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SUMMARY

More than 500,000 km of embankment are used in Europe for transport and flood defence, representing a € 1bn infrastructure asset base, which supports and protects the economy of Europe (e.g. property worth some € 2,000 bn is protected from flooding.) Presently the state and performance of these embankments can only be investigated visually or by slow intrusive methods (boreholes etc.) Potential now exists to apply a geophysical investigation tool, originally developed for military applications, for rapid non-intrusive identification of ‘hot spots’ of deterioration in embankments. Better targeting of maintenance interventions using this approach will achieve substantial whole-life cost savings and avoid failures costly for the economy and society. Geophysical investigation involves generating electro-magnetic fields and mapping their propagation through soils and structures. The method finds perturbations in the electro-magnetic fields arising from concealed boundaries or changed materials.

Previous tools and approaches have shown limited effectiveness and poor data interpretation accuracy compared with conventional intrusive geotechnical investigation and description methods. Speed has been affected by the need to repeatedly remount transmitters and receivers. The new technology Geophysical Monitoring system (GMS), using GEM2 tool, could provide a breakthrough in an area of science in which infrastructure managers and engineers have been highly sceptical. Preliminary trials suggest the tool could identify soft spots and water leakage paths in embankments.
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1. Introduction to GMS development

1.1 Background

In the latest years we have witnessed increasing occurrence of extreme climatic changes. One of these is frequent and intensive rainfalls which create dangerous flood conditions in our rivers. That is why great attention has been paid to flood protection measures in river-basins, to the management of countryside water regime and to the development of water conditions information system applied to individual river-basins.

As a basic flood protection measurement, flood protection dikes which guide river waters in high level state are commonly used. Many EU and other countries have thousands of kilometres of such dikes. The experience with catastrophic floods from last decade show that the dikes quality and their geomechanical state often makes the difference in flooding vast land areas. But the dikes have been built for many decades. Often there is no basic construction documentation, no information on materials used and the question of “quality” level of construction work can be only speculated on. This applies mainly to Eastern European and developing countries. The dikes condition is only checked visually (if at all), which has lately been supplemented by aerial and satellite pictures analysis (in well developed countries). These checks only reveal significant and visible defects and this is often not until the dangerous water leaks occur.

The insufficiency of dike checks can be largely eliminated by using the proper set of geophysical measurements. Geophysical research methods are non-destructive, relatively cheap and provide basic information on dike construction and materials used. Such usage of geophysical research for dike checks has been studied by project IMPACT, part WP6. This project has been financed by European Commission within the 5th framework program. The Impact project output is a complex methodology of long-term observation of flood protection dikes condition using a set of geophysical methods summarised under the name GMS (Geophysical Monitoring System).

The main task during the monitoring system GMS preparation was the choice of optimal geophysical method for basic description of long dike sections within the whole river-basin (so called Quick Testing Measurement as a part of GMS). The suitable method had to fulfil several basic requirements. The most important requirement is to provide the high work productivity (the minimum limit was set at the value of 10 km per day) while keeping high sensitivity of the measurement and easy operation (trained laymen or the River-basin Office worker should be able to carry the measurements out). At the same time the measurement should provide usable information required by River-basin Offices.

The crucial factor for dikes condition monitoring is the repeatability of measured parameters. All these procedures have to be relatively low cost for River-basin Offices. After evaluating all these aspects the most suitable method was chosen, namely Dipole Electromagnetic Profiling (method DEMP = EFM) using unique multi-frequency apparatus GEM2 (manufactured by GEOPHEX USA).

The IMPACT project outputs are used by geophysical part of running project FLOODSite which undertakes the complex study of flood risks with respect to human lives and property protection. In compliance with IMPACT project recommendations and outputs the apparatus GEM 2 was bought for the FLOODSite project. The main task of geophysical part of FLOODSite project (into the Task 4) is to check the usability of DEMP method for GMS purposes in real conditions of specific river-basin. While the IMPACT project included the dikes tests in the length of tens of metres, now several kilometres long passages of dikes were tested. Suggested method has also been tested in real conditions of European river-basins.

As part of FLOODSite project – task 4 - we have also considered several possibilities of GEM2 tool testing in Vitava / Labe and other Czech stream river-basins and pond areas (for example Trebon fishery). Finally it has been proved that for the successful implementation of new embankments check method the help and willingness of specialists intended to use the GMS database results in future is crucial. That is why Odra River-basin was finally chosen again, because the co-operation with the River-basin Office employees and feedback there has been on a very high level.
2. GMS

2.1 Fast test measurement of flood protection dikes as a main part of GMS (Geophysical Monitoring System)

The analysis of flood protection dikes defects formation shows that with most defects “hidden” causes of their occurrence can be discovered which developed gradually or existed even before or in the course of the dike construction. It can be both natural conditions (for example founding the dike in the place of a hidden old river channel filled with permeable sediments) and the construction faults and unsuitable materials used in the course of building the dike. Also repeated water attacks during regular floods can bear a serious influence, when subsoil or dike body material is flushed out and away or when the hillsides of the dike are continuously deformed and eroded. In this context we can speak about pre-breach formed defects (see the scheme – Fig.1).

