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Water Reservoir Within the Karst Field Overburden: Gusić Polje, Croatia

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Abstract

The Gusić reservoir is a compensation basin constructed in the karst field. The reservoir lies on a Quaternary overburden free of ponors (sinkholes) and suffosions. After the reservoir filling the water losses were up to <6.4 m^3/s. The bottom impermeability has been ensured with a 0.4 m thick clay base blanket. During reservoir exploitation, suffosions and ponors developed through which 2 m^3/s water was lost. Such conditions required reservoir repair within a short time frame of approximately 10 days during which the power plant was shut down. When the reservoir was emptied, a resistivity sounding (Wenner electrodes arrangement at five depth levels) was conducted on the reservoir bottom and clay blanket. An alternative concept has also been considered - the construction of a new reservoir area that has similar hydrogeological conditions. The solution for the possible impact of groundwater (air) "pressure" could be the construction of a horizontal "vent" in the deepest part of the palaeodepression, where the bedrock karstification is the most intensive and the interrelation between groundwater and air pressure on the overburden is possible. The reservoir bottom impermeability could be resolved with a clay blanket or with synthetic materials.

1. INTRODUCTION

The Gusić polje compensation basin is part of the hydroenergetic system HP Senj and is used for daily levelling of natural inflows of the Lika and Gacka rivers. Although the basin is constructed in part of the polje where ponors and suffosions have not been found, after the test filling in 1965 the water losses were up to 6.4 m^3/s (ELEKTROPROJEKT, 1965[4], 1966[5]). Therefore additional embankments were constructed inside the basin and the remediation of basin with a clay carpet was undertaken. However, ponors have still been opening and closing during repair of the plant, and water losses are between 0.5 and 1.0 m^3/s, depending on the remediation level (ELEKTROPROJEKT, 1983[6]; PAVIČIĆ, 1986).

The compensation basin (Fig. 1) was constructed on the basis of prediction of the satisfactory water holding capacity of the Quaternary cover. Karstic limestone bedrock was not taken in consideration. It was left to the test filling to determine the water-retention of the Quaternary deposits, which was only done immediately before inauguration of the Senj power plant. The causes of detected water losses (6.4 m^3/s) were not found. For new losses, the technical solutions for remediation of places of water loss were determined. First of these appearances was the ponor in the bottom of the basin, with diameter of 2 m and depth of over 3 m. The following appearances had diameters up to 5 m and depth up to 6 m. Several causes for water loss were supposed - poor construction or non existence of clay carpet in the zone of the canal, as well as the existence of ponors underneath the Quaternary deposits. Also, occasional moisturizing of Quaternary deposits through carbonate bedrock is unfavourable for the stability of Quaternary deposits.

For the design of optimal remediation, which should be realized as soon as possible, geophysical investigations were performed (BENAMATIĆ et al., 1997[7]; PEŠT, 1999[8]). These investigations consisted of geoelectrical profiling and resistivity sounding. The aim of the investigation was to determine the thickness and lithological composition of the cover deposits and karstification of the carbonate bedrock. To determine the dominant directions of groundwater seepage and zones of water sinking from the basin, the self potential mea-

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[4] ELEKTROPROJEKT (1965): Pojave ustanovljene kod pokusnog punjenja bazena Gusić polje.- Unpubl. report, Archive of Elektroprojekt, Zagreb.

[5] ELEKTROPROJEKT (1966): Mjerenje procjednih gubitaka u Gusić polju.- Unpubl. report, Archive of Elektroprojekt, Zagreb.

[6] ELEKTROPROJEKT (1983): Sanacija kompenzacijskog bazena Gusić polje - hidrogeološki radovi.- Unpubl. report, Archive of Inst. of Geology, 12/93, Zagreb.

[7] BENAMATIĆ, D., DUJMIĆ, D., KASAPOVIĆ, S., PEŠT, D. & SALKOVIĆ, A. (1997): Kompenzacijski bazen Gusić polje, geofizička istraživanja.- Unpubl. report, Archive of Moho, Zagreb

[8] PEŠT, D. (1999): Kompenzacijski bazen Gusić polje, mjerenje vlastitog potencijala.- Unpubl. report, Archive of Moho, Zagreb.

