The Fontanelle Cemetery: Between legend and reality

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ABSTRACT: The paper reports the history of the “Cimitero delle Fontanelle” (literally: cemetery of the small fountains), one of the most fascinating among the cavities of the subsoil of Naples. During its four centuries of life this cave has experienced a number of events, until it found in the modern age its final destination as a place of warship and became part of the cultural heritage of the city. After touching historical, urban and social aspects, an evaluation of the stability condition of the cavity is attempted. The state of stress in the tuff, in which the excavation has been carried out when the present cemetery was an underground tuff quarry, is analyzed by means of a 3D finite difference code, taking into account the various stages of excavation and subsequent partial filling. The results obtained show that there are some stability problems for the roof of the cavity; further investigations on the shape of the pillars, partially hidden by the fill, and on the mechanical properties of the tuff are needed for a more satisfactory evaluation.

1 INTRODUCTION

The sacred remains of the queens of the Mediterranean (Athens, Syracuse, Rome and their colonies), rich in history and culture, are also characterized by a subsoil crossed by an intricate network of tunnels, shafts and tanks. The subsoil of Naples does not escape this feature; it is characterized by the widespread presence of the Neapolitan Yellow Tuff (NYT), a soft rock of volcanic origin through which the system of cavities has been excavated in the centuries (Melisurgo 1889; Puntillo 1994).

Though being not particularly beautiful neither rich or famous, one of the most fascinating among the Neapolitan cavities is the so called Fontanelle Cemetery (Esposito 1992), Figure 1.

It is an ancient tuff quarry, destined to become an ossuary in the XVIII century and progressively turned into a Christian worship place of the Neapolitan lower class. This paper aims to report not only the geomorphological and geotechnical aspects of the Cemetery, but also the historical, social and environmental ones, in order to highlight the tight connections between the past of the cavity and the history of the city.

2 MORPHOLOGICAL ENVIRONMENT

The city is located at the southern border of an upland plain of volcanic origin known as Terra di Lavoro, formed around 35,000 years ago as the results of a gigantic eruptive explosion, Figure 2. The territory of the ancient city of Naples may be ideally split into two areas with rather different morphology. The western area exhibits a hilly and articulated morphology, while the eastern one is gently sloping towards the sea from north to south. This gentle slope, called “Pendino”, is the seat of the historical centre; here Naples, unique in the world, after almost three millennia still bears the original structure of the former Greek city. This structure is characterized by three greek “plateiai”, later Roman “decumani”, 6 m wide and oriented in the east-west direction, intersected at right angle in the north-south direction by the “stenopoi”, or “cardi”, only 3 m wide.

The eastern and western parts of the city are split by a road running in north-south direction, on the line of the present Via Toledo, Via Santa Teresa degli Scalzi and Corso Amedeo di Savoia. The road connects the coast to Capodimonte, a piece of the Terra di Lavoro separated from the upland plane by the canyon of the Vallone San Rocco. Corso Amedeo di Savoia overpasses...
with a bridge the densely populated district of Vergini—Sanità.

The backbone of the hills is the NYT, covered by pyroclastic soils (pozzolana and pumices) that are easily eroded by rain water; deep gorges have been hence excavated in the slopes. The materials eroded were transported by mud and debris flows, the so called “lava dei Vergini”, through the valley of Vergini, at present densely urbanized. So frequent was this event, that the lower classes had invented the practice of “passalava”: a porter who carried the lords across the roads invaded by the mud and debris, in order not to let them get dirty. Disastrous floods are known to have occurred in 1435 (the so called “diluvio della Conocchia), 1566 and 1569. Such an eroding action going on through the centuries exposed the underlying tuff on the sides of the valleys, creating the optimal conditions for quarrying it as a construction material. As a matter of fact, the bridge over the Sanità and all the houses were built with the stones extracted from the hills where the tuff outcrops. There are at least seven large underground quarries left along Corso Amedeo di Savoia, with volumes up to 372,000 m³. The same road, via Fontanelle, where the cemetery is located, is an old water course; on its sides several quarries have provided the building materials for the constructions in the city and are today addressed to different uses. It is to mention that the Neapolitan laws of XVII century forbade quarrying the tuff inside the city, so that the quarries were concentrated just out of the walls, right in this zone (Rosi 1994).