“Hidden” causes of dike defects often develop years before final destruction of these water-work bodies.

Locating, status and development of these “hidden” causes of dike defects is the area where the geophysical method usage is very sensible and can bring invaluable insight.

![Time aspects in the relation of breach formation and their “hidden” causes](image)

Based on the analysis of geophysical measurements carried out on the dikes and based on the discussion with the dike owners/caretakers representatives it can be stated that for maintenance and check of the dikes there are 3 basic types of tasks that can be effectively covered using geophysical methods. First task includes long dikes sections research, the second refers to detailed research of problem sections and the third aims at providing basic data for geomechanical description of the dikes material.

Geophysical Monitoring System (GMS) was built as a construction set under the IMPACT project in such a way to include (if possible) the guide for above mentioned tasks solution. The core part of the GMS is a database of repeated geophysical measurements which were and will be carried out within the river-basin.
The GMS system is composed of 3 basic building blocks:

1. **Quick testing measurement** – fast and cheap measurement for basic evaluation of the dike condition and homogeneity within the whole river-basin. This method is also the core for repeated (monitoring) measurement. As a method for this purpose we suggest DEMP using multi-frequency tool (for example GEM2) This method testing is the goal of geophysical part of the FLOODSite project (Task 4).

2. **Diagnostic measurement** – detailed measurement of the eroded (non-homogeneous) sections aimed at finding hidden defects of the dikes. The method is based on the application of the set of geo-electric methods, especially multi-probe resistance method MEM complemented by another independent method based on the type of the defect searched for accordingly.

3. **Measurement of geotechnical condition** – geophysical measurement to monitor geomechanical condition of eroded dike sections. For the analysis of dikes geomechanical characteristics especially seismic methods and micro-gravimetry will be used.

The GMS system asset lies in the possibility of objective evaluation of dikes homogeneity and condition. Geophysical methods are suitable supplement for current methods of checks (visual check, aerial and satellite pictures analysis). Monitoring function of GMS lies in the analysis of relative changes of geophysical parameters.

**Initial stage of GMS** is based on quick testing measurement of dikes within the whole area of the river-basin and following diagnostic measurement of selected problem sections. These checks result in complex evaluation of dikes condition in the river-basin including the suggestion of the necessary repairs. Special selected sections may be checked using measurement of geotechnical condition.

**Check stages** are suggested to be carried out where the dikes were built to protect against high water level (flood protection). In Europe, the check stage should be carried out after 3 years at the latest without the reference to flood conditions. Check stages may of course be carried out based on agreement at whatever times according to the needs of the dike owner/caretaker, e.g. in limited time setting during floods. The check stage includes repeated quick testing measurement and comparison of the acquired data with the data from previous stages (when using the results to eliminate the influence of climatic conditions). Thanks to analysis of repeated measurements we are able to locate time unstable anomaly areas which often coincide with the places where the dike ruptures occur. The check stage can be supplemented with diagnostic measurement if needed.

The GMS system success is largely based on narrow cooperation between geophysics specialists and dikes caretakers. They have large quantity of information which can help in making the geophysical measurements interpretation much more precise. Without mutual trust and communication the GMS database program has no meaning.

### 2.2 Test sites on dikes in Odra River-basin

Geophysical part of the Task 4 of the FLOODSite project aims at checking the “real” application of DEMP method using GEM2 tool for quick testing measurement. The test of GEM2 tool was performed in 3 specific localities – dikes in the Odra river-basin. The localities were chosen with active help of specialist from the River-basin Office.

#### 2.2.1 Locality Stary Bohumin.

It is right side dike of the Odra river located NW of the town Stary Bohumin. The Odra river forms the boarder with Poland here. The dike had a rupture in several places during catastrophe floods in 1997.
The ruptures caused the flooding of the town Stary Bohumin including historical centre. After the flood the dike was repaired and partially rebuilt. The waterfront side of the dike was rebuilt and strengthened in some places with quarry stone. The dikes sides has the incline 1: 2.5/2, the height of the dike is mostly about 3 meters. More detailed information and the technical documentation of the dike are not available.

The tested section is 1087.5 m long, local footage of the test profile grows in the direction of the stream flow. Local footage 0 m is at the edge of the railway embankment where the flood protection dike is connected. In the dike vicinity there are different buildings, fences and water management objects (floodgates, overflow channels). At 567 m the profile cuts across the road which goes to the boarder crossing. In the road vicinity there are numerous civil works. The profile situation is depicted on Fig. 2.