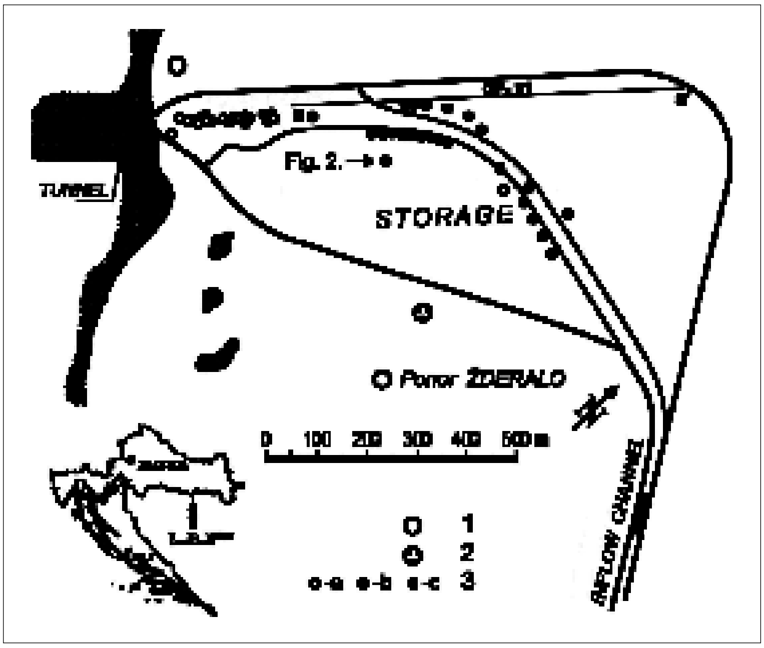

Fig. 1 Location map and hydrogeological map of the Gusić Polje reservoir. Legend: 1) ponor (swallow hole); 2) suffosion phenomenon; 3) suffosion ponnors: a) hole appeared once, b) hole appeared twice, c) hole appeared many times.

suring on the whole area of the basin was foreseen. Conducting of self potential measuring was planned during the normal work of the power plant in a basin full of water. Geoelectrical methods were chosen, because of their speed and of the non-destructive characteristics of indirect (surface) investigations.

2. HYDROGEOLOGICAL RELATIONS

The area of Gusić polje is built of limestones of Jurassic age with interbeds and lenses of dolomite (VELIĆ et al., 1974). There were clays deposited on them, with thickness up to several metres, depending on the palaeorelief of the polje. The clays are covered with younger travertine-silty deposits of variable degrees of lithification. The average thickness is 1-2 m.

The permeability of silty travertine is $k = 10^{-4}$ cm/s and of clay is $K = 10^{-6}$ to 10^{-7} cm/s. Clayey marls are determined as impermeable rocks. During the remediation it was seen that inside the silty travertine small channels could develop and on the border with clay, the concentrated flow of groundwater towards the ponors (suffosions) could emerge.

Newly formed ponors and suffosions appear in the part of polje where the Quaternary deposits have the greatest thickness. Once repaired the appearance of sinking in that part of polje usually reappears.

The existing water level data show sudden decrease of water table in the area with thick marl clays, which exist up to 396 m above sea level, i.e. 36 m below the surface of polje. Upstream from this clay barrier, water levels are always higher than at this spot height. Downstream, before the construction of the basin, the lowest level was ten or more meters below that spot height, and the highest one was in the level of polje (around 432 m above sea level). Today the differences between minimum and maximum levels downstream of the deepest clays are smaller and they differ in range from 386 to 413 m above sea level, and exceptionally between 364 and 377 m above sea level along the south border of polje.

Geomorphological processes, which led to the present hydrogeological characteristics of Gusić polje, are connected with karstification of the wider area and the escarpment of the Gacka karst river, which flows through the polje. The first ponors in Gusić polje were developed during the modelling of palaeorelief (at the end of Pleistocene), before the deposition of Quaternary sediments (PRELOGOVIĆ, 1989; PAVIČIĆ & RENIĆ, 1992). It was then that the basic underground drainage net was developed. The depth of karstification was gradually increased, and in the dry period the water level decreased over 50 m below the polje. Due to the erosion of the clay material through the canals of ponors in weathered rock, the unstable conditions in Quaternary deposits began (PAVIČIĆ & FRITZ, 1995).

At sudden changes of groundwater level the conditions for appearance of pressure and under pressure exist. They have probably greater values after the clay carpet was made, because natural ventilation conditions were changed. Washing out of clay and travertine silt on the contact with the palaeorelief increased as well as the genesis of holes that lead to caves in ponors (Fig. 2).

The water holding capacity of the basin, based on the water holding of Quaternary deposits, was not realistic. By subsequent construction of the clay carpet, the losses were reduced, and additional losses are attributed to lack of clay carpet below the supply canal and

