

The preservation of Agrigento Cathedral

La conservation de la cathédrale d'Agrigente

Valore C., Zicarelli M.

DICAM - Dept. of Civil, Environmental, Aerospace and Materials Engineering – Università di Palermo – Italy

ABSTRACT: The Agrigento Cathedral was built about nine centuries ago on the edge of a steep slope made up of alternating inclined layers of soft calcarenites and fine-grained soils; its behaviour has never been satisfactory especially as far as the North aisle is concerned. Many corrective measures have been attempted during its lifespan and also a few years ago. They have been proved invariably to be unsuccessful. Recent geotechnical investigations, referred to in the paper, permitted to find out that the main cause of the Cathedral distress is a sliding mechanism involving the upper zone of the slope underlying the North aisle; consequently the essential requirement for the preservation of the Cathedral is the stabilisation of the slope.

RÉSUMÉ: Le Cathédrale d'Agrigente a été élevée voici environ neuf siècles sur le bord d'une pente raide, composée d'une alternance de couches inclinées de calcarénites tendres et de sols à grain fin. Le comportement de la Cathédrale n'a jamais été satisfaisant en particulier dans sa nef Nord. De nombreux remèdes ont été essayés au cours de sa vie et jusqu'à il y a quelques années. Ils se sont révélés toujours sans succès. De récentes investigations géotechniques, décrites dans le papier, ont permis de découvrir que la principale cause de la désordre de la Cathédrale est un mécanisme de glissement impliquant la zone supérieure de la pente située sous la nef Nord. En conséquence, la condition essentielle pour la préservation de la Cathédrale est la stabilisation de la pente.

KEYWORDS: Agrigento Cathedral; preservation; slope stability; clay; calcarenite.

1 INTRODUCTION

The Girgenti (now Agrigento, Sicily) gothic Cathedral was built in the XI century on the top of Agrigento Hill right on the edge of a steep slope about 40m high and inclined from 40 up to 50° towards North, Fig.1. The Cathedral has been profoundly changed during the XIV, XVI and XVII centuries as a consequence of structural damages caused by differential settlements of the foundations as well as by the horizontal thrust exerted on the northern masonry wall by the barrel vault which once covered the northern aisle. Other damages have been caused by earthquakes. Baroque superfetations were introduced during the XV century and were partially removed at the beginning of the XX century. A massive still unfinished bell tower, adjoining the church on the western side, was built in the XV century. The plan of the Cathedral is shown in Fig.1.

The building was originally smaller and located in the area of the present apse (East side); later extension towards the West required the construction of a rather high fill in order to keep unaltered the floor elevation. The present elevation of the nave floor is 327.54 m a.m.s.l.

The behaviour of the Cathedral has never been satisfactory: it has undergone settlements, tilting, distortions, partial collapses. Many interventions, including partial demolitions and reconstructions, have been carried out in the last century. The most notable remedial measure was the underpinning of the columns and the northern wall by means of Fondedile "pali radice" (root piles) in 1976-1980 (Lizzi, 1993). Almost all interventions as yet carried out have been unsuccessful, and sometimes even self-defeating.

As a matter of fact, the fissuration pattern of the Cathedral observed after each intervention was a replica of the previous ones. The settlements and the horizontal outward movements of the North aisle have never stopped. In 2010, just a few years after the completion of the last stabilising works, the

Cathedral has to be closed. Recently, systematic in situ geotechnical investigations and monitoring of ground movements as well as a precise survey of the Cathedral by the laser-scanner technique have been started. The main results of these investigations and an outline of the causes of the malfunctioning of the Cathedral are reported in the paper.

