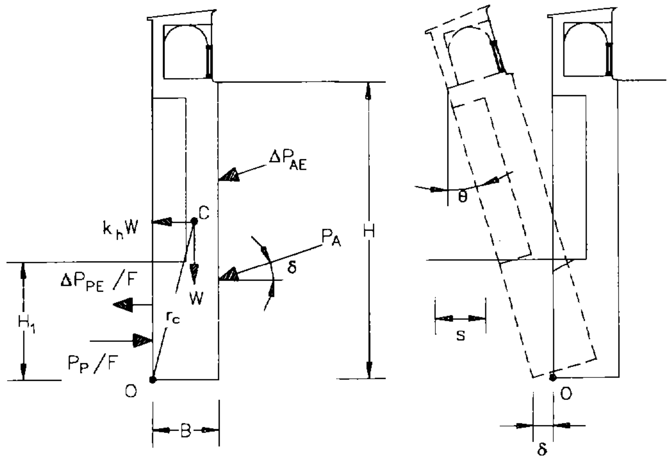
I_A: Arias intensity; T_o: fundamental period; D_B: bracketed duration; D_T: Trifunac duration

STATIC, PSEUDO-STATIC AND DYNAMIC ANALYSES OF THE «SOSTRUZIONE» WALL

The static, pseudo-static and dynamic analyses of the «sostruzione» wall were performed with reference to the four sections: A, B, C, D, indicated in the plan of Figure 2 and schematically represented in Figure 3.

Section A is that of the maximum net height, $H-H_1$, but is also the one that most greatly feels the three-dimensional effects because it is the one closest to the constrained extremity of the wall. The greatest overall height, H, corresponds to section B. Section C is in correspondence with the apex of the arch delineated by the system of lesions in the pavement of the square. Section D is of a lesser free height, but also of a lesser embedment depth, and it is outside the zone in which evident lesions appeared.

For the four sections, the weight W, the position of the centre of mass C, and the barycentric moments of inertia J_x, J_y, and J_C were determined by taking into account the three-dimensional geometry of the wall (with arches and ribbings on the external face and the loggia at the top) and the different materials of which it consists (stone masonry, brick masonry, marble).



Section	A	B	C	D
B (m)	4	4	4	4
H (m)	16.9	18	17.2	11.2
H_1 (m)	4.6	6.1	6.1	2.1

Figure 3. Scheme, symbols and dimensions of the four analysed sections.

The value f = tan (2/3 ϕ') = 0.404 was used as the interface friction coefficient at the base of the wall.

To calculate the earth pressures, a soil-wall friction angle $\phi_U = 2/3\ \phi' = 22°$ upstream and $\phi_D = 0°$ downstream was assumed. The resistant downstream earth pressures were assumed to be equal to half of the limit passive earth pressures. In other words, the passive earth pressure coefficient was divided by an F = 2 factor.

The static component of the total active earth pressures was applied at an elevation H/3, and the total seismic earth pressure increment at 2/3 H.

The pseudo-static seismic analysis was performed with the Mononobe Okabe method, assuming $k_h = 0.07$ and $k_v = 0$, in agreement with the Italian seismic code for 2nd-category seismic zones.

The threshold seismic coefficient in rotation $k_{c,rot}$ was determined by imposing the limit equilibrium condition with respect to the outer edge O of the wall.
The threshold seismic coefficient in translation $k_{c,trans}$ was determined by imposing the limit equilibrium condition to the horizontal displacement of the wall.
The permanent rotation and translation movements of the wall were obtained through the numerical integration of the corresponding motion equations with reference to Newmark's rigid block model.
With reference to the symbols in Figure 3, the motion equations to be integrated numerically are equation (1) for rotation movement and equation (2) for translation movement.
By considering the orientation of the wall (NW-SE) both horizontal components of the accelerometric records of the three main events were utilised. The movements of the wall calculated with the NS and WE components did not differ greatly, and the mean was assumed as a representative value.
The results of the calculation are summarised in Table 2. In Figure 4, the time histories of the WE component of the three recorded motions used in the analyses and the cumulated rotations for the four sections of the wall are represented. The measured and calculated values of the permanent out of plumb movements of the wall are represented in Figure 5. In the abscissa is indicated the distance of the section from the constrained extremity of the wall.