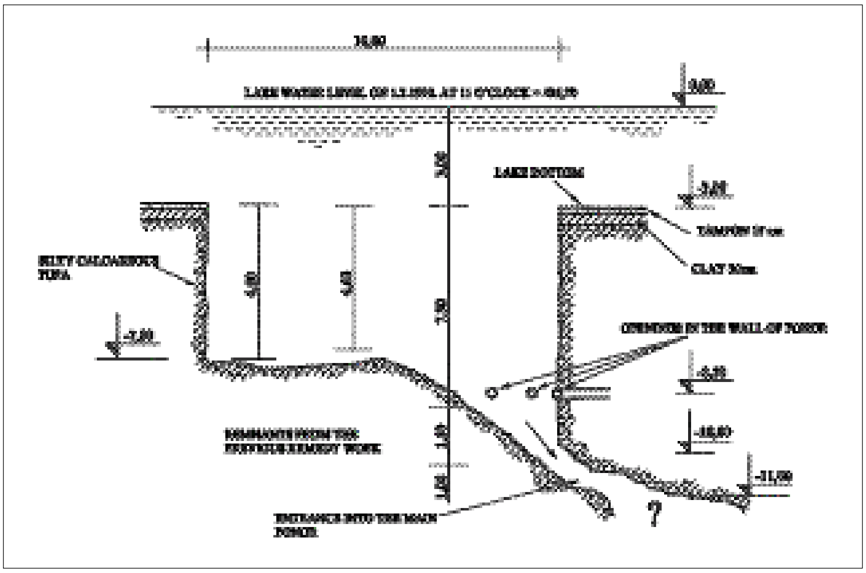

Fig. 2 Ponor within the Gusić Polje reservoir.

accompanying embankments and locally to an incomplete clay carpet in the basin.

Shallower suffosions along the canal and accompanying embankments, after the remediation do not reappear. The majorities of ponors (suffosions), that appear, that are repaired and then reappear, are inside Quaternary deposits thicker than 6-7 m, i.e. inside the depressions in palaeorelief, which is connected with reactivation of old ponors, that have been active before the sedimentation of Quaternary deposits. At the same time, these are basic dangers for water losses and genesis of cave in ponors (PAVIČIĆ, 1992[9]).

Without the investigations within the area of the basin, a method of complete remediation of the basin is impossible to perceive. Due to the short period of time when the basin is empty (during the annual repair) it was necessary to select the geophysical method of investigations that can be applied when the basin is full of water. Therefore, with methods that are conveyed on dry land, the self potential method was successfully used.

3. GEOPHYSICAL INVESTIGATIONS

During the repair of the plant the investigation of the bottom of basin - clay carpet, was carried out using non-destructive geoelectrical methods (BENAMATIĆ et al., 2000). On the old accumulation (G.P.I.), the investigation of the thickness of artificial clay carpet was carried out, in the conditions of empty accumulation, using geoelectrical profiling and Wenner electrodes, at five levels of depth.

The tectonic structure of the polje beneath the bottom of the basin (carpet and bedrock) was investigated with a net of geoelectrical sounds with AB/2=50 m with Schlumberger position of electrodes, because the geology of the polje was known from previous investigations. In conditions when accumulation was full the measuring of spontaneous potential was carried out. The aim of this method was to locate the positions where the water was lost, in order to establish zones in the accumulation area, for the design of basin remediation. Realization of new accumulation on the part of the polje outside the present accumulation, with similar hydrogeological conditions, was considered as an alternative solution. On that future accumulation, the undisturbed systematic investigations are possible, as well as solutions, based on experience in karst terrains and previous investigations for a new basin.

3.1. Resistivity sounding and geoelectrical profiling

Resistivity sounding should determine the thickness of Quaternary deposits (travertine, clay and calcareous clay) with poor geotechnical characteristics. According to present acknowledgments, new ponors and suffosions occurred in the part of the polje where the Quaternary deposits are thickest, i.e. inside the depressions in palaeorelief, as the result of reactivation of old ponors, which were active before the sedimentation of Quaternary deposits. For that purpose some 200 geoelectrical measurements with Schlumberger position of electrodes (AB/2=50 m) were conducted over the whole basin area, positioned in rectangular net with inner distances of 40 m.

Figure 3 shows the characteristic geoelectrical cross-section GP-21. The results of sounding confirmed the existence of distinguished palaeodepression in carbonate bedrock and determined its strike. According to

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[9] PAVIČIĆ, A. (1992): Sanacija kompenzacijskog bazena Gusić polje - hidrogeološki radovi.- Unpubl. report, Archive of Inst. of Geology, 80/92, Zagreb.