2 GEOTECHNICAL INVESTIGATIONS AND FIELD INSTRUMENTATION

The Cathedral foundation soils have been explored on many occasions, namely:

- in 1904, when an exploratory shaft 24m deep was excavated inside the Cathedral nearby its North-West corner; the shaft was filled with mass concrete intermingled with irregular calcarenite blocks;
- in 1976-80, when many vertical borings about 15m deep, were drilled inside and along the perimeter of the Cathedral, on the occasion of underpinning works by means of Fondedile root piles;
- in 2005: 8 vertical borings (marked with an asterisk in Fig. 1) located on the area of the Cathedral parvis and around the ex Diocesan museum were drilled; 2 open standpipe piezometers and 5 inclinometer tubes were installed in the boreholes. Inclinometric measurements have been carried out in 2005-2006 and subsequently restarted in June 2011 with a new initial reading;
- in 2008: 20 vertical borings located inside and around the Cathedral were drilled (S12-S29 in Fig. 1); max depth: 62m; 3 Casagrande, 4 open standpipe piezometers and 6 inclinometer tubes were installed in the boreholes. Inclinometric measurements started only in June 2011;
- in 2012: 30 vertical and 6 inclined borings (S201-S227 in Fig.1) were drilled inside and around the

Cathedral as well as on the adjacent northern slope; (max depth of borings: 70m); 14 vibrating wire piezometric cells, 1 Casagrande piezometer, 2 open standpipe piezometers, and 7 inclinometer tubes were installed. Piezometric and inclinometric readings started in 2012 and are still carried out. Five exploratory pits were also excavated in the Cathedral.

During the 2012 investigation campaign: SPT, Menard pressurimeter and in situ permeability tests were carried out, and many undisturbed samples were taken for laboratory testing.

3 GROUND CONDITIONS

The Agrigento Hill is made up of layers of soils and soft rocks belonging to the northern limb of an asymmetric syncline with approximately E-W axis (Croce et al., 1980; Cotecchia et al., 2005). The core of the syncline is known as Agrigento Formation, AF, and dates back to Lower Pleistocene; it overlies Monte Narbone Formation, MNF, (Middle-Upper Pliocene). Within the area pertaining to the Cathedral the following layers have been recognised from bottom to top:

- a) Grey, heavily overconsolidated clay with rare, thin lenses of silty sand, A; this layer is about 200 m thick and belongs to the MNF; its altered upper part A' contains gypsum veins.
- b) Soft, reddish biocalcarenites interbedded with yellowish calcarenitic sands, CLR. The thickness of this layer ranges from 24 to 37m. The contact with the underlying clay is sharp and dips approximately towards the South.
- c) Grey clay AG, and grey-yellowish clay with thin subvertical veins or spars of minute crystals of secondary gypsum, AGG. The overall thickness of this layer (AG plus

AGG) is about 12m. The contact with the underlying calcarenites is clearly defined by a thin transition layer, made up of clay intermingled with carbonatic shell shreds, and dipping 15-18° towards the South.

d) Silty sand and sandy silt, from grey to yellowish, SL. The thickness of this layer ranges from 4 to 6m.

e) Soft yellowish or reddish calcarenite interbedded with yellowish silty sand, CL. The rocks are frequently fractured. The thickness of this layer ranges from 4 to 12m. Small cavities have been found in these rocks in which an unlined passable adit has been excavated many years ago (Ismani hypogeous in Fig. 1).

Soil and rock b, c, d, e belong to AF.

A schematic vertical profile of the ground is shown in Fig. 2. It may be noted that the various layers bend down when approaching the slope. Similar ground conditions have been ascertained within the zone relevant to the Cathedral.

4 GEOTECHNICAL PROPERTIES OF SOILS AND ROCKS

Some data derived from results of laboratory and in situ tests are summarised in tables 1 and 2.

5 POREWATER PRESSURES

The few available piezometric data point out to the existence of a perched groundwater table within the fine-grained soils overlying calcarenites CLR. This hypothesis is consistent with the high permeability coefficient of calcarenites CLR and CL and with the observation that drilling water was systematically lost when boring in these rocks. A tentative groundwater table is drawn in Fig. 2.