All these cavities are rather large, with a total volume of the order of six millions of cubic meters. Many of them were later used for Pagan and Christian worshipping (Puntillo 1994; Esposito 2007). Each cavity has its own complex story, but that of Fontanelle is particularly suggestive.

3 THE HISTORY OF FONTANELLE CEMETERY

The ancient tuff quarry named “Cimitero delle Fontanelle” is located near the church of Maria Santissima del Carmine, at the boundary of the densely populated district of Vergini—Sanità, just outside the ancient Greek—Roman necropolis, Fig. 2. This area was chosen for the pagan—and later Christian—cemeteries. The cavity in question has no particular architectural features, nor its size (width and height) is worthy of special note. Its particularity is that it was used for different purposes and, since its excavation, experienced several changes.

The origin of the quarry may be traced back to the XVI century, and its expansion to the XVII century. At that time, the city was scourged in rapid succession by popular rebellions, famines, earthquakes, eruptions of the Vesuvius and epidemics. Being our cavity located in an isolated place, outside...
the walls of the city but close to them, it was used to collect the corpses of the victims. It is said that in 1656, after a deadly plague, the walls that closed the cave were broken and 250,000 corpses (other sources quote a figure of 300,000) out of a population of 400,000 inhabitants where accumulated. The canon Andrea de Iorio reports that, at the end of XVIII century, all well-to-do persons wanted to be buried in churches where, however, there was not more space left. It happened so that the grave diggers pretended to adhere to the request of burial in the church and then, late at night, the corpse was put in a sack and “they went to put it back in the quarry of the Fontanelle, which was no longer in use”.

In 1764 the architect Carlo Praus confirms this practice by stating that that the quarry was used to bury the bodies of the lower class. But due to a sudden flood into the cave, the corpses were dragged outside and ended up to clogging the great sewer running beneath Via Toledo. Later the bones were reassembled in the cavity, a wall and an alter were built and the place began the charnel house of the neighbouring districts. Still in 1834 the bones removed from the burial of the churches were laid in this ossuary. In 1872 some faithful people, led by father Gaetano Barbati, arranged the thousands of bones in neat stacks in various distinct areas, and from then on a spontaneous and strong popular devotion arose for those unidentified dead. Some skulls were adopted by the faithful, placed in special glass and wood cases and treated so that they might come in a dream and predict the future. Only the identity of two people, Filippo Carafa Count of Cerreto and his wife, is known. It seems that the stones cut from the quarry was indeed used for the construction of the mansions of Prince Carafa.

The ossuary was closed in 1969, by order of the Archbishop of Naples, due to religious deviations that were believed to take place there. Despite this, in the following years the devotion for these corpses increased; the devotees identified in them the souls of the Purgatory that needed care and attention. The cavity was reopened only in 2010, after some consolidation interventions carried out in 2002.

The ossuary of the Fontanelle emblematically represents the horror of the plague and death. The figuration and remind of those dramas take the value of tools for a reflection on the disrupting effects of the disasters caused by the human sin, on the pain and on the death.

4 STRUCTURAL DESCRIPTION OF THE CAVITY

The Fontanelle Cemetery is a chamber and pillar cavity with two direct access; the roof is supported by 9 isolated pillars (P1 to P9) and 4 further vertical elements or septums (SE1 to SE4) protruding from the walls (Fig. 3).

The portal is made of piperno stone; at the entrance there is a very wide area, the roof of which is supported by three isolated pillars (P1, P4 and P8) and three septums (SE1, SE2 and SE3).

The overall shape in plan is rectangular, elongated in a north-south direction and consisting of three naves (Fig. 3). The intermediate one is called “navata degli Appestati” (nave of the plague stricken persons) and the second one is the “navata dei Preti” (nave of the priests). Entering on the right, there is a third secondary aisle with an inclination of 45° respect to the other ones and a smaller span, called “navata dei Pezzentelli” (nave of the small beggars). The overall width of the two main naves is 40 meters and the length 105 m, with a total area of more than 3,000 square meters.

