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Structural Assessment of the Vaulted Masonry Ice Storage Glacières Royales (1874) in Brussels

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Abstract The function of the underground ice storage, *Glacières Royales*, was to efficiently conserve ice during all seasons. It consists of a large vaulted structure in masonry from floor to walls and ceiling, covering 460 m². This remarkable ice storage is no longer in use today but is one of the last monumental witnesses of the European industry of ice and is therefore listed since 1993.
A real estate project influencing the immediate surroundings of this ice storage motivated a thorough evaluation of its condition and stability.
The actual structural behaviour of the underground ice storage, *Glacières Royales,* was studied. 2D and 3D numerical models based on linear elastic finite elements were used for the masonry. The soil-structure interaction was modelled by linear and non linear models using the Plaxis software. Analyses are presented both on the level of stability of the *Glacières Royales* in its present and future conditions imposed by the real estate project.

Keywords: Ice storage, vault, masonry, soil-structure interaction, stability, numerical model

Introduction

The underground ice storage, named *Glacières Royales*, consists of two large rooms constructed in masonry by J.P. Sommereyns, mason and owner of the plot (Fig. 1). This historic building was erected in two phases corresponding to the two rooms, firstly in 1874 and then in 1894 (Fig. 2).

Figure 1: Overview of the ice storage, room dating from 1894 (Lambrecht 2002)

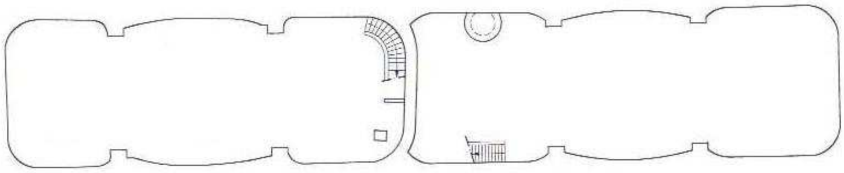

Figure 2: Plan of the ice house (left side 1874; right side 1894) (Van der Wee 2002)

The location of this ice storage in Auderghem (South-West district of Brussels, Belgium) was commercialy strategic. It was close to training fields for the Belgian army and easily accessible thanks to a new constructed road. Since 1993 it has been listed as historic monument by the government of the Region of Brussels, especially for its exceptional size. The primary function of an ice house is to conserve properly ice during all seasons. The average temperature is constant around 15°C with about 95% relative humidity. Ice storages were extensively used until the invention of the fridge. The *Glacières Royales* were exploited until the First World War.

The aims of this in-depth study are twofold. Firstly, the structural behaviour of this tall ice storage is analysed in order to identify possible weaknesses, even if the structure seems to be in a relative good state of conservation. The actual stability of the vaulted structure is complex to evaluate mainly because of the modelling of the soil pressure. Therefore, the Plaxis software, which is a convenient tool to model non linear behaviour of the soil, was used.

Secondly, the consequences of future immediate constructions are assessed. Indeed, a real estate project influencing the immediate surroundings motivates this thorough evaluation of the conditions of stability of this construction. Guidelines for the new constructions are addressed in order to preserve, for a long time, the *Glacières Royales*.

Current Structural Behaviour

Firstly, simple two-dimensional models were used to understand rapidly the structural behaviour. 2D representation helps also to calibrate further 3D models. Then, three-dimensional modelling was been set up to take into account spatial interactions and to fully approach the behaviour of the ice storage. The methodology is similar for the second part of the study, the interaction with the new construction. The parameters of these models are the global and local geometries, the properties of the masonry and the applied loads.

Geometric and Material Investigations The plan and section show two similar ice storages,tangent to each other and divided in three bays (Fig. 2). In-situ investigations (visual survey, borings, etc.) have determined the geometrical characteristics and the type of soil. Each bay is based on a rectangle of about 9 m. The corners are rounded and the walls are straight but slightly curved for the central area. Large interior buttresses thick of 80 cm border each bays. The vertical walls are 6 m high and are covered by a semi-circular vault of 9 m span with a rise of 3.2 m. The intrados of the vault is 1.40 m below the slab of the ground floor.

The different periods of construction appear clearly in the layout of the wall. However, the arrangement of bricks of the earliest storage is the worst and therefore will be considered in the following study. Briefly speaking, walls are made of two layers of bricks of 30 cm each with 10 cm of air in between as shown in Fig. 3. Transversal ordinary bricks connect the two walls; they are located randomly and represent about 10% of the surface. Therefore, wall cannot be considered monolithic and shear forces cannot pass through the brick connectors The floor is concave and made of several layers of bricks with a total thickness of 20 cm. The ceiling is made of a full masonry with a thickness of 36 cm, underneath backfill (rubble, stones, sand). One quarter of the ice storage, is sufficient, with adequate boundary conditions, to model the entire structure thanks to its symmetrical geometry (Fig. 3).