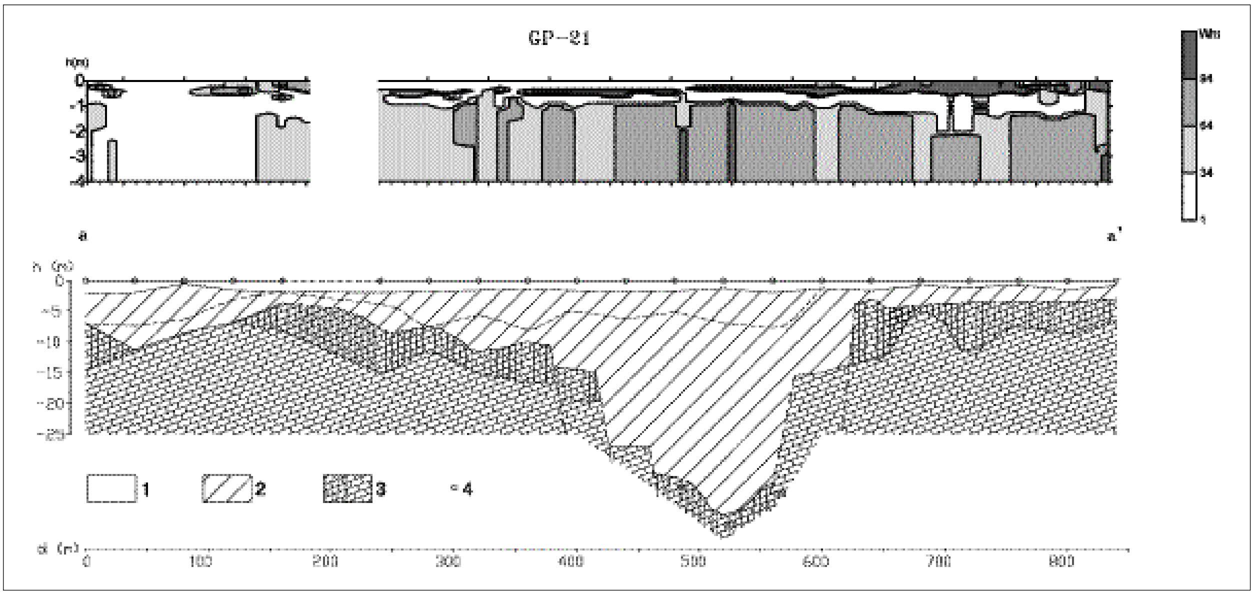

Fig. 3 The characteristic geoelectric profile (GP-21) with results of geoelectric profiling (upper part) and vertical electrical sounding (bottom). Legend: 1) 20-1400 Ωm, surface layer; 2) 25-70 Ωm, quaternary deposits; 3) 65-420 Ωm, limestones; 4) fault determined by geological and geophysical investigations.

these results, ponors are connected to the drainage net from the time of palaeodepression, which is at present time the basis for groundwater outflow from Gusić polje. However, smaller ponors (suffosions) appear on the surface outside the deepest parts of the palaeodepression, but they are connected with ponors inside the palaeodepression.

The priority of geoelectrical profiling was to determine the condition of the protective rock aggregate and clay carpet. According to the design, a protective rock aggregate (with thickness of 15 cm) and impermeable clay carpet (with thickness of 30 cm) were constructed over the whole area of the basin. It was foreseen that the mud thickness is around 10 cm. Such an arrangement of layers is favourable for geoelectrical investigation methods, because between two layers with low resistivity (clay and mud) there is a layer with high resistivity (protective rock aggregate). Geoelectrical profiling was adapted to such, expected, arrangement of layers: five spacing of electrodes (depths) - 0.25, 0.5, 1.0, 2.0 and 4.0 m.

Geoelectrical profiling was conducted on 1540 measuring locations positioned in rectangular net with sides 20 x 10 m, covering the whole area of the basin, except the inflow canal and accompanying embankments. The computer controlled measuring instrument with Wenner offset arranged electrodes was used for five mentioned depth ranges. In this way the average efficiency of 180 measuring points per day was accomplished, which is significant because of the limited period of access to the basin during the plant repair.

The biggest problem during the measurement and interpretation of results was the fact that the humus sediment on the rock aggregate was significantly thicker than the predicted 10 cm. Locally, along the edge of the supplying canal, it reached values of 70 cm. Sediment 40 cm thick physically slowed measuring and during the interpretation it decreased the expected differentiation of layers, because of the relatively smaller thickness of the remaining two layers. Therefore, the planned range to investigate depth lost the initial objective, because the first of depth of 0.25 m stayed in the layer of humus.

The measuring results were supposed to isolate zones of damage in rock and clay layers with tendency to form a ponor. However, the results suggested that the cause of water loss was not damage, but an incomplete protective carpet on the bottom of the basin and along the central embankments. According to the measuring results (Fig. 4) in the northeast part of basin, low values of resistivity, which correspond to the clay carpet were not recorded. Measured high values were not from protective rock aggregate, but from indigenous travertine cover below the humus layer. As this part of the basin is on higher spot heights than the rest, and as it is not always under water, the ponors do not emerge here, but water probably seeps through travertine not allowing further filling of the basin.

Similarly along the base of the inner embankments, resistivities that correspond to the protective clay carpet were not recorded. This is in accordance with the facts that the majority of new ponors appeared along the base of the inner embankments, and that those embankments were built before the clay carpet was placed on the bottom of the basin. The above mentioned conclusions should be verified through direct investigations.