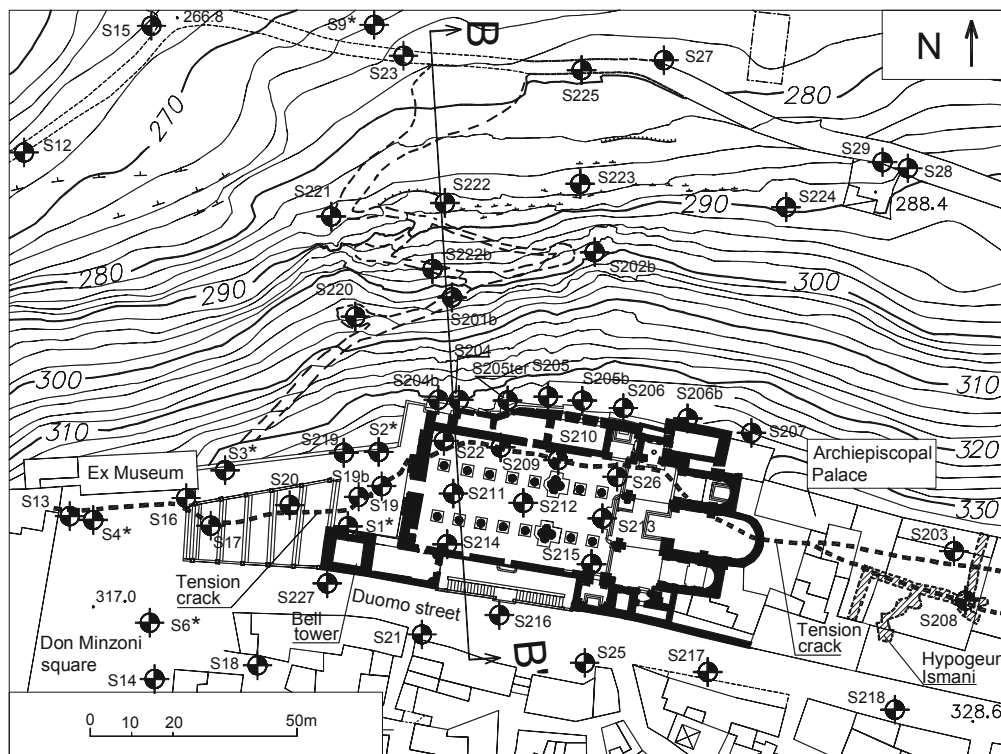


Fig. 1. Schematic plan of the Cathedral and of the adjacent slope, and location of the most relevant borings. It is also shown the longitudinal fracture or tension crack running through the northern aisle, the archiepiscopal palace and the Ismani hypogeous on the East side, and through the parvis and Don Minzoni square on the West side. Borings S201-S227 drilled in 2012; borings S12-S29 drilled in 2008; borings S1*-S9* drilled in 2005. Boreholes equipped with inclinometer tube: S1*, S2*, S3*, S4*; S13, S16, S20, S22, S26, S29; S203, S204, S207, S208, S209, S220, S221.

6 FOUNDATIONS OF THE CATHEDRAL

The columns and the southern wall have been founded directly on, or slightly above, the top surface of calcarenites

CL, whilst the northern wall and a small stretch of western (facade) wall rest on intensely fractured calcarenites or on silty sands SL, see Fig. 2. The columns have been underpinned by groups of fourteen “root piles” about 15 m long, slightly inclined to the vertical so to describe a ruled surface flaring downwards (Lizzi, 1993). Each root pile was reinforced with a single, 24 mm diameter, steel bar. Shorter root piles were used to underpin the northern wall of the Cathedral. Root piles groups under the nave columns have been tied at the top by a grid of reinforced concrete beams. It is clear from Fig. 2 that the foundation ground of the Cathedral is far from uniform and that the thickness of the soft calcarenite layer CL diminishes or vanishes as the northern slope is approached. During the underpinning works in 1976-1980 it was ascertained that the CL calcarenite layer was dissected by a long and deep fracture (or tension crack) located inside the Cathedral near the northern wall, as shown in figures 1 and 2; it was “stitched” by cement pressure grouting.