The height of the “navata dei Preti” is 7 m, while the “navata degli Appestati” is 10 m high. The
cover above the roof (tuff plus pyroclastic soils) ranges between 8 and 10 m. In the entrance and in the central chamber the height of the roof rises up to 12.0 m, while the cover is 30 m thick.

The naves sections have a trapezoidal shape with a flat roof and walls inclined of 10°–15° to the vertical; the pillars, consequently, have a structural section decreasing with depth.

The material below the present floor level (72 m a.s.l.) is composed by an inter-bedding of anthropic fill and cineritic levels of different grain size and alluvial origin. The floor of the ancient quarry lies at an average depth of 9.0 m from the actual walking level. It is therefore believed that the pillars, for a substantial stretch, are buried in the filling material.

An intense fracturation is present in the central part of the roof at the entrance, with a prevailing northwest-southeast orientation; for its persistence, this is probably the main discontinuity family. There is probably a second discontinuity system in the east-west direction; it appears in the points where there are variations of height of the cavity. A few vertical discontinuities have been found in the navata dei Pezzentelli, at the intersection between the roof and the pillar.

A systematic survey of the discontinuities is not available, and accordingly they have been considered only marginally in the following analyses.

5 POSSIBLE MODALITY OF EXCAVATION OF THE CAVITY

Even if the cavity has been interested by several inspections, a systematic and exhaustive campaign of geological, geotechnical and structural investigations has never been performed. Due to the complexity of the problem, a number of uncertainties remain concerning the hidden geometry of the cave, the profile of soils and rocks, the structural characterization of the rock above the roof and the mechanical properties of the materials.

One of the major uncertainties is connected to the hidden geometry below the present floor, that is closely related to the unknown details of the excavation technique. It is well-known, however, that in Central and Southern Italy the extraction of the tuff was often carried out underground to preserve the ground level and to use the soil in situ for rural activities (Minardi 1999; Padovan 2009). The most widespread technique was the “chamber and pillars” one: the quarries have generally a regular layout in plan, with mutually orthogonal directions of excavation to create a mesh of isolated pillars. A number of vertical shafts, communicating with the outer surface, allowed the ventilation and the evacuation of the quarried material.

Figure 4 shows a picture of the pillar P4, in which there are clear traces of steps cut into the tuff to allow the quarrymen to leave the cavity through a shaft. The treads could be also made by a folded iron bar cemented into the rock.

It is to remind that, in the XVII century, the transportation of large rock boulders outside the cavity was not easy. For this reason the building stones were cut in the quarries, leaving the debris of this activity inside.

The possible excavation technique of the Fontanelle Cemetery, therefore, seems to follow these phases: (1) excavation of a vertical shaft in the pozolana till to the top of the NYT and then at least 8 m inside the tuff; (2) underground horizontal excavation leaving above a tuff slab of 8 m thickness to act as a roof structure and to preserve the pozolana in situ; in this way the roof is bounded to the lateral walls of the cavity.

The excavation went on gradually deepening the floor of the chambers, until a height of around 20 m of the cavity is achieved, and leaving the pillars in proper position.

With this modality of excavation, the bottom of the cavity reached an average level of 60 m a.s.l. (Old Level, OP) and 9 pillars and 4 septums were left to support the roof structure.

A period of inactivity inside the cavity follows. On the bottom of the excavation a mixture of tuff cuttings, debris and mud transported by the floods gradually accumulated, where human remains were buried or simply abandoned by the gravediggers. This material has been regularized and levelled to the present ground floor level has risen, at an elevation of 72 m a.s.l. (Present Floor Level PFL).

The present entrance and ticket office is at an elevation of 75 m a.s.l. According to this reconstruction of the sequence of events, currently in the cavity the exposed height of the pillars is on average 9 m, while the remaining part, of which the shape is unknown, is buried in the fill for an average length of 11 m.

Figure 4. Picture of the pillar P4 on which the traces of the ladders, used by the quarrymen, are visible.
6 SIMPLIFIED ANALYSIS OF THE CAVITY

The state of stress around an underground cavern and its static conditions may be evaluated following different approaches with different accuracy.