The results of geoelectrical profiling were reinterpreted as small geoelectrical sounds to better determine

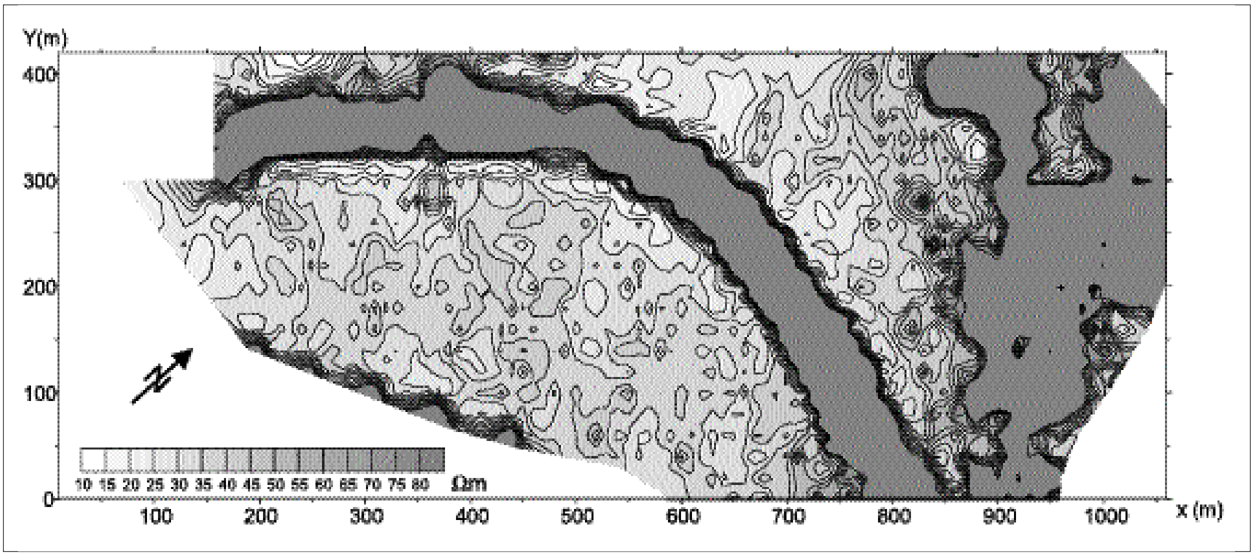

Fig. 4 The results of geoelectrical tomography for depth level of 0.5 m. The dark tone represents sector with high electrical resistivity, and therefore it belongs to the zone where clayey carpet is damaged or missing.

the extent of particular materials in the surface part of the bottom of the basin. A hypothetical model of extent of particular materials, with variable layer thickness and resistivity, was used. In this way we obtained the spatial arrangement of real resistivities, by which the possible areas of protective layer damage were isolated as layer discontinuities. This procedure did not show new, significant areas of damage, besides those already isolated, but it enabled easier inspection of the measured results. On Fig. 3 the extension of particular sediments can be traced below the protective layer and separating the areas of low resistivity with clay sediments, from the areas of high resistivity, where travertine deposits are just below the protective layer.

3.2. Self potential

To determine the dominant directions of groundwater seepage and zones of water sinking from the basin, the measuring of self potential through the whole area of basin was foreseen. Conduction of measurement was planed during the normal work of the power plant with the basin full of water. Measuring of self potential was conducted on 1680 locations positioned into rectangular net dimensions 10x20 m, covering the whole area of basin. By that, one electrode was used as a reference point outside the basin and the other electrode was lowered to the bottom of the basin. The characteristic fact for this type of investigation was the low deviation of the measured values during the study (the values were "calm" and "stable") and showed only a small variation along the cross section (low gradient of SP). Calculated values of SP are shown on the map of self potential field (Fig. 5), which shows that the canal is clearly distinguished with lower values of potential (dark) and some anomaly minimums. Low values of potential are zones from where the water is sinking into the lower areas. Because the water is above the ground in this case, the areas with minimum values of potential would be the places of sinking of water into the ground. Anomalies of especially low values of potential do not have to mean that the sinking is proportionally expressed at those locations. In contrast, it is interesting to notice that mainly greater values of potential are recorded on the accompanying embankments in regard to other areas. This indicates seepage of water from the surrounding areas towards the embankments. The same is valid for the outer embankments toward which the values of potential increase. Besides, on the areas of additional basins (north and south) there are no anomalies in potential values, but the recorded values are uniform leading to the conclusion that no new ponors have emerged in those areas.

If we compare the results of geoelectrical profiling and self potential, we can conclude that the area of increased resistivity (dark) follows the area of increased potential fairly well, especially along the north edge of the basin. There, the zone of low resistivity, extending like a narrow band, is identical to the local minimum of self potential. Consequently, the locations of high resistivity are the zones towards which the groundwater flows, probably through the surface layer. This confirms the presumption that the clay carpet was not constructed on that location.

The investigations for a new basin have been completed. The refraction survey, gama and gama-gama logging were used among the methods of applied geophysics. The goal of the geophysical investigations was to separate the cover deposits from the bedrock (refractor).