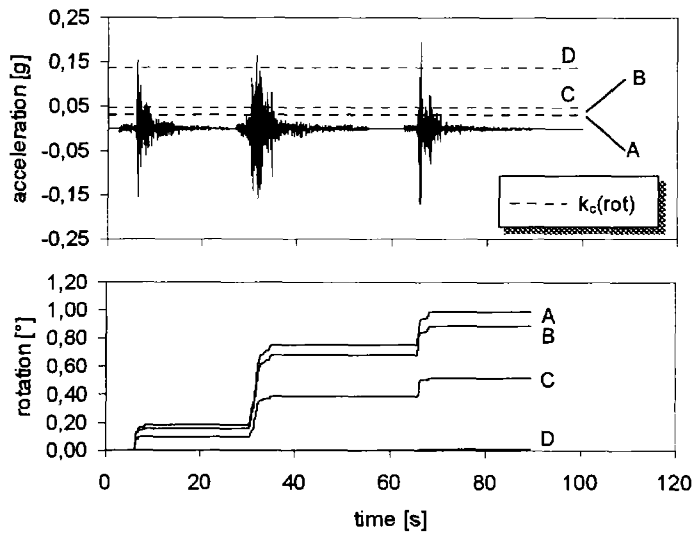


Figure 4. WE component of the three main shocks of 1997 seismic sequence recorded at the Assisi-Stallone accelerometric station and cumulated rotation of the upper wall in the four analysed sections.

COMMENT ON THE RESULTS AND A COMPARISON BETWEEN CALCULATED AND MEASURED MOVEMENTS

The analyses were performed with reference to plane sections, and disregarded the three-dimensional effects. This definitely led to an overestimate of the actions and movements for section A, close to the constrained extremity of the wall, and to an underestimate of the actions and movements of section D, of the lowest height (Figure 5). In addition, reasonable but simplified design hypotheses were made with regard to the geometry of the wall, (which in its underground part is only partially known), the geotechnical properties of the filling soil (which was assumed to be homogeneous), the partial mobilisation of the passive earth pressure, the elevation of the static and dynamic earth pressures, the kinematic mechanisms of the wall. Lastly, the seismic input was assumed to be uniform along the height of the wall and coincident with the accelerometric records of the Assisi Stallone station, disregarding amplification phenomena. Despite all this, the results were good. In fact:

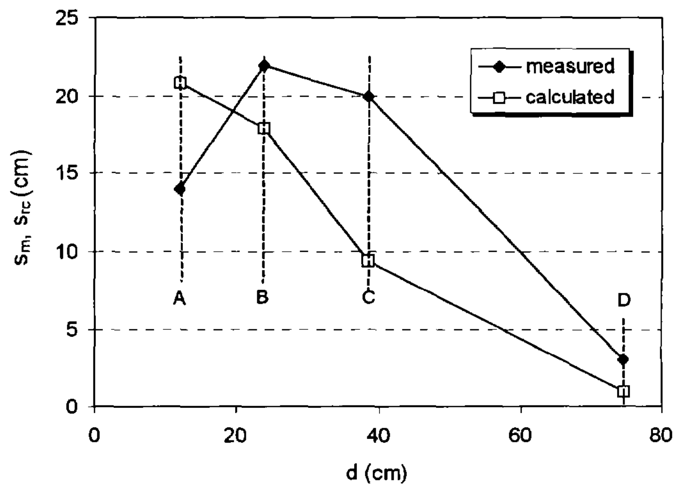


Figure 5. Measured and calculated movements of the wall in the four analysed sections.