**Figure 2** Pilot site Stary Bohumin. GEM2 tool measurement

### 2.2.2 Locality Opava – Palhanec

The tested profile is situated on the right-hand embankment of the Opava river NE of the town baring the same name - Opava (city part Palhanec). The dike was constructed between 1967 and 1970 to lead meandering river stream and to provide flood protection of the town. The dike was built using earth-sand material mixed with gravel and construction debris at some places. During the floods in 1997 the dike was destructed in several places and the town Opava was flooded. The ruptures were fixed using sand-clay material, the dike was strengthened and the surface of the dike was finished by grass. The dike sides incline is 1: 2.5/2, the height of the dike ranges from 2.5 to 3 m above surrounding terrain.

The measured section is 1809 m long. Local footage grows in the stream flow direction point zero is located near train track at the embankment inroad from the air-front side of the dike. The profile goes along the river footage 39.415 to 41.224. In section 0 to 1485 the dike was reconstructed, section 1485 to 1809 of the dike has been left in the original condition. The dike at 425 a 1485 m is cut through by local road network connected with bridges. In the vicinity of the middle of the tested part there are many family houses with lots of fences, civil works and water management structures. The measurements by GEM2 can be seen on Fig. 3.
During the floods in 1997 the dike was ruptured close to the footage 1440, 1095, 690 and 70 to 120 m. The destruction of the dike around the footage 1440 m was most probably caused by concentrated water overflow after water level raise at the bridge on the footage 485 m (there is a weir at the place and the stronger dynamic strain of the dike can not be excluded). The rupture at the length 1095 was probably caused by combined effect of water overflow and leakage through the subsoil of the dike at the place of eroded sealing pelitic layer by drainage channel at the air front side of the dike. Similar influences probably caused the rupture at the footage 690. The rupture at the footage 70 to 120 m is located in the close vicinity of floodgate water-gang. During the flood in 1997 the dike was not overflowed due to waste inundation area. Water only reached some 0.5 above the surrounding terrain. The rupture was most probably caused by the dike landslide caused by low transverse cohesion of the dike material and subsoil sediments. The damaged sections of the dike were reconstructed using compacted clay-sand fill and injections (with the exclusion of the footage 1440 m). The sections at the footage 690 and 70 to 120 were at the waterfront side fortified by stone packing. (Bradáč V., 2000, Opava, pravobřežní hráz km 39,400 – 40,600, Inženýrskogeologické posouzení, ALGOMAN s.r.o., Opava).

2.2.3 Locality Ostrava - Lhotka

This locality is placed near the Opava and Odra river junction not far from the centre of Ostrava city. Along the dike (some 100 m far) there is a chemical plant facility. The tested section is 2820 m long. The dike was built in the sixties of the last century as a part of the Odra river stream realignment. The dike has been repaired several times since then and even elevated at some places. The whole area is subjected to the drops due to mining activity. According to the available bore documentation the dike is built by alluvial clays and gravel from the valley terrace. At some places some unsuitable anthropogenous materials as waste-dump material and construction debris were used. The dike sides inclination is 1 : 2,5/2, the height of the dike is about 3,5 m. At some places the air-front side has been rebuilt using backfill placed as far as the chemical plant area so that the dike creates a plateau of its kind. (Bradáč V., 1998 –1999, Odra, hráz km 8,600 – 21,995, Inženýrskogeologické posouzení, I., II., III. Etapa, ALGOMAN s.r.o., Opava).

Local footage of the tested profile grows down the river stream. The zero point is situated some 70 m far from the rail track embankment at the river junction, the end of the profile (footage 2820 m) is at the axis of the weir Lhotka. The tested section is located along the river length footage 17,76 – 14,94 km. The dike is cut through at several places by local road network. The most significant cut is at the footage 400, 1000 (footbridge), 2500 (highway bridge) and 2820 (weir Lotka with the footbridge). Near the dike there are many fences, civil networks and water management facilities. The profile characteristics can be seen on Fig. 4.
During the floods in 1997 the dike in the measured section was damaged at 2 places. The first rupture was located at the footage 160 to 220 m, the second dike damage happened near the joint of the dike with the bridge construction at the footage 990 to 1000 m. The rupture at the footage 160 to 220 was probably caused by cracks in the sealing pelitic layer of the alluvial sediments at the dike base which were created by the drop caused by the mining activity. During longer water attack during the flood the dike became unstable due to leakage at the base and drenching of material happened at the same time as the overflow.