The whole polje was covered with 135 spacings of 100 metres, set in 21 profiles, which enabled the investigation down to a depth of 40 m. On the basis of the

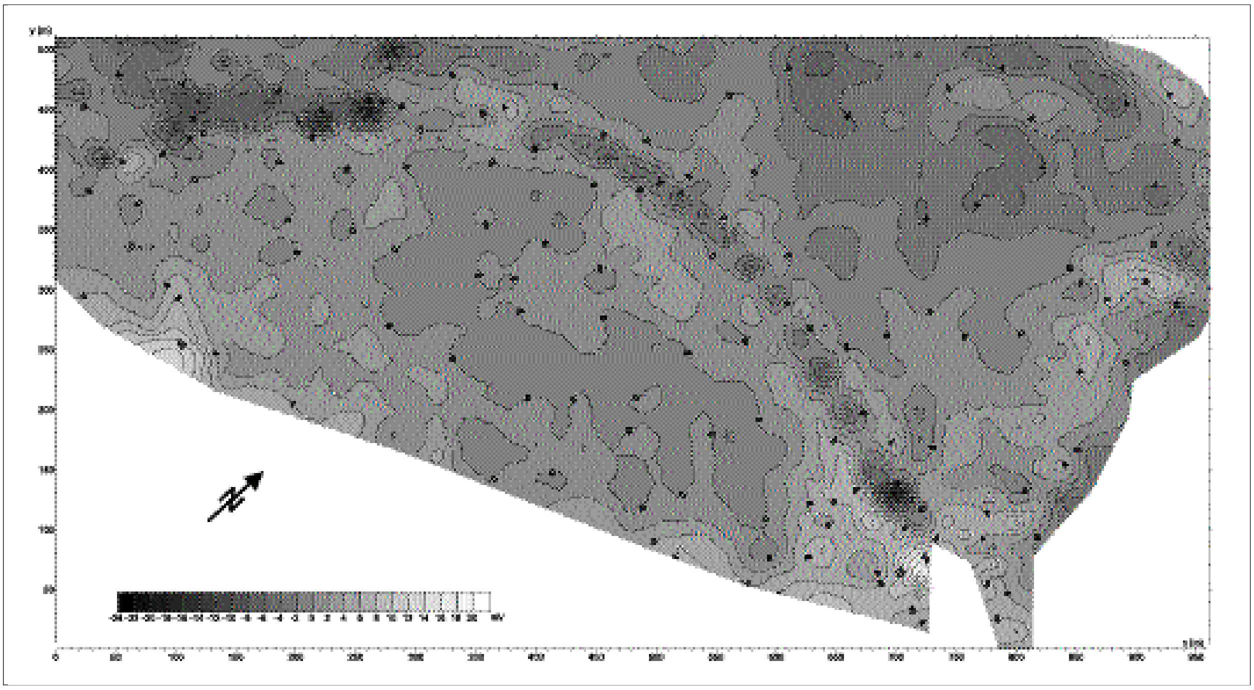

Fig. 5 The spontaneous potential map. Supposed groundwater flow is from dark toward white areas.

refraction survey in a new basin, 9 investigation boreholes were located, to verify and correlate borehole and seismic data. Using the results of the refraction survey, maps of surface complex thickness (cover) were made, as well as a map of deposit thickness above the hard basic carbonate rock massif.

Also, a map of velocities in upper part of basic rock massif was produced, which includes the velocity range from 1400 to 4000 m/s.

The anomaly zones are controlled with the borehole next to the recently active ponor on the surface, which verified the anomaly connected to the palaeorelief filled with travertine, which is in direct contact with the basic rock with poor mechanical characteristics and good permeability.

4. SUGGESTED REMEDIATION SOLUTIONS

4.1. Remediation of the existing basin

Based on the investigation results, it is determined that the highest seepages are in the area of the canal, which is covered with concrete plates under which a protective clay layer was not constructed. Due to the fact that investigations inside the basin are possible only during the annual one month reparation of the plant, the solution was chosen for remediation of the canal area, which can be performed in phases over several years. The economic-technical comparison of various possible solutions led to the choice of a method, that includes construction of a protective impermeable cover of the canal, made of foil which is laid on a geotextile layer with a density of 300 g/m^2 over the existing concrete plates of canal (Fig. 6). The foil is anchored in the canal bottom and on the slopes of accompanying embankments, where the connection between foil and clay carpet, in the form of a 5 m wide overlap is made.

The foil of CHD type is chosen (modified PHD - polyethilene high density foil used for potable water) due to ecological requirements, because water from the basin is also used for the public water supply.

In the areas inside the basin, where geophysical investigations determined the possibility of water loss or discontinuity of a clay carpet, a new clay carpet or the strengthening of the existing one is foreseen. The

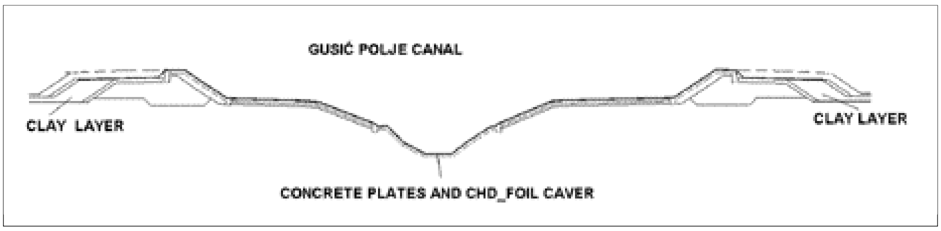

Fig. 6 Gusić polje canal cross-section.