- the static stability analysis both in rotation and translation is satisfied for all sections. The pseudo-static stability analysis in rotation, using Mononobe Okabe method with the seismic coefficient provided by Italian seismic code, was not satisfied for sections A, B and C and the safety factors range between 0.8 and 0.9, while it was satisfied for section D. The pseudo-static stability analysis in translation was satisfied for all sections. The threshold seismic coefficients for rotation of the wall around the outside edge of the foundation were clearly inferior to the critical seismic coefficients for horizontal translation for sections A, B and C, while for section D the threshold coefficient for rotation was slightly superior to the threshold translation coefficient. The PGA of the seismic sequence considered were larger than the values of the threshold rotation and translation coefficients for all four sections. Therefore, both types of movement were calculated. However, the translation displacement was small, and almost zero for sections B and C. This allows us to compare calculated and measured displacements, since the evaluation of the real permanent movements of the wall was based on the out of plumb measurements and, therefore, possible displacements due to rigid translation could not be surveyed.

$$\left(J_C + \frac{W}{g}\cdot r_C^2\right)\cdot\ddot{\theta} = \left(P_A + 2\cdot\Delta P_{AE}\right)\cdot\cos\delta\cdot\frac{H}{3} + W\cdot\left(k_h\cdot y_C - x_C\right) - \left(P_A + 2\cdot\Delta P_{AE}\right)\cdot\operatorname{sen}\delta\cdot B - \left(\frac{P_P - 2\cdot\Delta P_{PE}}{F}\right)\cdot\frac{H_1}{3} \tag{1}$$

$$\left(\frac{W}{g}\right)\cdot\ddot{x} = \left(P_A + \Delta P_{AE}\right)\cdot\cos\delta + W\cdot k_h - \left(\frac{P_P - \Delta P_{PE}}{F}\right) - f\cdot\left[\left(P_A + \Delta P_{AE}\right)\cdot\operatorname{sen}\delta + W\right] \tag{2}$$

Table 2. Results of the stability analyses for the «sostruzione» wall

Section	A	B	C	D
Geometric and inertial characteristics				
L (m)	4.74	4.775	4.75	4.9
B (m)	4	4	4	4
H (m)	16.9	18	17.2	11.2
H_l (m)	4.6	6.1	6.1	2.1
W (kN/m)	1268	1376	1326	860
x_C (m)	2.18	2.16	2.15	2.16
y_C (m)	8.76	9.16	8.79	6.27
J_x (kN s^2)	4230	5023	4469	1473
J_y (kN s^2)	175	191	184	122
J_C (kN s^2)	4405	5214	4653	1595
r_C (m)	9.03	9.41	9.05	6.64
Static analysis				
P_A (kN/m)	680	771	704	299
P_P/F (kN/m)	323	568	568	67
FS_{rot}	1.207	1.232	1.353	2.278
FS_{trans}	2.003	4.574	7.570	1.874
Pseudo-static analysis according to Italian seismic code ($k_h = 0.07$, $k_v = 0$)				
ΔP_{AE} (kN/m)	112	127	116	49
$\Delta P_{PE}/F$ (kN/m)	12.5	22	22	2.6
FS_{rot}	0.805	0.821	0.891	1.384
FS_{trans}	1.235	1.807	2.150	1.259
Critical seismic coefficients				
k_c(rot)	0.029	0.033	0.048	0.138
k_c(trans)	0.112	0.161	0.179	0.124
Dynamic analysis - rotation movement around 0				
θ_c (°)	0.973	0.866	0.483	0.060
s_{rc} (cm)	20.9	18.0	9.4	1.0
Dynamic analysis – translation movement				
s_{tc}(cm)	0.75	0.05	0.00	0.34
Measured movements of the wall				
θ_m (°)	0.652	1.059	1.032	0.189
s_m (cm)	14	22	20	3

- for sections C and D, far away from the constrained extremity, the measured movements were from two to three times greater than the calculated movements. This was justified by the fact that the measurements referred to the initial non-deformed configuration, and included the movements accumulated from the period during which the wall was built (1509) up to today: during this period, at least three strong earthquakes have occurred, in addition to the one in 1997. For section A, the closest to the constrained extremity of the wall, the movements measured were inferior to the calculated ones; for section B, they were just a little larger.

Since the wall is 4 m thick and has a total height of about 18 m in the end zone and decreases as on moving away from it, it is reasonable that the three-dimensional boundary effects are felt in appreciable manner within a distance of the order of twice the maximum height. Since the distance between the constrained extremity and sections A and B is of approximately 12 m and 24 m, respectively, both feel - even if in a different manner - the constraining boundary effects, that are disregarded in the two-dimensional calculation.

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