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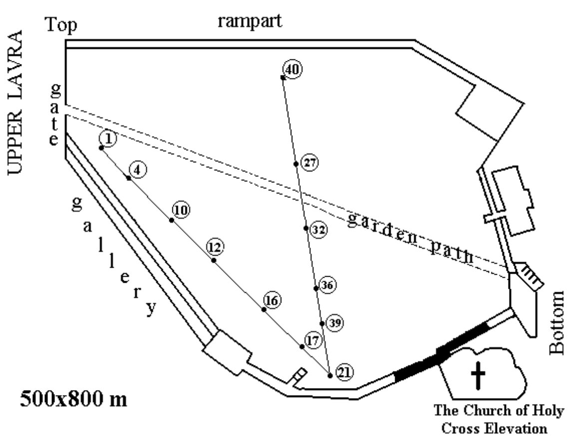
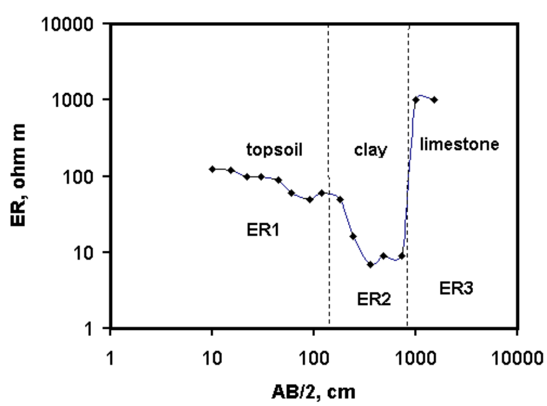
Electrical geophysical methods to study subsurface water movement in urban areas

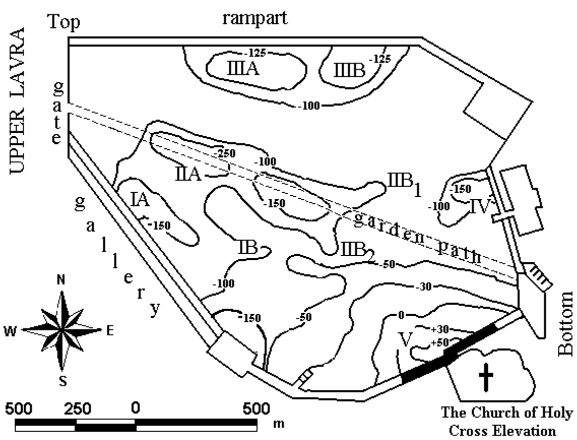
Hazardous hydrological situation caused by unknown factors appeared in Kiev-Pechersk Lavra (Kiev, Ukraine) near The Church of Holy Cross Elevation in 1987. The church was built in 1700 above the holy caves, a place of pilgrimage of Russian Christians since XI century. The monastery is located on the high bank (near 200-m height) of the Dnipro river. The core of the bank is formed by limestone, which is covered by Quaternary deposits of loamy sand and sandy clay loam textures. The soil within a Patriarch garden was classified as eroded ordinary chernozems (Haplic Chernozems, FAO-UNESCO; Argiudolls, USA Soil Taxonomy). The caves are formed naturally in limestone and extend 228 m in length, with various depths from 5 to 20 m. The groundwater penetrated in the caves and partly destroyed wall frescoes and other masterpieces in the caves and church interiors. The problem was attributable to temporary subsurface water fluxes fed by precipitation. Excess water accumulated in subsurface in spring because of snow melting and in summer during intensive rainfalls. Due to the hill topography, water could accumulate in soil covering the whole territory of Upper Lavra and then flow into the Patriarch Garden as shallow subsurface fluxes.

We used the vertical electrical sounding (VES) and electrical profiling (EP) methods to investigate the properties of water-bearing and waterproof layers essential for the development of the subsurface water fluxes. The directions and intensities of the fluxes were evaluated with the self-potential (SP) method (LandMapper ERM-02 can be used).





The VES and EP methods revealed complex stratification of the hill slope in the Patriarch garden near The Church of Holy Cross Elevation (Figs). All the VES curves revealed three-layer soil profile with apparent $ER_1 > ER_2 < ER_3$. The top layer was represented by the eroded Chernozem of coarse textures with electrical resistivity (ER_1) about 125 ohm m for loamy sand and about 50 ohm m for sandy clay loam. The second layer was a thick clay layer (7 m) with low electrical resistivity (ER_2) from 2 to 16 ohm m. The clay was saturated and gleyed in some places, which was indicated by 2 ohm m resistivity. The third layer with the resistivity (ER_3) about 2000 ohm m was horizontally deposed limestone. The results of sounding were verified with boring at the same 12 locations. The thickness of clay layer decreased from 8 to 2 m along the line from the top of the hill to the tier wall. The low and almost constant electrical resistivity (8 ohm) for the AB/2 from 3.6 to 7.2 m for the second layer shown that clay did not bear any intrusions of sand or sandy loam, which was verified with boring. Therefore, water flow inside second layer was impossible. The water flow could be formed only in the topsoil over the layer of waterproof clay.



Although undetectable on the surface, three gullies were revealed in the second layer of waterproof clays by the VES and EP methods. The subsurface water flow could be formed in such gullies. The method of self-potential was used to estimate water flux directions and intensities through the measured variation in electrical potential on the soil surface. An iso-potential map (Figure) was developed with the method on a 5 x 10 m grid; 299 locations were measured with five replications. Three major iso-potential areas detected from the figure. Two areas with negative potentials were formed near rampart and along the gallery (including the garden path) and indicated the areas of water infiltration into the soil and development of groundwater flow (I, II, and III). The third area with positive potentials outlined the seepage zone near The Church of Holy Cross Elevation (V). The most negative potentials (-250 mV) along the garden path indicated the most intensive subsurface water flow in this area (IIA, IIB_1, and IIB_2). The –250-mV iso-potential area developed in surface peaty sand with electrical resistivity (ER_1) about 170 ohm m. The less negative potentials (-150 mV) and, therefore, the less intensive water flow occurred near the gallery (IA and IB). The same negative potential areas were detected in the middle of the garden path and near the rampart (IIIA, IIIB, and IV). The seepage area was outlined by the 0-mV iso-potential near The Church of Holy Cross Elevation (V). The seepage area was enriched with clay material having electrical resistivity about 5 ohm m. The percentage of clay in the soil increased toward the corner of the church along with the electrical potential.

To protect The Church of Holy Cross Elevation, the following procedures were proposed based on our geophysical exploration near the architecture memorial. First, a hedge should be constructed across the gate to the garden to prevent the surface water flow to the Patriarch Garden from the pavement of Upper Lavra. Second, a small dike should be built perpendicular to the gallery and the garden path to direct subsurface water flow from fluxes II and I into the drain system. Third, to enhance evapotranspiration, trees and bushes with the intensive transpiration ability, such as willows and poplars, should be planted along the gallery and rampart, especially in the areas indicated by low potentials. All the measures were implemented in 1990 and still provide adequate preservation for the church and the surrounding caves. The cost of the proposed measures was about one twentieth of the previous construction of concrete wall, which, nevertheless, did not solve the problem of water penetration into the caves.