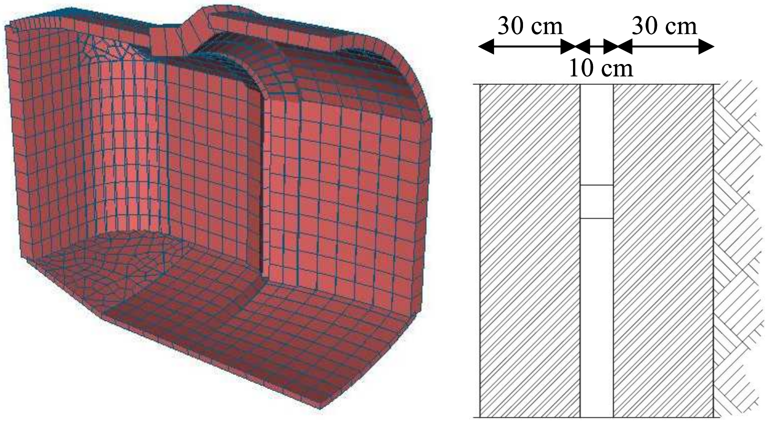

Figure 3: Left: 3D model of a quarter of one ice house with the different thicknesses (Finelg, Greisch 2008); Right: Local geometry of the walls

Clay bricks and lime mortar constitute the masonry structure. Their characteristics, for a macro-modelling of masonry, are represented by an equivalent Young modulus E = 5000 MPa, Poisson's ratio ν = 0.15, specific weight ρ = 18 kN/m³. Masonry is modelled as an elastic linear material, without taking into account the actual influence of cracking on the behaviour of the masonry, which is obviously an approximation. However this reduction is acceptable for such overall structural analysis (Lourenço 2002). The type of soil is basically a sand, representative of Brussels ground.

The applied loads on the masonry structure are its self weight, the backfill resting on the ceiling and the soil pressure all around the ice house. Calculations are made without safety coefficient.

Evaluation of the Models The stability assessment assumes that masonry does not bear tensile stresses (Heyman 1995). The resultant of the internal forces should stay inside the section and not too close from the edge. However, it could be outside the central core. Moreover, stresses are compared to maximal stresses at the serviceability limit state, approximately equal to 1.4MPa, according to this type of masonry. The outputs of the models are the values of bending moment, normal force and displacement of the masonry structure. Therefore, the eccentricity, e = M/N, can be deduced and maximal stresses can be calculated and compared to acceptable values for this specific type of masonry.

With our stability criteria, calculations have shown that 2D models are unable to carry more 30% of the loads. A more accurate modelling of the structure is therefore needed to assess its actual safety. For 3D modelling of the masonry, the finite element software Finelg was then used (Finelg). The ice storage is represented by four-nodes shell elements. The membrane thickness and the bending thickness are different for the walls, representing the actual configuration of double wall. In this modelling, buttresses in masonry lay down on stiff strip foundations. However, the structural behaviour was not satisfactory with too high stresses inside the masonry. The structure withstands only 60% of the loads with this 3D model. The last parameter which could have an influence on the stability is the soil. So far, the soil has been modelled as an elastic foundation with a neutral earth pressure K_0 equal to 0.5. Therefore, the soil is more accurately represented thanks to the Hardening Soil Model of the software Plaxis (Table 1).

Table 1: Overview of the parameters used during simulations with the Hardening Soil Model

c	0 kPa	E_{ur}	120 MPa
φ	30°	P_{ref}	100 kN/m²
ψ	0°	m	0.5
$E_{oed} = E_{50,ref}$	40 MPa	υ	0.2

With c = cohesion; φ = angle of internal friction; ψ = dilatancy angle; υ = Poisson's ratio; E_{oed} = tangent stiffness for primary oedometer loading; $E_{50,ref}$ = secant stiffness in standard drained triaxial test; E_{ur} = unloading/reloading stiffness; P_{ref} = reference stress for stifnesses; m = power for stress-level dependency of stiffness (Schanz et al. 1999).

Two phases should be taken into account in the model.

