Topographic Effects on Radio Magnetotelluric Simulations on Levees: Numerical Modelling for Future Comparison With Fields Results

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Abstract: We study the influence of the topography of a levee model on the electric resistivity signal obtained with the Radio-Magnetotelluric method (RMT). The model is based on a real structure located in Orléans along the Loire river (France).
The effect of the incident electromagnetic field direction is studied with two different incident wave directions: BBC 5 from Salford (UK) and France-Inter from Allouis (France).
The simulations highlight the tri-dimensional effects of the geometry in the apparent resistivity observed on the crest of the levee. This response depends on the incident field direction and the topography.

Keywords: Levee - Radio Magnetotelluric – Apparent Resistivity – Topographic Effects

1. Introduction

Our work aims to study the influence of the topography of levees on the apparent electrical resistivity measured with the Radio-Magnetotelluric method (RMT).
First, the basic principle of the RMT method is reminded. Second, we present the geometry of the structure, the initial and boundary conditions used in our model. Finally, some numerical results are discussed for different orientations and frequencies of the incident fields.

2. Radio-Magnetotelluric principle

2.1 Definition

The RMT method is based on the measurement of the secondary horizontal electric field $\mathbf{E}_z$, induced in the soil according to the Biot and Savart law and the primary horizontal magnetic field $\mathbf{H}_{px}$ (Fig.1). The frequency band used in RMT classically ranges from few kHz to 1 MHz.

The induced field $\mathbf{E}_Z$ is defined as:

$$E_z = E_0 e^{-j k_{0rfw} y}$$

The magnetic field $\mathbf{H}_{px}$ is defined as:

$$H_{px} = H_0 e^{-j k_{0rfw} y}$$

where k_{0rfw} is the magnitude of the wave vector and y is the depth (m). Both fields decrease exponentially into the soil.

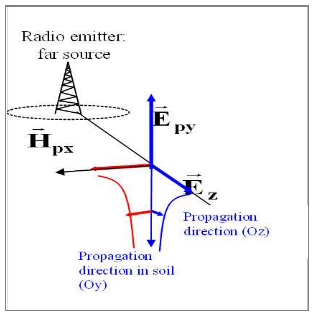

Figure 1. RMT principle.

The apparent resistivity ρ_a (Ω.m) is proportionnal to the electromagnetic surface impedance $\mathbf{E}_z/\mathbf{H}_{px}$ and is defined by the Cagniard formula [1]:

$$\rho_a = \frac{1}{2\pi\mu_0 f}\frac{|E_z|^2}{|H_{px}|^2} \quad (1)$$

where μ_0 is the magnetic permeability of vacuum, $\mu_0=4\pi 10^{-7}$ (H.m^{-1}), and f (Hz), the frequency.

2.2 Skin depth and depth of investigation:

At a given location, away from the RMT source, the amplitude of the secondary electric field decreases exponentially inside the soil, which may be considered as a conductive media in the frequency range [~kHz, 1MHz]. The depth at which the amplitude of the electromgnetic field is attenuated by a factor 1/e~1/2,718 is defined as the skin depth δ(m):

$$\delta = \sqrt{\frac{2}{\mu_0 . \omega . \sigma}} \quad (2)$$

where σ(S/m) is the conductivity (inverse of the measured resistivity ρ) and ω (rad/s) is the pulsation defined $\omega = 2\pi f$.
The depth of investigation of the RMT is usually considered as the half of the skin depth. For a given frequency, the more resistant the media is, the greater the penetration depth is. For a given soil, the higher the frequency of measurement is, the lower the penetration depth is.

3. Finite Element Modelling of the RMT signal on a levee

The lack of analytical solutions [2,3] for the electromagnetic response of a complex 3D structure led us to use a finite element approach with Comsol Multiphysics. This type of study has already been realized by [4].

3.1 Geometry of the levee

The levee geometry is based on a real case study in Orléans along the Loire river (Fig.2).

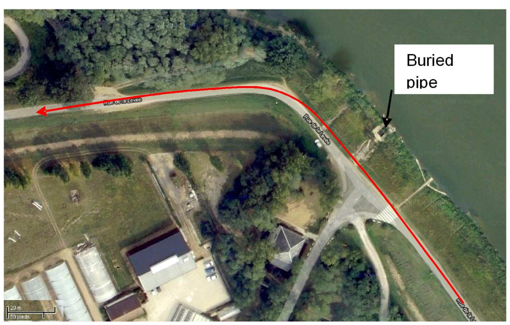

Figure 2: Aerial view of the levee.