The dike was rebuilt using slag material, sealing clay core, plastic foil (PVC) and the panels located at the waterfront side. The dike at the footage 980 to 1000 m was damaged at the top part in the length of some 20 m and depth of some 1 to 1.5 m. When the flood in 1997 culminated the water level raised 0.7 above the dike top. The area had already been disrupted by mining activity (the drops up to 1 meter) and that is why the dike was increased in its height by 1 m using waste-dump material in 1978.

The drenching of material probably happened due to the use of unsuitable gravel material for the dike elevation. Moreover the situation at the point of rupture is complicated by the floodgate which is located nearby, where the adequate compacting of the material was not possible.

### 2.3 Test measurements methodology

DEMP method which is the core of the recommended quick testing measurement falls among geoelectrical and geophysical methods. The parameter measured is the apparent conductivity (or the apparent specific resistance) of the geological environment at the point of the measurement. Using the resistance parameters it is possible to interpret the lines of individual layers of the environment and to evaluate their characteristics. During the dikes checks it is possible to use this to monitor the fluctuation of the clay and sand fraction content of the dikes material and its subsoil (relative permeability of the environment). Clays have generally lower resistance characteristics compared to sands and gravel (see Table1). Similarly the resistance level fluctuation within the dikes can be used to map soaked places, supposing the dike body material is homogeneous from the resistance point of view. The lower resistance areas correspond then with the places with increased humidity.

<table>
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<th>Material</th>
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<tr>
<td>Pure clay</td>
<td>1 to 20</td>
</tr>
<tr>
<td>Pure sand</td>
<td>100 to 800</td>
</tr>
<tr>
<td>Pure gravel</td>
<td>300 to 2000</td>
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</table>

*Table1: Typical specific resistance of sediments used for dikes construction*
DEMP method is based on measurements of primary electromagnetic field induction of transmitting coil in surrounding tested environment. Due to primary field induction the secondary field is created which intensity is given by the conductivity (resistance) of the environment in the vicinity of the transmitting coil. In our case these are the sediments of the dike body and the rock in its subsoil. The length range of the information on the conductivity depends on the primary electromagnetic field frequency. High frequencies have lower depths range than higher frequencies. This is important for the collected data interpretation. In the positive case it is possible to tell if the anomaly of the conductivity (e.g. leakage or porous section) is located in the dike body or in the subsoil of the dike.

Currently only single frequency tools are used, which transmit monochromatic harmonic signal (e.g. EM-31, EM-34, EM-38 made by GEONICS). To measure more depth levels it is then necessary to repeat the measurement using more tools working with suitable frequencies. This drawback has been ultimately removed by the unique tool GEM2 made by GEOPHEX which was recommended as the most suitable tool for check measurement of flood protection dikes by the IMPACT project.

GEM2 tool operates as a broadband digital multi-frequency electromagnetic instrument. It can use 15 work frequencies simultaneously. In this way it removes above mentioned limitation when the measurements have to be repeated using another tool to get the results for different depth layers. The tool is based on revolutionary design using frequency synthesis of transmitted signal which enables mutual superposition of the selected number of frequencies. Individual frequencies are then separated from the measured signal using de-convolution so that they can be separately analysed and recalculated to conductivity values. The measured parameters are real and imaginary section of the secondary field normalised to the primary field strength (measured in dimension-free unit ppm). These values are then transformed based on apparent specific conductivity. Described sensor was originally designed for military services to search for ammunition, civil networks.

2.4 Quick testing measurement (QTM) method and its interpretation

2.4.1 QTM

Usually in the Task 4 – project FLOODSite, tested profiles were performed in longitudinal axis at the top of selected sections of the dikes. As described above, the profiles local footage grows from zero down the river stream to the end of the profile. River footage is not easily usable for our purposes because it refers to the centre of the river. The distance of the dikes from the river bed varies and the fault between river footage and the dike profile footage may reach dozens of metres on 1 km of the profile. End points of the profiles were marked at the tested localities using wooden peg. Local footage at the profiles was not traced out because for the tests carried out by GEM2 tool the GPS system was used. The overall length of the profile was checked by measuring wheel.

To locate the position on the profile standard technical GPS tool was used. The receiving aerial was fastened on the rod in the same height as the head of the operator. The GPS system was powered by 12 V battery (typically used for video-cameras) which was located at the backpack carried by the operator.

Suitable battery (smaller one in spite of lower capacity) placed on the rod near the GPS aerial has lower disturbing effect. GPS station which we used provided primary accuracy around 3 m. With post processing this inaccuracy can be lowered to less then 1 meter (this procedure was not used during the tests).