Firstly, the initial state of stresses should be assessed to determine the pre-existing stresses, thanks to the following formula (1) and (2), with σ'_h = horizontal stresses; σ'_v = vertical stresses; K_0 = neutral earth pressure coefficient; z = depth.

$$\sigma'_v = z\,(m) \times 18\ kN/m^3 \quad (1)$$
$$\sigma'_h = K_0 \times \sigma'_v \quad (2)$$

Secondly, the present state of stresses in the structure and inside the soil should be checked out (Fig. 4). After several iterations, the calculation gives the theoretical present state of stresses.

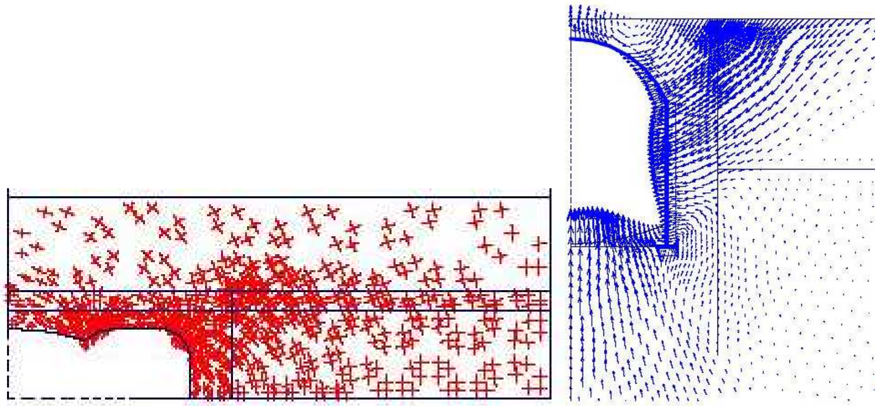

Figure 4: Horizontal and vertical cross sections: stresses in the soil due to the construction of the ice house (on the left) and displacement of the structure after excavation (on the right) (Plaxis)

This representation allows, indeed, to decrease the loads on the masonry structure. From the horizontal cross section, two phenomena are observed. A global pressure arch appears which unloads partially the construction. The earth pressure coefficient on the structure has a value of 0.41 corresponding to a common value in case of deformable retaining walls. A second effect is that limited pressure arches appear locally between two buttresses. These confined pressure arches relieve the bending stresses in masonry. In the vertical plane, the current situation can only be stable if compression loads are attracted by butresses, meaning that pressure arches can be developped.

The stresses due to combination of compression and bending are calculated in elastic (with maximum allowable tensile stress of 0.2 MPa) and plastic states (by neglecting tensile strength of masonry), in five critical locations of the structures where bending moments reach their maximum (Fig. 5). The results of stresses indicate that the structure is currently stable in its actual environment.

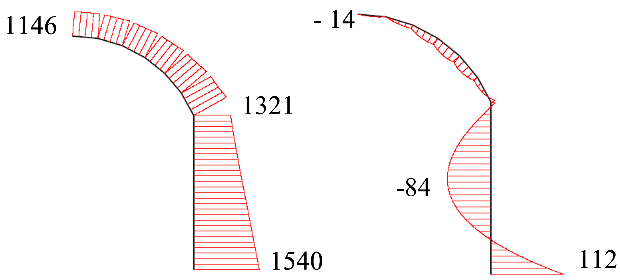

Figure 5: Normal forces (kN) and bending moment in the vertical section (kNm) (Finelg)

Eventually, modelling the present soil as precisely as possible allows highlighting pressure arches in the ground, which decrease the pressure on the walls and concentrate stresses in the stiff buttresses.

This approach generates consequential benefits, which are sufficient to demonstrate the stability of the ice storage in its current situation.

Influence of the Surrounded Construction

Building a retaining wall next to the ice storage has a strong influence on its structural behaviour. The stability model of the ice house should therefore take into account the consequences of the future situation. Indeed, the aim of this analysis is to determine the criteria that need to be fulfilled by the adjacent construction to ensure the preservation of the ice house. Therefore, one more step in the model is necessary. A new continuous wall in reinforced concrete 50 cm thick and anchored on top should be added. After a first calculation, the displacement of the wall should be lower than 1 cm to allow the presence of arch pressure, necessary for the stability of the ice house.