7 GROUND MOVEMENTS, FISSURATION PATTERN OF THE CATHEDRAL AND CAUSES OF ITS UNSATISFACTORY BEHAVIOUR

The most striking sign of ground movement is a longitudinal subvertical tension crack running in East-West direction through the floor of the northern aisle, and extending continuously to the parvis, the staircase and the Don Minzoni square, and in the opposite direction to the apse, the archiepiscopal palace and the Ismani Hypogeum as shown in Fig.1. This fracture has been firstly surveyed by Commissione del Ministero dei Lavori Pubblici for the investigation of the great “Addolorata landslide” (1968). The aperture of this fracture exceeds more than 20 centimeters in the Ismani hypogeum. After the restoration works completed in 2000, the fracture formed again in the Cathedral floor and in the parvis; its aperture slowly progresses and has now attained 4 cm. There is a step, from 2 to 3 cm high, between the northern and the southern walls of the fracture. The northern wall settled about 4 cm

The floor of the nave and the southern aisle have undergone negligible settlements.

Table 1. Geotechnical properties of soils R, SL, AG, AGG.

Soil	w_n (%)	w_l (%)	w_p (%)	S (%)	CF (%)	γ_s (kN/m ³)	γ_{sat} (kN/m ³)	c'_p (kPa)	ϕ'_p (°)	ϕ'_r (°)	E_{ed} (MPa)
R	/	/	/	/	/	/	/	0	30-35	/	/
SL	11-28	35-40	18-23	100	2-10	27-27.4	19.5-20.5	15-25	29-30	/	4-20
AGG	18-30	45-55	20-22	100	35-45	26.8-27.3	19.6-20.5	30-35	27-29	14	10-40
AG	18-30	43-51	20-23.3	100	31-43	26.9-27.4	20.2-20.7	30-40	28-30	16	20-60

Table 2. Geotechnical properties of calcarenites CL and CLR.

Calcarenite	n (%)	γ_s (kN/m ³)	γ_{sat} (kN/m ³)	σ_r (MPa)	k (cm/s)	E' (MPa)
CL and CLR	0.36-0.46	26.9-27.4	18.8-20.6	1.1-4.6	$10^{-2} - 10^{-4}$	300-700

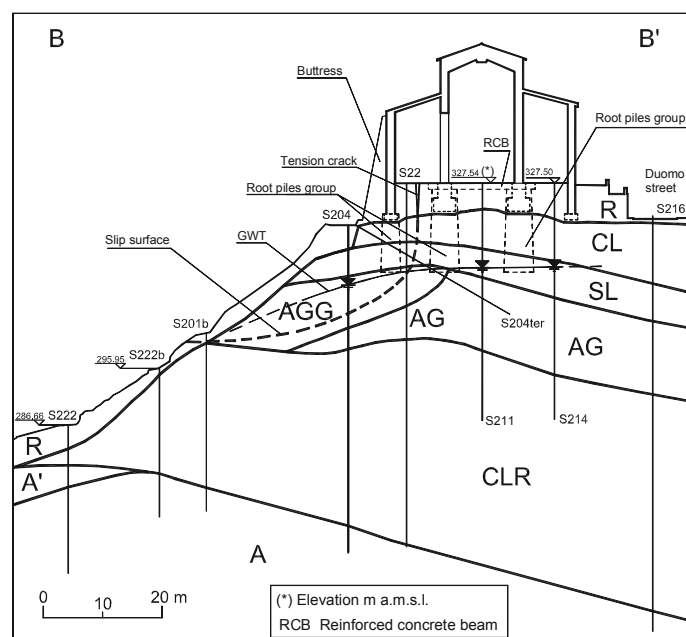


Fig. 2. Vertical cross ground profile B-B'. R: made ground or topsoil; CL: upper soft yellowish or reddish biocalcarenes interbedded with sand lenses; SL: silty sands and sandy silts; AG: grey clays; AGG: grey-yellowish or light brown clay with veins of minute crystals of secondary gypsum; CLR: lower soft reddish biocalcarenes with sand lenses; A: heavily overconsolidated grey clays; A': grey-yellowish clays with gypsum veins.

An idea of the cumulative differential settlements and horizontal displacements towards the slope of the northern wall can be drawn from the deformed shape of an arch transversal to the axis of the northern aisle and adjacent to the transept. According to a fairly credible reconstruction depicted in Fig. 3, the northern springline of the arch might have undergone an horizontal displacement so large as 69 cm and a settlement of 93 cm relative to the other springline.