The levees are sized so as to show the edge effects under two directions of propagation. The soil dimensions are defined in order to take into account the depth of investigation depending on the electric resistivity and the applied frequency (f = 163 kHz, France-Inter; f = 693 kHz, BBC5, Fig.5). For the BBC5 and the France-Inter emitters, the skin depths are approximately 38 m and 111 m, taking into account a soil resistivity of 4000 Ω.m and 8000 Ω.m, respectively. These values correspond to a two-layers soil (sandy materials in the levee lying on a chalky subtratum).

The dimensions of the system [soil+levee+air] are then defined using a rectangular volume of 310 m wide, 340 m long and 100 m high (20 m for the air and 80 m for the soil, Fig. 3 and Fig.4). The maximum investigated depth is 80 m because of memory limitation.

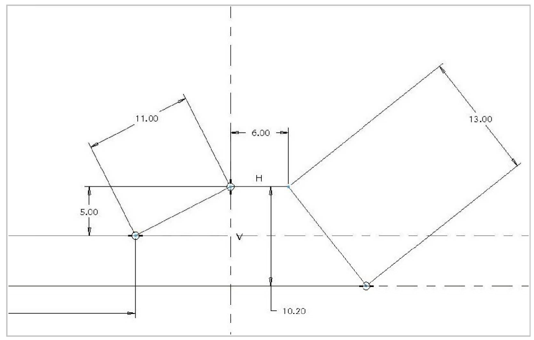

Figure 3: Dimensions of the levee.

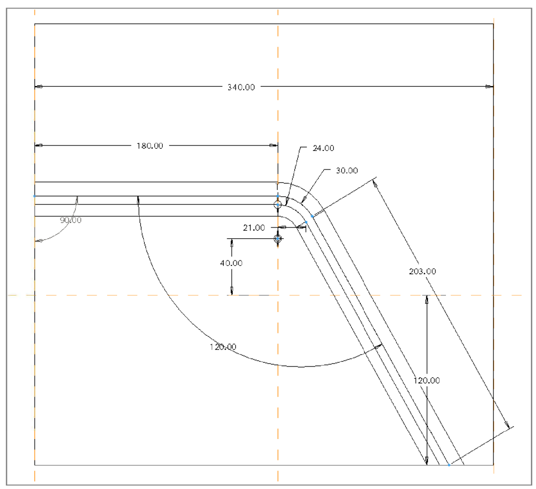

Figure 4: Top view of the levee.

The slope of the levee is one meter in height and two meters wide. The 3D modelling of the levee is created in a CAD system and exported as a STL format. Then, this part is imported into Comsol 4.2 and the whole model is created with air and the levee substratum as a solid in three dimensions into Comsol.
Fig.6 presents the mesh choosen for the simulation. It is refined on the crest of the levee in order to get high resolution results where the RMT method is performed.

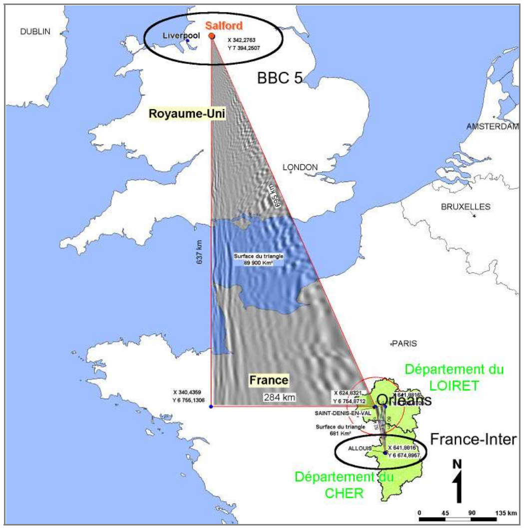

Figure 5: Locations of Allouis and BBC5 emitters.