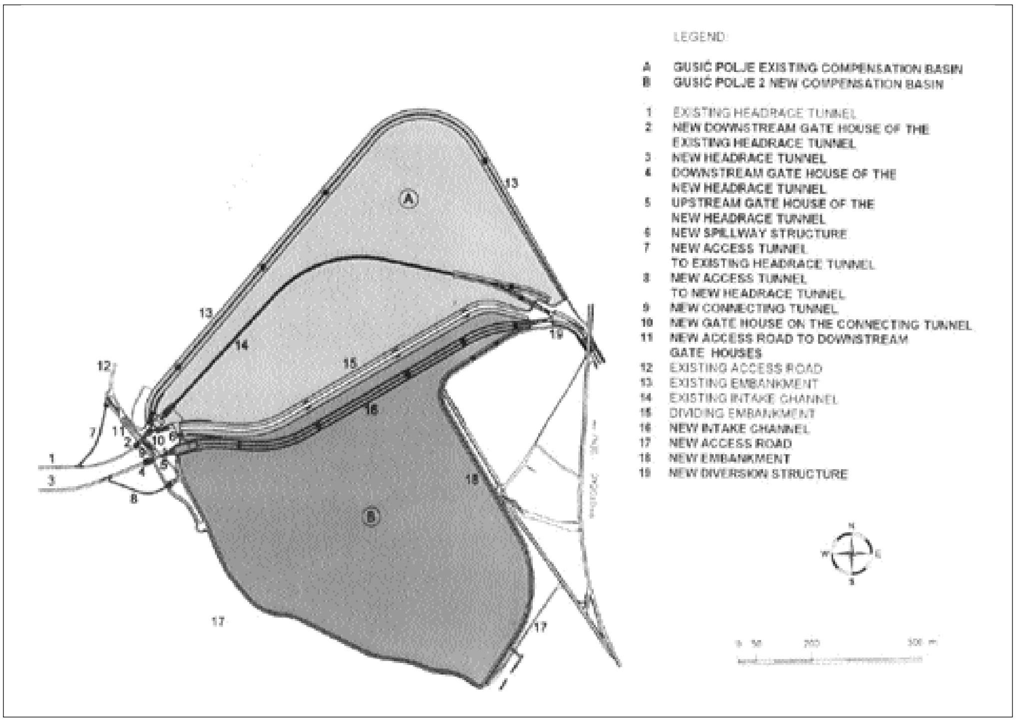

Fig. 7 Gusić polje basins layout.

whole remediation implies incorporating about 100,000 m^2 of foil and construction of about 120,000 m^2 of new clay carpet. The mentioned quantity of works is planned for a two year period during the annual interruption of plant work.

4.1. Building of a new basin

Due to the increase of installed flow of HP Senj, the building of a new compensation basin, 2.0 mil. m^3 in volume, is planned, next to the existing basin (Fig. 7).

This basin is planned to be built on similar geological foundations. Assurance of the water holding capacity of the basin bottom and embankment slopes was taken into consideration in the variant of using artificial materials and clay (Fig. 8). In the vicinity of the basin there is a source with sufficient quantities of quality clay, the economic-technical comparison of variants showed the worthiness of constructing the clay carpet with a thickness of 50 cm. The clay carpet is laid on the geotextile layer with the density of 500 g/m^2, which is laid on the neat and compacted bottom of the basin. It is also foreseen that the layer of geotextile with density of 500 g/m^2 will be laid on the surface layer of clay and then covered with layer of crushed rock 30 cm thick. The geological investigations determined several faults in the basin area, which in case of sudden changes in the groundwater level, could alter the pressure on the bottom of the basin. Therefore the possibility for draining the air below the clay carpet is foreseen, using the system of drainage tubes which are laid along the faults with exits on air slopes of embankment.

According to the available data on groundwater levels in the basin area, it could be considered that there would be no elevation of groundwater above the basin bottom, which, together with the aeration system, assures stability of the basin bottom.

5. CONCLUSION

By realization of surface accumulation in the karst polje, the water holding capacity of which is based on the impermeability of the Quaternary clayey-silty deposits, one should take into account the stability of the Quaternary cover. Therefore during the preliminary design phase, it is necessary to carry out extensive investigations to learn about the genesis of the terrain, hydrogeological relations and hydrological conditions that were present in the creation of the polje, as well as after the sedimentation of Quaternary cover. Besides surveying boreholes and measuring groundwater levels, it is necessary to perform geophysical investigations to estimate the thickness and lithological composition of the cover, as well as the condition and karstification of the carbonate bedrock. To solve the problem of the water holding capacity of the basin and remediation of losses through suffosions in already existing basins, geoelectric investigation methods have proved to be suitable in the conditions of exploitation when the investigation is time limited and the bottom of the basin is covered with soft deposits. The self potential method applied on the basin filled with water recorded traces of water seepage and sinking.