GEM2 tool was used with 4 working frequencies which seemed to be most suitable based on the analysis of the electromagnetic noise in the localities. These frequencies were used: 6525 Hz, 13025 Hz, 27025 Hz and 47025 Hz. In different countries / localities the suitable frequencies may vary. It is largely dependant on electromagnetic noises level. In industrial countries it will probably not be possible to use frequencies lower than 5000 Hz due to noises.
The tests were performed with stacking 5, which means that the tool memory kept the average of the last 5 consecutive measured values. It is the basic filtration of measured data which reduces the noise level of the subsequently analysed data and also optimises the measurement density as well as measured sets volume. When using the above described setting the tool recorded 5 sets of 4 values of conductivity every second (for 4 work frequencies) and related set of accompanying measured parameters (e.g. ordinal number of the measurement, position taken from the GPS system, 50 Hz frequency noise, magnetic susceptibility etc.) The measurement was carried out continuously during slow walk at the speed 4 km/h). Average measurement density was then about 4 measurements per 1 meter of the profile. This represents very high sensitivity even when subsequent data filtration is taken into account.

The measurement was performed in two stages. The first stage was performed on 7 March 2005 when there was a tough winter at the measured sections area. The temperature at the time of measurement was lower than –5° C and the dikes were frozen to the depth of some 0.4 m. The surface was covered by the layer of snow ranging from 20 to 50 cm. Water was at some 70 % of its standard flow. The second stage was performed on 21 March 2005 immediately after the snow melted. The temperature at the localities reached about +5° C, the water reached the 20 years flood level. At some places the water spilt out of the river bed. The surface of the dikes was soaked with water and mushy.

In every stage the tested profile were measured at least three times, twice with the horizontal position of the coils and the tool in a longitudinal direction with the profile (hmd_in orientation) and twice with the coils in the horizontal position and the tool transversally to the profile (hmd_br orientation). The measurements were doubled so that they could be used to check the repeatability of the procedure. The change of orientation of measuring coils and the tool towards the tested profile serves for example to check the change in the sensitivity based on the presence of local conductors (civil networks). Altogether at least 17 km of profile was measured during the day.

2.4.2 QTM interpretation

The interpretation of QTM measurement brings 3 basic types of information. The first type of information is a possibility to divide the measured segment into so-called quasihomogeneous blocks. The second type of information relates to the delimitation of sharp local resistivity anomalies or boundaries in the measured dike segment. The third type of information is based on the analysis of repeated QTM measurements which are conducted in different climatic and hydrologic conditions. The analysis of repeated measurements is aimed at the delimitation of dike segments where shape and relative amplitude of the resistivity anomalies gradually change. Such areas, unstable over time, often correspond to disturbed dike segments where during the floods repeated seepage events occur.

The basic way of QTM measurement interpretation so is represented by the measured dike division into so-called quasihomogeneous blocks. These are dike segments where the measured resistivity values range within a certain interval, or where the measured resistivity curves show a similar character (for example, a segment with frequently alternating resistivities, or a segment, where resistivities corresponding to the selected operating frequency are systematically higher/lower than it is for another comparative frequency). Mostly, two types of block levels are used: regional block and detailed block. Within the blocks delimited in this way then we assume the same geotechnical properties of the dike (for example, permeability – porosity) and similar lithological composition.

Such way of interpretation is based on the assumption that conductivity, or resistivity of the dike material depends on its geological composition (the contents of clays, sands, gravels, lithology) and on water contents in the dike body. This general dependence is largely known and accepted, and serves as a basis of the interpretation of geophysical geoelectric methods. However, it has to be stated that the dependence concerned is not exact. We used two ways to try to find out the level of how such dependence is close and demonstrable. We made use of the existing QTM measurements conducted at the sites under the FLOODSite project (Palhanec and Lhotka sites) as well as of the archival results of geotechnical investigations carried out after the flood events in 1997. Unfortunately, the scope of archival information for the analysis was insufficient, particularly as regarded the laboratory tests. Therefore, in phase 2, within a complement to the FLOODSite project, entirely new measurement was conducted at Hrušov – Bohumin site (Odra River catchment area), where based on QTM results holes were drilled and a set of laboratory tests performed.
As regards the archival materials for Palhanec and Lhotka sites, mainly drillholes descriptions in accordance with Czech State Standard ČSN 72 1002 were available, with 5 – 15 drillholes existing for each of the sites. Part of the holes were drilled at the places of dike breaches prior to the dike repairs. We did not use these drillholes for the analysis as their descriptions after the dike repairs no more correspond to the current dike composition. The laboratory tests of the samples (grain-size analysis and basic geotechnical properties) were conducted to a limited extent only (approx. 1 - 3 samples for each of the sites), and no correlation with the measured resistivities could have been done.