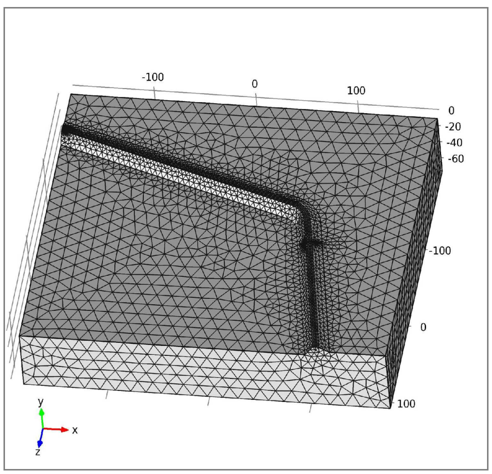

Figure 6: Mesh used for levee.

3.2 Comsol modes used for the modelling

The RMT method is considered as a low frequency electromagnetic method. Thus, the RF Module (diffusion equation, with the "electromagnetic waves (enmw)"model) or by AC/DC Module (quasi-static case, the Magnetic Field "magnetic fields (mf)") may be suitable for our modelling.

3.3 Inital and boundary conditions :

A plane wave is used to generate the electric field propagating in y direction. The value of the magnetic field is initialized along z: $\mathbf{H_x}$ = [1, 0, 0] (A/m).The magnetic field is athen applied in the air, the soil and the levee surfaces. Perfect Matched Layers and scattering boundary conditions are used in order to avoid irrelevant reflections at the boundaries. .
The second physical model in the AC/DC mode is created with the “magnetic fields” (mf) model. Magnetic insulation conditions are used on the external sides. A sketch of the levee and its boundary conditions is shown in Fig.7 in Salford case (BBC5). The simulation with the second emitter (France-Inter) is performed just by changing the orientation of the levee in function of the location of the emitter.

In both cases, similar physical properties are used within the soil and the levee: the relative dielectric permittivity ε_r is equal to 8, the electrical conductivity σ is equal to 0,01 S/m, and the relative permeability μ_r is equal to 1.

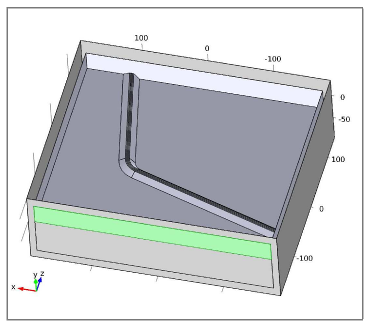

Figure 7: Magnetic field $\mathbf{H_x}$ initialization (green face). The system is surrounded by boudary conditions depending on the mode used in Comsol.

4. Results

4. 1 First case: BBC5 emitter

4.1.1 Variation of the apparent resistivity along the levee crest

Fig. 8 and Fig. 9 show the variation of the apparent resistivity along the crest obtained on three paths: two at 1 m from the crest edges and one in the middle. The distance between the profiles is 1.5 m.

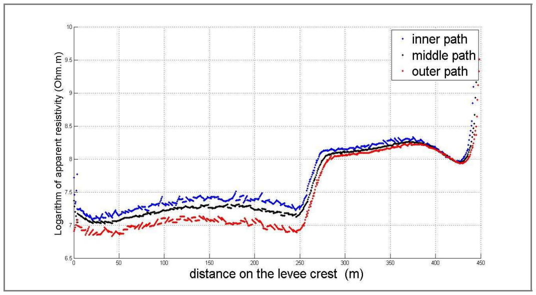

Figure 8: Logarithm of the apparent resistivity along the levee crest for the BBC5 emitter case (RF Module).

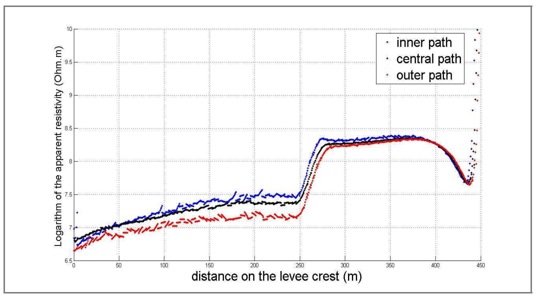

Figure 9: Logarithm of the apparent resistivity along the levee crest for the BBC5 emitter case (AC/DC Module).

First, the apparent resistivity strongly depends on the levee direction to the emitter position. The calculated values range from 1000 (Ω.m) in the first part of the levee and reach 4000 (Ω.m) in the second part before strongly diverging due to some edge effects. Second, the apparent resistivity is influenced by the distance between each profile and the edges of the crest.

