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Ground-penetrating radar investigation of St. Leonard's Crypt under the Wawel Cathedral (Cracow, Poland) - COST Action TU1208

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The Wawel ensemble, including the Royal Castle, the Wawel Cathedral and other monuments, is perched on top of the Wawel hill immediately south of the Cracow Old Town, and is by far the most important collection of buildings in Poland. St. Leonard's Crypt is located under the Wawel Cathedral of St Stanislaus BM and St Wenceslaus M. It was built in the years 1090-1117 and was the western crypt of the pre-existing Romanesque Wawel Cathedral, so-called Hermanowska. Pope John Paul II said his first Mass on the altar of St. Leonard's Crypt on November 2, 1946, one day after his priestly ordination.

The interior of the crypt is divided by eight columns into three naves with vaulted ceiling and ended with one apse. The tomb of Bishop Maurus, who died in 1118, is in the middle of the crypt under the floor; an inscription "+ MAVRVS EPC MCXVIII +" indicates the burial place and was made in 1938 after the completion of archaeological works which resulted in the discovery of this tomb. Moreover, the crypt hosts the tombs of six Polish kings and heroes: Michał Korybut Wiśniowiecki (King of the Polish-Lithuanian Commonwealth), Jan III Sobieski (King of the Polish-Lithuanian Commonwealth and Commander at the Battle of Vienna), Maria Kazimiera (Queen of the Polish-Lithuanian Commonwealth and consort to Jan III Sobieski), Józef Poniatowski (Prince of Poland and Marshal of France), Tadeusz Kościuszko (Polish general, revolutionary and a Brigadier General in the American Revolutionary War) and Władysław Sikorski (Prime Minister of the Polish Government in Exile and Commander-in-Chief of the Polish Armed Forces). The adjacent six crypts and corridors host the tombs of the other Polish kings, from Sigismund the Old to Augustus II the Strong, their families and several Polish heroes.

In May 2015, the COST (European COoperation in Science and Technology) Action TU1208 "Civil engineering applications of Ground Penetrating Radar" organised and offered a Training School (TS) on the "Applications of Ground Penetrating Radar in urban areas: the sensitive case of historical cities." The Action TU1208 is coordinated by "Roma Tre University" (Rome, Italy) and the TS was hosted by the Cracow University of Technology (Cracow, Poland). It was attended by 25 PhD students and early-career investigators coming from Albania, Belgium, Germany, Italy, Poland, Romania, Russia and Slovenia. Trainers and Trainees had the great honour and privilege to carry out practical sessions in St Leonard's Crypt, in cooperation with the companies Restauro (Toruń, Poland) and Geoservice (Athens, Greece).

Over the centuries, city centres have been continuously changing, developing and adapting to the requirements of society, architectural planning and advancing technology. Under the pressure of urbanisation, many cities and towns have significantly expanded and the limited space in their centres has been exploited more intensively. The shallow subsurface of historical cities is nowadays a very complicated scenario including reams of pipes, cables, rubble, bars and slabs of reinforced concrete, backfilled excavation trenches and pits, cellars, wells, cavities, tunnels, graves, walls and foundations of former houses, churches, monasteries, town fortifications, along with several other modern and ancient structures and manufacts. For the prospection of such a diversified, multilayered, intricate and complex underground environment, both for archaeological and civil-engineering purposes, Ground Penetrating Radar (GPR) is a very effective non-destructive geophysical method. GPR is a powerful tool not only for the prospection of subsurface but also for the non-invasive testing of historical buildings, fountains, historical bridges, sculptures, frescoes, pottery and other objects collected in museums: it can give information about their state of preservation, it can significantly help to address a restoration project properly, and sometimes it can also help to achieve information of historical interest.

The TS presented an insight into the challenges, advantages and potential of GPR prospection in historical cities. Data examples from urban historical centres were presented and discussed. An introduction to electro-

magnetic modelling of GPR was provided. To widen the perspective, the school included an introduction to urban remote sensing, describing how high-resolution satellite imagery or alternative sources of image date can be exploited for urban feature extraction, to analyse population, energy use, and other aspects of the urban environment.

In this work, data collected in St Leonard's Crypt will be presented for the first time. The activities focused on surveying the floor of the crypt, in order to obtain an image of the tomb of Bishop Maurus, verify whether further cavities were present and collect information about the subsurface of the crypt. GPR scans were taken on a 20 cm x 20 cm grid. Subsequently, an interesting area of smaller extent was chosen, where further data were collected on a 10 cm x 10 cm grid. We found out that the tomb of Bishop Maurus is shifted with respect to the inscription placed in the middle of the crypt and supposed to indicate its position. We could also detect the presence of another large cavity and estimate their size. All measurements were performed by using a CX-12 GPR pulsed system of MALA Geoscience.

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