To correlate the results of QTM measurement of resistivities and the „material“ composition of the dike according to archival geological drillhole descriptions (ČSN 72 1002) we used conversion of ČSN 72 1002 categories to the values of „expected, estimated“ pseudo-resistivities (see Table 2). The conversion was done as weighted average of resistivities (layer after layer according to drillhole description) to reach a depth of 4 m, with a thickness of the given layer having been used for weight. With regard to average thickness of the investigated dikes (approx. 2 – 4 m), we used for correlation the value of resistivities for the frequency of 47025 Hz (red curve in QTM diagrams), which shows comparable penetration depth (approx. 4 m). Correlation of both parameters (measured resistivity according to QTM and pseudo-resistivity according to ČSN 72 1002 description) was assessed as simple linear dependence.

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<td>F8</td>
<td>high plasticity clay</td>
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<td>F7</td>
<td>high plasticity loam</td>
<td>5</td>
</tr>
<tr>
<td>F6</td>
<td>low plasticity clay</td>
<td>10</td>
</tr>
<tr>
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<td>low plasticity loam</td>
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</tr>
<tr>
<td>F4</td>
<td>sandy clay</td>
<td>30</td>
</tr>
<tr>
<td>F3, S5</td>
<td>sandy loam, clayey sand</td>
<td>40</td>
</tr>
<tr>
<td>F2</td>
<td>gravelly clay</td>
<td>50</td>
</tr>
<tr>
<td>F1, S4</td>
<td>gravelly loam, loamy sand</td>
<td>60</td>
</tr>
<tr>
<td>G5, S3</td>
<td>clayey gravel, sand with admixture of clay</td>
<td>100</td>
</tr>
<tr>
<td>G4, S2</td>
<td>loamy gravel, poorly graded sand</td>
<td>250</td>
</tr>
<tr>
<td>G3, S1</td>
<td>gravel with admixture of clay, well graded sand</td>
<td>500</td>
</tr>
<tr>
<td>G2</td>
<td>poorly graded gravel</td>
<td>750</td>
</tr>
<tr>
<td>G1</td>
<td>well graded gravel</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 2: „pseudo-resistivity“ values for soil categories according to ČSN 72 1002

For comparison, the same procedure for correlation of geological drillhole description and QTM resistivity values was also used at a new Hrušov – Bohumín site. Furthermore, here also correlation of laboratory tests results of drillhole soil samples and QTM resistivities was done. Relation between granulometric properties of soils and resistivities and also correlation of permeability of soils and resistivities was examined. As regards granulometric properties of the sediments, relation of resistivities to the contents of clayey particles, gravelly particles, to grain size for a point corresponding to 50 % of the grains content, and for (contents of sandy particles + contents of gravelly particles) / contents of clayey particles ratio.

The correlation was calculated separately for drillholes in the dike where the material was dry, and for drillholes into underlier at the dike base with increased moisture content (at places, the assessed penetration depth of 4 m was reached by groundwater level). In analyzing the relation of laboratory tests results with the measured resistivities, in correlation diagrams every point has the weight.
represented by a thickness of the layer which the sample was collected from, in comparison with penetration depth of QTM measurement (4 m).

Note: the number of drillholes and laboratory tests at Hrušov – Bohumín site was limited by financial resources available for the investigation. The investigation was not funded from the FLOODSite project budget.

The second type of QTM measurement interpretation consists in the delimitation of sharp local inhomogeneities or resistivity contacts which mostly correspond to a sharp material boundary in the dike (repairs, rectifications, construction changes, poor quality materials and building work). These anomalies may pose certain risk as at the contact of different materials shrinkage cracks often occur due to repeated dike wetting and drying. Plausibility of QTM interpretation in this field was validated on the basis of comparison of the existence and extent of QTM anomalies at Jílešovice and Špluchov sites (project IMPACT) and at Lhotka and Palhanec sites (project IMPACT) with archival information on dike repairs performed after the flood events in 1997.

Finally, we also tried to validate plausibility of so-called over time unstable anomalies. These anomalies are interpreted on the basis of repeated QTM measurements which are the main component of the monitoring function of GMS system. In the interpretation of the repeated – monitoring measurements, we concentrate on the detection of relative shape changes in the measured curves. This serves to inhibit the effect of soil resistivities fluctuation in dependence on climatic conditions at the time of measurement. At the places where seepages and potentially also repeated fine-grained fraction washing out of the dike material occur, also dike material resistivity shows changes in comparison with the ambient medium. The reason for that is anomalous content of water (at increased water level) or increased material porosity (occurrence of cracks, a showing of sediments wash-out, etc.).

To validate the interpretation of repeated QTM measurements, we used the measurements conducted within the project of Academy of Science CR at Lednice and Opatov sites. We exploited the fact that in spring 2006 flood occurred at these sites and the tested dikes remained under water attack for a few days. At several places, visible seepage events occurred, which allowed us to compare the location of unstable anomalies with the location of seepages.