Fig.10 and Fig.11 present the 2D apparent resistivity calculated on the levee. It allows a better visualization of the edges effects of the crest. The apparent resistivities calculated in both Comsol modes are similar.

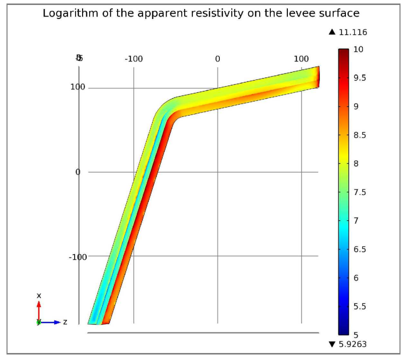

Figure 10: Logarithm of the 2D apparent resistivity on the levee for the BBC5 emitter case (RF Module).

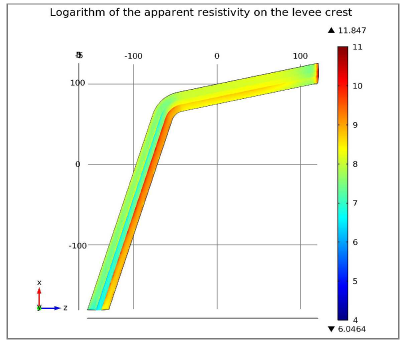

Figure 11: Logarithm of the 2D apparent resistivity on the levee for the BBC5 emitter case (AC/DC Module).

4.1.2 Influence of a pipe buried within the levee

A metallic buried pipe is placed inside the levee at 2 m depth. Its diameter is 0.5 m. The apparent resistivity strongly varies at the pipe location and shows a typical RMT signature for such object with both Comsol modes. ([1], Fig.12 and Fig. 13).

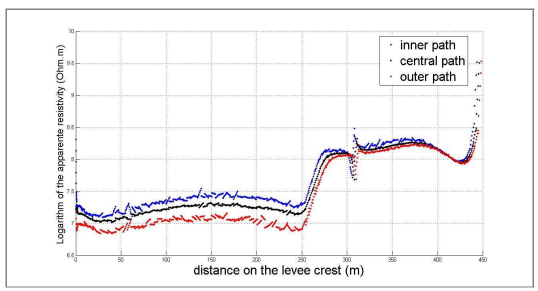

Figure 12: Influence of a buried pipe on the apparent resistivity along the levee crest for the BBC5 emitter case (RF Module).

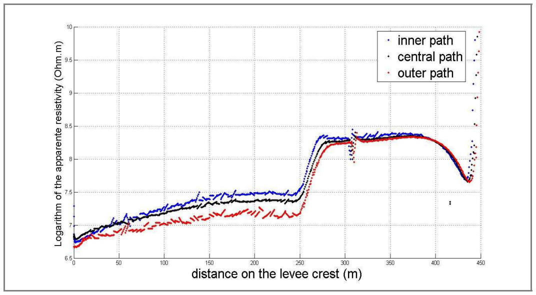

Figure 13: Influence of a buried pipe on the apparent resistivity along the levee crest for the BBC5 emitter case (AC/DC Module).

4. 2 Second case: France-Inter emitter

4.2.1 Variation of the apparent resistivity along the levee crest

Fig. 14 and Fig. 15 show the variation of the apparent resistivity along the crest obtained on three paths: two at 1 m from the crest edges and one in the middle. The distance between the profiles is 1.5 m.

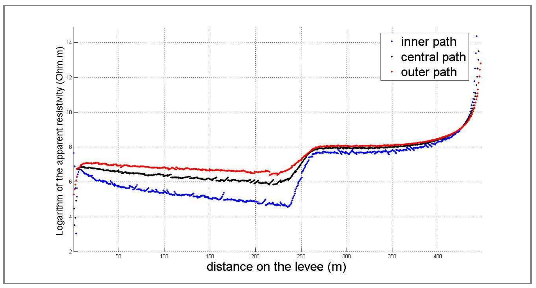

Figure 14: Logarithm of the apparent resistivity on the crest for the France-Inter case (RF Module).