To evaluate the vertical stress acting on the pillars, the so-called ‘area of influence’ method may be adopted (Evangelista et al., 2002). The stress in the pillars is evaluated through equilibrium conditions between the vertical load in the pillar and the weight of the roof and the cover materials, corresponding to their area of influence, defined by geometric conditions. The weight is determined by taking into account the external morphology of the soil and assigning for the tuff rock and the covering soil a unit weight respectively equal to 14 kN/m³ and 15 kN/m³. The values of the average vertical compression stress on the pillars, σc, determined at the present planking level as a function of the height h, are reported in Table 1. In the same Table, the value of the base area of the section, Ap, the relative influence area, Ai, as well the thickness of the cover soils, Sp, are reported for each pillar.

The safety factor, FS, can be estimated as the ratio between the uniaxial compression strength σc, assumed equally to 3 MPa for the intact rock (Evangelista et al., 1998; Aversa & Evangelista 1998), and the average vertical stress σv in the pillar. It has been found that FS is nearly unity for pillar 4, and takes relatively low values for pillars 2 and 7; all the remaining pillars appears to be safe with ample margin.

The method of the areas of influence is generally conservative. No account has been taken of any defect or major variation of the section of the pillars, which may increase the stress level. Moreover, a significant scale effect is known to occur for pillars, which may increase the stress level. Moreo

<table>
<thead>
<tr>
<th>Pillar</th>
<th>Ai</th>
<th>Ap</th>
<th>h</th>
<th>Sp</th>
<th>σv</th>
<th>FS</th>
</tr>
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<tbody>
<tr>
<td>P1</td>
<td>107.6</td>
<td>384.9</td>
<td>11.0</td>
<td>13.0</td>
<td>852.0</td>
<td>3.5</td>
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<td>P2</td>
<td>101.4</td>
<td>389.6</td>
<td>7.0</td>
<td>17.0</td>
<td>1079.0</td>
<td>2.8</td>
</tr>
<tr>
<td>P3</td>
<td>197.8</td>
<td>540.0</td>
<td>7.0</td>
<td>23.0</td>
<td>1040.0</td>
<td>2.9</td>
</tr>
<tr>
<td>P4</td>
<td>68.37</td>
<td>493.7</td>
<td>12.0</td>
<td>25.0</td>
<td>2876.0</td>
<td>1.0</td>
</tr>
<tr>
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<td>267.0</td>
<td>7.0</td>
<td>13.5</td>
<td>631.0</td>
<td>4.7</td>
</tr>
<tr>
<td>P6</td>
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<td>321.9</td>
<td>7.0</td>
<td>14.0</td>
<td>545.0</td>
<td>5.5</td>
</tr>
<tr>
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<td>253.7</td>
<td>643.5</td>
<td>7.0</td>
<td>27.0</td>
<td>1124.0</td>
<td>2.7</td>
</tr>
<tr>
<td>P8</td>
<td>88.55</td>
<td>232.5</td>
<td>8.0</td>
<td>6.0</td>
<td>328.0</td>
<td>8.6</td>
</tr>
<tr>
<td>P9</td>
<td>101.8</td>
<td>275.7</td>
<td>7.0</td>
<td>10.0</td>
<td>505.0</td>
<td>6.0</td>
</tr>
<tr>
<td>SE1</td>
<td>204.0</td>
<td>516.0</td>
<td>12.0</td>
<td>15.0</td>
<td>737.0</td>
<td>4.0</td>
</tr>
<tr>
<td>SE2</td>
<td>208.0</td>
<td>649.0</td>
<td>7.0</td>
<td>6.0</td>
<td>378.0</td>
<td>7.9</td>
</tr>
<tr>
<td>SE3</td>
<td>262.7</td>
<td>516.7</td>
<td>12.0</td>
<td>25.0</td>
<td>905.0</td>
<td>3.3</td>
</tr>
<tr>
<td>SE4</td>
<td>180.0</td>
<td>591.0</td>
<td>7.0</td>
<td>12.0</td>
<td>689.0</td>
<td>4.3</td>
</tr>
</tbody>
</table>

determined on core samples (Paparo Filomarino & Pellegrino 1980). For all these factors, the reported evaluations are to be considered as a first approximation. Simple analyses of the safety of the roof have been carried out under plane strain conditions and adopting a limiting equilibrium methods; mechanisms of partial or total collapse have been considered. The coefficient of safety against failure of the roof is calculated as the ratio between the existing span and the critical span evaluated by the limit equilibrium approach (Evangelista et al., 2000). In the case of Fontanelle cemetery the total collapse of the roof may be excluded, while the detachment and fall of blocks of tuff is possible and could endanger the stability of the whole cave.