2.5 Validation of QTM Measurement Interpretation for Description of Material Composition of the Dikes and Their Permeability

2.5.1 Hrušov – Bohumín site: validation site

At Hrušov - Bohumín site, complementary investigation by means of QTM measurement was carried out followed up with the drilling investigation. At the site, QTM measurement was performed at two profiles: profile P2 was routed in dike axis, profile P1 was situated in original terrain at upstream heel of the dike. The measurement was carried out in October 2005 in dry weather at a temperature of around 20°C.

Based on the results of QTM measurements, in total 11 locations were proposed to be investigated by drillholes. The drilling was performed both at the top of the dike and at upstream heel of the dike. In total, 22 drillholes were installed. From the drillholes, disturbed samples from the selected representative layers were collected. The extent of the drilling and laboratory tests was limited by financial resources allocated for the investigation. Layout of the measured profiles and the drillholes were documented.

Diagrams expressing the correlation of resistivities measured by means of GEM2 apparatus at an operating frequency of 47025 Hz and so-called pseudo-resistivities which were calculated on the basis of geological descriptions of the drillholes were used. The procedure of calculation of pseudo-resistivities was described above. In the top part, correlation for the drillholes at the top of the dike (red diagram), and in the bottom part the diagram for the drillholes in original terrain (blue diagram) is presented. It is shown that correlation is quite close for the dried medium of the dike material.
(coefficient of correlation 0.85). In the wet medium below the dike, the situation is more complicated. Correlation straight line slope is much lower, which is a showing of reduction in resistivities measured by QTM method, due to water contained in the pores. It is particularly evident for the drillholes J22 and J12 which reached the gravelly sediments. It can be stated that the differences in resistivities between clayey and gravelly sediments are smaller at increased moisture content and correlation is less close.

Figure 5  Boreholes on the pilot site Bohumin - Hrusov

QTM resistivities from Hrusov – Bohumin site were further compared with grain size parameters and with permeability of samples collected from the drillholes. An advantage of this correlation is the fact that the parameters identified by means of the laboratory tests are objective, in contrast to the calculation of pseudo-resistivities. However, the number of the samples was limited due to high money-consuming character of the laboratory tests.
Obr. 2b Přehledný graf měrných odporů. Měření metodou DEMP, aparátoru GEM2

měření metodou DEMP, aparátoru GEM2

profil P1
pata hráze
na návodní straně

Ostrava - ochranné protipovodňové hráze
Lokalita: řeka Odra, pravobřežní hráz, úsek Hrušov - Bohumín

pravobřežní hráz
GEM 2, vmd_in
Figure 6: Site Hrušov – Bohumín: measurements by apparatus GEM-2 (results)
2.6 Validation of Repeated QTM Measurement Interpretation for Detection of Seepage Events in the Dike Body

We tried to validate plausibility of the interpretation of repeated QTM measurements at Lednice site (Morava River catchment area) and Opatov site (Labe River catchment area), where the testing monitoring measurements are carried out within the framework of the project funded by Academy of Sciences of the Czech Republic. The interpretation of the monitoring measurements consists in the delimitation of those profile segments where local relative changes in the shape of resistivity curves over time occur. To inhibit „normal“ fluctuation of resistivities of the dike material in dependence on moisture content in the dike material at the time of measurement, we do not analyze the differences directly in the measured data but we observe the changes in so-called relative residual resistivity anomalies \( R_{res} \). Relative residual resistivity anomalies are given by the following relation:

\[
R_{res} = 100 \times \frac{R_{meas} - R_{reg}}{R_{meas}} \quad \% 
\]

- \( R_{res} \) - relative residual resistivity anomaly
- \( R_{meas} \) - resistivities measured by GEM2 apparatus
- \( R_{reg} \) - regional trend \( R_{meas} \) (calculation using polynomial regression)

The interpretation of time-unstable resistivity anomalies is based on the assumption that at the places where seepage events, tension cracks and repeated wash-outs of fine-grained fraction from the dike material occur, there also occur changes in the dike material resistivities in comparison with the ambient medium. The reason for local changes in the resistivities is increased content of water in such anomalous segment, which will be demonstrated in the event of dike saturation with water. On the other hand, in the event of dike drying, the given segment may show an increase in the porosity of the material caused by occurrence of the cracks and by repeated washing out of the sediments.

The interpretation was tested on the pilot sites Lednice, Opatov and on the usual test sites of the Odra river basin (Palhanec, Lhotka).

2.7 Conclusions and Recommendations for QTM Measurement Interpretation

The results of validation of the interpretation of the resistivity measurements so far carried out by GEM2 apparatus within the QTM check of flood control dikes can be summarized as follows:

The conductivity (or resistivity) measured by means of GEM2 apparatus is an appropriate parameter for the basic description of the dike material composition. The correlation between the resistivity and the actual dike composition according to the drill core („pseudo-resistivity“ values calculated on the basis of geological description of soils according to ČSN 72 1002) was definitely demonstrated. Similarly, close correlation between the granulometric composition of the materials, coefficient of permeability and the measured resistivities was identified.