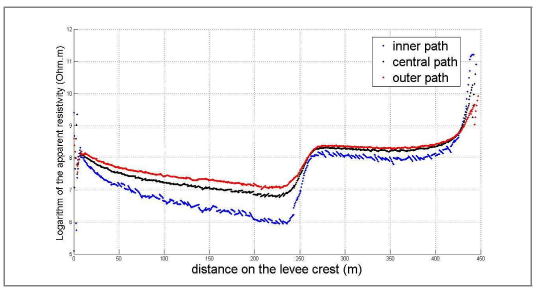

Figure 15: Logarithm of the apparent resistivity on the crest for the France-Inter case (AC/DC Module).

As for the first case (section 4.1), the apparent resistivity obtained by the RMT method first strongly depends on the levee direction to the emitter position. The calculated values vary from 1000 (Ω.m) in the first part of the levee to 4000 (Ω.m) in the second part, before strongly diverging near the model boundary. The apparent resisitivity is also influenced by the distance between each profile and the edges of the crest.

Fig.16 and Fig.17 present the 2D apparent resistivity calculated on the levee with the RF and AC/DC comsol modes. Again, the results are similar for both modes. They clearly show the large influence of the topography of the levee on the apparent resistivity. Large variations due to the change of the incident propagation wave direction are also observed, as for the first case.

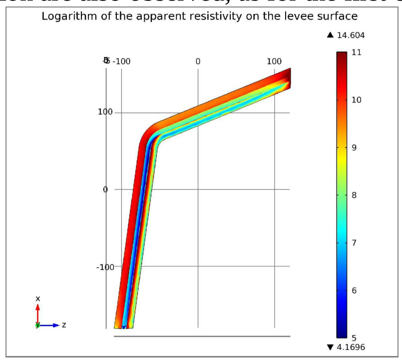

Figure 16: Logarithm of the 2D apparent resistivity on the levee for the France-Inter case (RF Module).

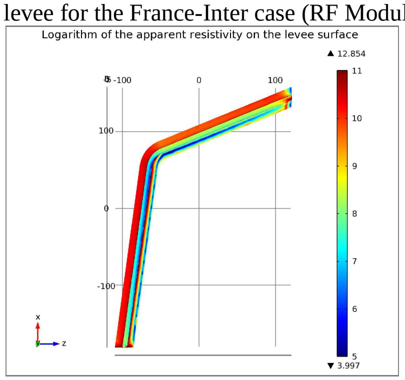

Figure 17: Logarithm of the 2D apparent resistivity on the levee for the France-Inter case (AC/DC Module).

The calculated values of apparent resistivity is half of the true resistivity (8000Ω.m) in the second part of the profiles. It may be due to i) a large influence of the topography; ii) an insufficient investigation depth of the model due to memory limitation.

4.2.2 Influence of a pipe buried within the levee

As for the BBC5 emitter case, the influence of a buried pipe on the apparent resistivity is investigated. The location of the pipe within the levee is similar to the first case. Again, the object influences the calculated resistivity (Fig. 18 and Fig.19).

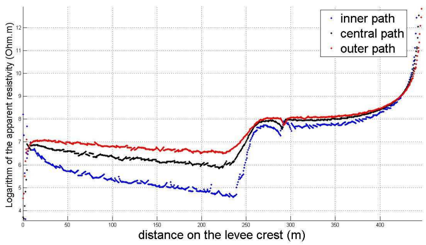

Figure 18: Influence of a buried pipe on the apparent resistivity along the levee crest for the France-Inter emitter case (RF Module).

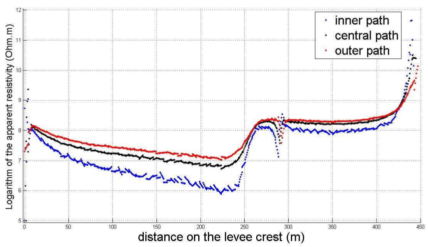

Figure 19. Influence of a buried pipe on the apparent resistivity along the levee crest for the France-Inter emitter case (AC/DC Module).

5. Conclusion

The RF and AC/DC modes give similar results for the calculation of apparent resistivity on a levee. However, the RF mode seem to be quicker than the AC/DC mode. The simulations clearly show the effects of the topography as well as the influence of the location of the emitter on the apparent resistivity. Both emitters seem to be effective for the detection of metallic pipes within earthen levees at these frequencies. The RMT method can bring useful information for the detection of metallic structures such as buried pipes.

Références

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