7 3D NUMERICAL ANALYSIS

The availability of efficient and low cost software and hardware encourages the designers and researchers to perform numerical calculations with complex constitutive laws. In spite of it, however, a sufficiently accurate evaluation of the stress and deformation field around existing underground cavities is far from an easy task. The reliability of the prediction depends entirely on the accuracy of the input data used in the model: the hidden geometry, the mechanical properties of the in situ rocks, the initial state of stress, the sequence of mining processes and so on. Due to the difficulty of getting a reliable evaluation of all these data, in this paper a three-dimensional finite difference method was adopted in a simplified way. The analyses have been performed by the code FLAC3D (Version 5, Itasca, 2012).

In the analyses of the cavity the geometry of the cavity has been simplified assuming that the pillars have their lateral surfaces inclined ±15° to the vertical from the roof' to the present fill level (PFL), while they are vertical till the base (OL).

The soil profile, starting from the top of the hill, is composed by pyroclastic soil (“pozzolana”) overlying pyroclastic soft rocks (NYT). Over the floor of the cavity a fill as described above has been considered. The materials have not yet been deeply investigated, especially for the debris that is indeed very peculiar. The mechanical properties adopted in the calculations are the average values available in the literature for Neapolitan materials (Evangelista et al., 1998; Picarelli et al., 2006), and are reported in Table 2.

Due to the lack of sufficient information about the discontinuities in the tuff, the properties of the intact material have been assumed for the rock mass. The materials were modelled as elastic-perfectly plastic, using the Mohr-Coulomb failure criterion.
The finite difference mesh adopted is shown in Figure 5. The mesh relates to the different possible configuration assumed by the cavity during its life:

a. the ancient cavity at the end of the mining works;
b. the present configuration after the slow filling with debris material.

The elements are square bricks of 100 cm and u-wedge (of the same dimensions) for the inclined walls of the portals, for a total of about 300,000 elements.

The boundary conditions are: at lateral boundaries the horizontal displacements prevented at the lateral boundaries, no displacement at the bottom. These hypotheses have almost negligible effects in our case, since a very low value of the Poisson’s ratio has been assumed.

The analyses don’t take into account the consolidation work, carried out in 2002, and which affected the roof in the entrance to the cavity and the last septum (SE4) in the nave of the Priests (Navata del Preti in Figure 4).

### RESULTS

The numerical analyses have been carried out in three phases:

1. evaluation of the initial state of stress in the hill \( k_o = 1 - \tan\phi \) before the underground opening;
2. excavation of the tuff up to the old level (OL) in steps of 20 m in longitudinal and transverse directions;
3. filling up to the present ground floor (PFL at 72 m a.s.l.) in three steps.

The results reported are expressed in terms of the vertical stresses, maximum shear stress and plastic zones in the horizontal section at OL and PFL and in the vertical section reported in Figure 3.

Figure 6 shows the vertical stress at the end of the three stages analyzed, at the section shown in Figure 3. It may be observed that the pillars are more loaded at the end of the phase 2 than after the refilling by the debris material, due to the presence of shear stresses at the interface between them.

The contours of the vertical stress in the pillars at the end of the phase 3 (present configuration) is reported in Figure 7 with a plan view of the 3D model at the PFL. It appears that the weight of the cover material is unevenly distributed on each pillar and septum; the structural elements that support the greater thickness of coverage result the most heavily loaded.

In Figure 8 the history of the vertical stress during the three phases analyzed are reported for the pillars P1, P2, P3 and P4 at the PFL. The load on the pillars grows from phase one to three with a delay depending on the mining procedure adopted.