The pattern of the present-day fissuration and movements remarkably resembles that observed recurrently since 1904 as documented by photos and descriptions recorded in archival sources (Di Fede, 2011).

The relevant inclinometer readings, begun on June 2011 and summarized in Tab. 3, show that the ground mass located downhill of the longitudinal fracture undergoes significant horizontal displacements and point out the existence of shear surfaces at depths between 7 and 17m.

Based on these data and observations it is possible to identify a slide mechanism shown in Fig. 2. Similar mechanisms apply for the whole length of the Cathedral and the parvis zone, the archiepiscopal palace and Ismani hypogeum.

The above mechanism appear to be the main reason for the anomalous behaviour of the ground-Cathedral system. It has not been identified nor postulated up to now, and consequently the attempts to stabilise the Cathedral were unfounded. The sliding mechanism passes along the subvertical fracture and through silty sands SL and altered clays AGG. A stability analysis of this sliding mechanism, which involves the North aisle of the Cathedral, points out that the use of peak or residual shear strength parameters of soils SL and AGG is not warranted. In fact, if peak parameters are considered values of the factor of safety FS within the range 1.4-1.6 will be calculated, whether if residual strength is considered a value of FS much smaller than 1 is obtained: these values are inconsistent with the observed behaviour of the ground-Cathedral system. It is likely that the shear strength is gradually approaching the fully softened value for which the value of FS is 1.05.

Table 3. Superficial (top) horizontal displacement δh , and depth d of sliding surface indicated by inclinometric measurements from June 2011 to Dec. 2012. Location of inclinometer tubes relative to the longitudinal fracture. U: uphill; D: downhill. N: north; NW: north-west.

Inclinometer tube	δh (mm)	Direction	d (m)	Location
S1*	2	/	/	U
S2*	12.8	NW	7	D
S3*	6	N	15; 22	D
S4*	4	/	/	U
S13	3.2	/	/	U
S16	8	NW	11;16	D
S20	8.3	N	17	D
S22	10	NW	6; 11	D
S26	2.3	/	/	U

8 CONCLUSIONS

The behaviour of Agrigento Cathedral has been unsatisfactory since its construction in the XI century on the crest of a very steep slope. Many attempts to stabilise the ground-Cathedral system have failed because a sound diagnosis of its problems has not been formulated.

Recent geotechnical investigations permitted to identify a rather large sliding mechanism involving the North aisle of the Cathedral as well as long adjacent stretches of the edge of the slope. It is now evident that the preservation of the Cathedral requires prioritarily the stabilisation of the slope.

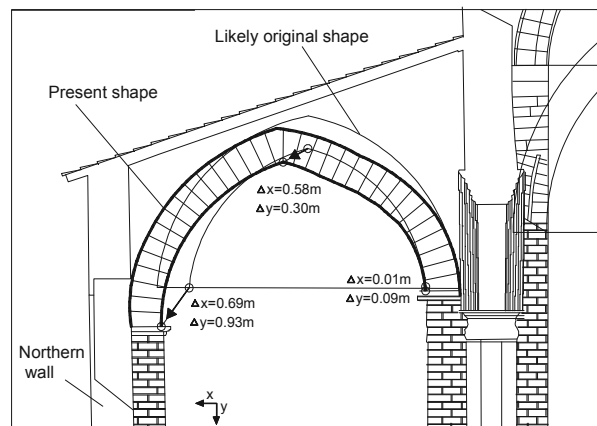


Fig. 3. Distorted arch located at the eastern extremity of the North aisle showing large differential movements between the springlines cumulated probably during some centuries. (Reconstruction by Arch. G. Renda).

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SYMBOLS

c'_p	peak cohesion intercept
E'	Young modulus
E_{ed}	constrained modulus
CF	clay fraction
k	coefficient of permeability
n	porosity
S	saturation degree
w_l	liquid limit
w_p	plasticity limit
w_n	natural water content
ϕ'_p	peak angle of shear strength
ϕ'_r	angle of residual shear strength
γ_s	specific weight
γ_{sat}	saturated unit weight
σ_f	uniaxial strength