It is evident that for the dike division into quasi-homogeneous blocks it is more appropriate to carry out QTM measurement in dry conditions. Correlation coefficients between the resistivities and the parameters corresponding to the dike composition were always higher for the measurement performed in „dry“ season. The reason for that is the fact that increased moisture content in the material or even saturation of the pores in the dike reduces and „blurs“ the resistivity differences in the dike.

This has to be kept in mind also in a description of expected material composition within a quasi-homogeneous block. In the conditions of our sites, when performing the measurement in dry season, we used for geological description the resistivity intervals presented in the following Table 3. It turns out that if we perform the measurement at a high level of moisture content in the dike material
or even during the flood event, the boundaries have to be reduced (see Table 4). Similarly, we should proceed when comparing the measurement performed on the dike and on original terrain at the dike base. Close to the river, the groundwater level is mostly very shallow, and for the measurement performed on original terrain it appears more plausible to use for geological description the resistivity boundaries according to Table 3.

<table>
<thead>
<tr>
<th>QTM resistivities (ohmm)</th>
<th>Predominant material in the dike</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mostly for operating frequency of 47025 Hz)</td>
<td>clays</td>
</tr>
<tr>
<td>&lt; 40</td>
<td>sandy clays</td>
</tr>
<tr>
<td>40 – 80</td>
<td>clayey sands and gravel sands</td>
</tr>
<tr>
<td>80 – 140</td>
<td>weakly clayey sands and gravel sands</td>
</tr>
<tr>
<td>&gt; 250</td>
<td>sands and gravel sands</td>
</tr>
</tbody>
</table>

Table 3 QTM resistivities and expected predominant dike material in the measurement performed in dry conditions

<table>
<thead>
<tr>
<th>QTM resistivities (ohmm)</th>
<th>Predominant material in the dike</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mostly for operating frequency of 47025 Hz)</td>
<td>clays</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>sandy clays</td>
</tr>
<tr>
<td>20 – 50</td>
<td>clayey sands and gravel sands</td>
</tr>
<tr>
<td>50 – 100</td>
<td>weakly clayey sands and gravel sands</td>
</tr>
<tr>
<td>100 – 160</td>
<td>sands and gravel sands</td>
</tr>
<tr>
<td>&gt; 160</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 QTM resistivities and expected predominant dike material in the measurement performed in moist conditions

Experience gained so far from the interpretation of repeated QTM measurement show that we are able in this way to delimitate the disturbed or poor quality dike segments where during the flood dangerous seepage events occur. In carrying out the repeated measurement, it is necessary to adhere to the identical methodology of the measurement (set-up of operating frequencies, signal filtration, a height of the apparatus above the ground, etc.). In the interpretation of the repeated measurement, due attention has to be paid to the determination of the regional trend of the resistivity curves for the particular stages of the measurement. This procedure must be identical for all stages of the measurement. It appears convenient to combine the measurement performed in extreme conditions, for example, long lasting drought, snow thawing – flood event. It may contribute to better „readability“ of the time-unstable anomalies and to their timely detection.

Thanks to the analysis of the measurements performed at the places of the known dike repairs it turned out that the majority of sharp local anomalies of QTM resistivities (if not caused by artificial conductors) corresponded to sharp material changes in the dike. In their interpretation, it is very convenient to observe also the development of other parameters measured by GEM2 apparatus. In particular, it is magnetic susceptibility and noise function at an industrial frequency of 50 Hz. This means that in some cases it is possible to identify in more detail the extent of the anomalous area or to point out the potential existence of distribution systems or metallic objects in the dike. GEM2 apparatus detects very well these sharp anomalies due to high density of the measurement. The image of the resistivities transition in the „classical“ direct-current resistivity profiling is somewhat „blurred“ due to the electrode array length itself and larger interval of the measurement.

The delimitation of these sharp transitions is of considerable significance. In the places of sharp material transitions, shrinkage cracks may occur in consequence of repeated dike wetting and drying. Such place is then susceptible to the occurrence of seepage events. The majority of the time-unstable anomalies, interpreted on the basis of the repeated measurements, concentrate in the vicinity to such transitions.
3. References

1. BRADÁČ V (2000) Opava, pravobřežní hráz km 39,400 – 40,600, Inženýrsko-geologické posouzení, ALGOMAN s.r.o., Opava

2. BRADÁČ V (1998 –1999) Odra, hráz km 8,600 – 21,995, Inženýrsko geologické posouzení, I., II. a III. Etapa, ALGOMAN s.r.o., Opava