The results of geoelectrical methods and self potential method separated problematic areas, the primary one being the canal zone and accompanying embankments, where increased values of resistivity and anom-

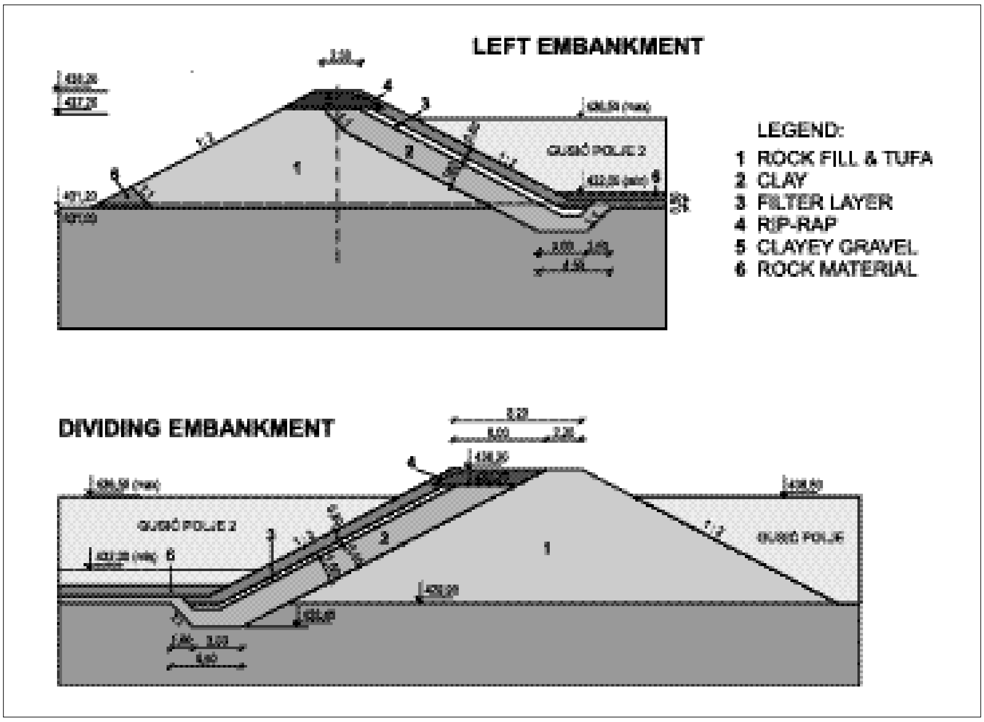

Fig. 8 Gusić polje basin embankments.

aly values of potential were recorded. This confirms that in this particular location the clay carpet was not fully constructed and water seeps toward that area. In the central parts of the accompanying basins the anomalies of self potential that would suggest the appearance of new ponors were not recorded, but according to geophysical investigations no significant damage of the clay carpet was recorded. It should be emphasized that the biggest problem for realization of the water holding capacity of surface accumulations in the karst polje is the stability of the bottom of the basin, because water holding can be solved with artificial materials, but without stability of the foundation, there is no permanent solution for undisturbed exploitation of the object.

6. REFERENCES

BENAMATIĆ, D., PEŠT, D. & PAVIČIĆ, A. (2000): Doprinos geofizičkih istraživanja pri lociranju gubitaka vode iz bazena Gusić polje.- In: VLAHOVIĆ, I. & BIONDIĆ, R. (eds.): 2nd Croatian Geological Congress, Cavtat-Dubrovnik, Proceedings, 525-530, Zagreb.

PAVIČIĆ, K. (1986): Teškoće u radu kompenzacijskog bazena Gusić-polje i njihovo uklanjanje.- Energija, 35/4, 275-278, Zagreb.

PAVIČIĆ, A. & FRITZ, F. (1995): Water holding of compensation basin Gusić polje.- In: VLAHOVIĆ, I., VELIĆ, I. & ŠPARICA, M. (eds.): 1. Croatian Geological Congress, Proceedings, 2, 431-434, Zagreb.

PAVIČIĆ, A. & RENIĆ, A. (1992): Recent karstification and water drenage from Bakovac Vally (Lika, Croatia).- Int. symp. “Geomorphology and Sea”, Mali Lošinj, Proceedings, 127-133, Zagreb.

PRELOGOVIĆ, E. (1989): Neotektonski pokreti u području sjevernog Velebita i dijela Like.- Geol. vjesnik, 42, 133-147.

VELIĆ, I., BAHUN, S., SOKAČ, B. & GALOVIĆ, I. (1974): Osnovna geološka karta SFRJ 1:100000, list Otočac, L33-115 (Basic Geological map of SFRJ, Otočac Sheet).- Inst. geol. istraž., Zagreb (1970-1974), Sav. geol. zavod, Beograd.

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