### Table 2. Mechanical properties of materials adopted.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \gamma ) kN/m(^3)</th>
<th>( E ) kPa</th>
<th>( v )</th>
<th>( \phi ) °</th>
<th>( c ) kPa</th>
<th>( \sigma_t ) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pozzolana</td>
<td>15.0</td>
<td>1.96e+5</td>
<td>0.30</td>
<td>33</td>
<td>15.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Tuff</td>
<td>14.0</td>
<td>9.81e+6</td>
<td>0.17</td>
<td>29</td>
<td>80.0</td>
<td>9.8</td>
</tr>
<tr>
<td>Debris</td>
<td>13.0</td>
<td>9.81e+4</td>
<td>0.37</td>
<td>25</td>
<td>0.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Figure 5.** Numerical models adopted; materials in situ and the possible sequence of excavations: (a) ancient cavity; (b) actual cavity.

**Figure 6.** Vertical stress at the end of the three phases analyzed: (a) initial state; (b) after excavation up to the OL; (c) after filling up to PFL.
Pillar 4 is more loaded than the other ones, due to its greater height and area of influence.

In Figure 9 the contours of the maximum shear stress in the cross-section of Figure 3 are reported. The maximum value occurs in the pillars P4 at the PPL, but it doesn’t reach the failure condition.

The computed vertical stress in the pillars are lower than those obtained previously with the simplified analyses and reported in Table 1. These results are confirmed by the shear stress distribution around the pillars after the filling of the cavity with debris materials (Fig. 9).

No dangerous stress state occur in the pyroclastic material that covers the tuff.

Figure 10 (a) reports the distribution of the plastic zones resulting from the computation; they are concentrated on the roof. The portions of the cavity mainly affected by tension failure are the “navata degli Appestati” and the “navata dei Pezzentelli”; in these galleries, the roof is interested by tensile vertical stress higher than the tensile strength of the tuff. This is in agreement with the distribution of the vertical stress on the roof, already reported in Figure 7, and with the in situ observations that show the presence of transverse cracks in the roof.

As said before, in the above analyses the influence of the fracture orientation and fracture persistence on the strength of the rock mass and its response to caving has been totally neglected.

An attempt to take it into account has been carried out, by modelling the rock mass with the ubiquitous joint technique.

Ubiquitous joint model is adopted here to account for the presence of weak plane. Yielding may occur either in the intact rock mass or along the weak planes, depending on the stress state, the
orientation of the weak planes and the material properties of the weak planes.

For the material properties of the joints the cohesion along the joints has been assumed equal to 265 kPa, the tensile strength to 2 kPa and the friction angle to 19°. Based on a preliminary analysis of the available data, the dip direction and dip of the weak planes are assumed respectively equal to 85° and 45°.

A comparison of the results obtained with this model with those previously reported shows that the state of vertical stress in the pillars is practically unaffected by the different models.

Substantial difference, on the contrary, have been found for the plastic zones in the roof. With the ubiquitous joint model, in fact, the tension failure condition spreads over the whole roof (Fig. 10b).

9 CONCLUDING REMARKS

The paper reports the story of one the most fascinating cavities of the subsoil of Naples, the Fontanelle Cemetery, which during 400 years of life experienced a series of events until it finds, in the modern age, its role as a place of worship for the population of the neighbouring districts.

The paper mixes historical, urban and social aspect, as well as technical results on the stability conditions of the cave.

A numerical study is presented to evaluate the stress state conditions around the cavity, carried out by the finite difference code FLAC3D Version 5 (Itasca, 2012). Through these numerical analyses, it was tried to reproduce the present state of stress of the structural components, taking into account the sequence of the excavations and the subsequent filling up of the cavity with human rests and debris of mud, till the present ground level.

The comparison between elasto-plastic numerical 3D analyses and a 2D rigid-plastic limit analysis confirms that the latter is conservative. The simple procedures, however, keep their validity if coupled to sound ‘Engineering judgments’. Two different failure criteria (Mohr Coulomb and ubiquitous joint) have been also adopted to evaluate the influence of weakness plane.

Due to the lack of an accurate and updated mechanical characterization of the materials, the results obtained represent but a rough estimate, which highlights however the occurrence of a critical situation in the cavity roof. It is believed, therefore, that the cavity should be subjected to furthermore complete and reliable investigations and analyses.

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REFERENCES