When the diaphragm wall is located at 5 m from the ice storage, the structure is slightly influenced but arches pressure are still present. However, if the diaphragm wall is located at 2.5 m, local pressure arches are distorted and the bending moments in the structure increase significantly. However, in such case, the Terzaghi silo theory can be applied due to the proximity between the retaining wall and the walls of the ice house (Schlosser 1990). The concept is that several vertical arches are created in the soil; each of them carrying its own self weight. Therefore, the horizontal pressure on the wall of the ice storage becomes constant below a certain depth, namely 5 m. Moreover, these arches imply also a vertical component. The walls of the ice house can take benefit from this added load which reduces the total stresses. The decrease of horizontal earth pressure is favourable for the longitudinal walls but leads negatively to a decrease of the normal stresses in the front walls. Therefore, a closed hedge around the existing ice storage should be implemented to allow the silo effect on all the walls.

Bending moment, normal force and eccentricity were computed with the silo theory in 2D and 3D. The values of eccentricity e_{xx} show two weak points on top of the vault, where the normal force is low (Fig. 6). However, the exact type of connection between wall and slab are still unknown but this configuration of weak connection is the most unfavourable. In the horizontal plane, the eccentricity e_{yy} exceeds acceptable values in many points (Fig. 6).

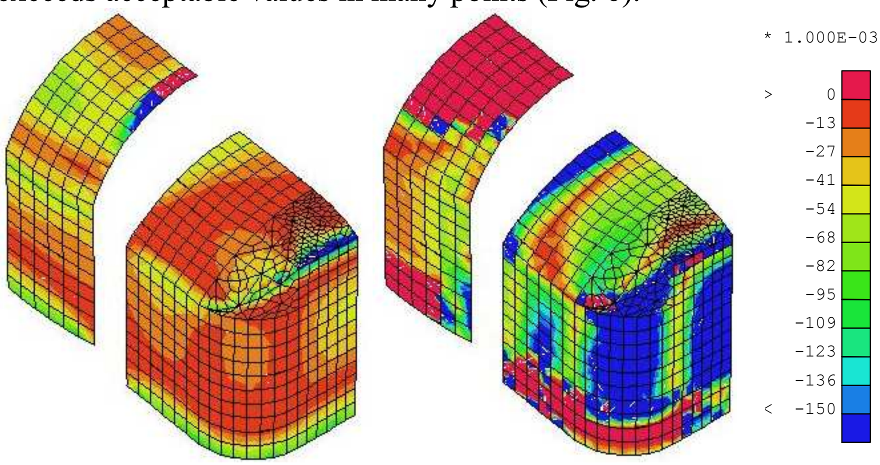

Figure 6: Eccentricity in the vertical plane e_{xx} (left) and horizontal plane e_{yy} (right) in m (Finelg)

This calculation shows therefore that the flow of stresses is essentially in the vertical plan. Indeed, the stability of the ice storage is also obtained with the 2D vertical model, which is a sufficient proof according to the lower bound theorem of plasticity. The values of stresses inside the masonry are now acceptable. Moreover, the pressure line remains inside the section.

Conclusions and Future Developments

Studying an ancient construction is often more complex than it appears to be. The case of the ice storage *Glacières Royales* is definitely not an exception. Numerous parameters need indeed to be considered but many are undefined or uncertain, such as the construction sequences, the loading history, the exact geometry, etc. Therefore, they should be evaluated as precisely as possible. Through the progress of the analysis, the assumptions need also to be regularly re-evaluated.

The first aim of this study was the analysis of the behaviour of the ice house in its static current situation. Several models were investigated, in 2D and 3D, with different hypotheses on the behaviour of the soil, on the type of foundations, on the connection between elements of the masonry. The methodology used in the assessment of the *Glacières Royales* is similar to the strategy adopted for many other appraisals of existing structures (Lourenço et al. 2008). It consists basically on an iterative process for achieving a satisfactory representation of the structure. The behaviour of this structure is sensitive to the soil pressure. Modelling of the ground increases the margin of safety, without satisfying fully current standards. Generally speaking, the safety level required for new constructions is not easily satisfied for an ancient structure. Eventually, a suitable representation of the structural model was developed, even if many results are more qualitative than quantitative. Limit analysis and nonlinear analysis should be applied, in the future, to assess more accurately and safely the behaviour of this masonry structure (Lourenço 2002).

Secondly, regarding the small margin of safety of the ice storage structure, some criteria should be fulfilled by the new adjacent construction. The diaphragm wall should be as stiff as possible, with a maximal admissible displacement of 1 cm, to ensure the validity of the silo theory. This wall should be located at least at 2.5 m from the exterior walls of the ice storage to avoid introducing more pressure. The foundations of the new construction should rest at a lower level than the ice storage to prevent interferences with the ice house.

Acknowledgements

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