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UNDERGROUND UTILITY ANALYSIS AND SOIL CHARACTERIZATION USING GROUND PENETRATING RADAR

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ABSTRACT
This paper describes modern, non-invasive data acquisition methods of underground utility detection. Basic parameters, methods and their influence on the acquisition speed and data quality are defined. This data can be used for development of complex Geographic Information Systems. The aim of this paper is to show data extraction from the hyperbolic reflection on the radargram. These data are used for pipe radius and soil moisture content estimation. Influence of determined dielectric permittivity was discussed in terms of pipe radius estimation. Also, soil characteristics influence on the velocity of propagation was analyzed. For complete analysis new application was developed. This application includes hyperbola fitting algorythm for the raw data and additional calculation of variables mentioned above from determinated hyperbolic function. The analysis was applied to a number of real radar data scans of relevant underground utilities.
Keywords: Ground Penetrating Radar, radargram, **RA**dar **D**ata **AN**alyzer, penetration depth, pipe radius, velocity of propagation, dielectric permittivity, soil moisture content

1. PHYSICAL CONCEPTS OF GPR WORK

The Ground Penetrating Radar (GPR) is a device used for non-invasive scanning and precise detection of underground utilities. When the GPR moves on the site surface the transmitting antenna sends polarized, high frequency electromagnetic (EM) waves in the ground. Because of different existing inhomogenities in the ground, part of the EM waves is reflected from the dielectric boundary between different materials and the other part is refracted and goes to the deeper layers. The described process is repeated until the EM waves become too weak. Reflection of EM waves from the dielectric boundary is the consequence of differences in the electric and magnetic properties of materials of infrastructural objects and soil layers [1]. Time necessary for the propagation of EM waves from transmit antenna to the boundary surface and its reflection back to the receiver antenna is defined as a two way travel t_R [ns] time. The GPR measures t_R, and finally calculates the relative depth of the underground object. Because each location has its specific soil structure, ε_R (dielectric permitivitty) has to be recalculated for each site. Methodology of radar scan generation is shown in Figure 1. A radar scan is a spatial section of the working area. The antenna's linear trajectory is shown on X axis, and Y axis shows the two way travel time $\mathbf{t_R}$ i.e. the relative depth $\mathbf{z}$ from the surface to the underground object. The distance between transmit and receive antenna is very small. Because of this, the distance from transmit antenna to boundary surface is approximately equal to the distance from boundary surface to the receiver antenna. The distance from antenna to the underground object continuously changes. Distances $r_0, r_1, ... r_N$ are projected ortogonally on the movement axis, see points

x_{-N} ... x_0 ... x_N (see middle section of Figure 1.). By sequentially connecting the ends of these segments, a geometrical hyperbola is formed [2]. All points on the scan include reflected wave amplitude data. Points on top of the segments have peak amplitude value. The peak on the shortest segment r_0 (antenna center is above the pipe axis) is highest (positive or negative). This value is criteria for scan searching and determination of location and depth of underground utility.

Transmit antenna radiates a conical EM wave beam with a bandwidth β=35°÷45°. Based on these facts, it is not necessary for the center of the antenna to be above the underground object to detect it. Figure 1 shows an ideal one-pipe radar scan in a homogenous soil layer. Antenna moved ortogonally to the pipeline axis. In real conditions scan is with different noises and hyperbolical reflections, caused by other infrastructural objects. Postprocessing with RADAN software can eliminate this [3].

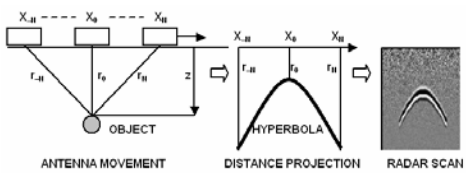

Figure. 1. Radar scan generation

2. GPR PARAMETER ACQUISITION METHODS

Parameters are detected by 2D and/or 3D scans of the site. 2D scanning is useful for quick underground utilities location. Orthogonal scanning is used to determine pipeline depth and direction. To determine pipeline direction, at least two scans are needed [4]. A regular hyperbola shows up on the scan when ortogonally crossing above the pipeline axis. When antenna crosses at a sharp angle above the pipeline axis, the hyperbola has a totally different shape, which is no longer hyperbolic. In an extreme case, when the antenna trajectory is along the pipeline axis, the hyperbola is distorted into a straight line [4]. In 3D scanning the software connects a number of 2D scans in a predefined sequence, hence creating a 3D model of the site. Voids between the 2D scans are filled with software interpolation methods. The 3D display has the advantage of looking at the entire survey site at once. Software RADAN is used for postprocessing of raw signals [7].

3. BRIEF ANALYSIS OF EXISTING PROCEDURES FOR RADIUS ESTIMATION

Basically, the estimation of the radius of the pipes from raw data can occur by the direct determination of the radius from the optimal set of raw data, or by fitting of hyperbola through the whole set of incoming data, and afterwards by the estimation of the radius on the basis of the fitted curve. Through the direct determination of the radius of pipeline, the problem of inaccuracy of the relations among the unknown variables takes place, as well as the influence of noise and quantity of the incoming data. Namely, during the formation of a scan GPR calculates average velocity V_0 of EM waves circulation. The velocity of the EM waves in the scan is spatially positioned which means that it is not uniformed and depends on a whole string of factors. Taking into consideration the unpredictability of influences, it is impossible to define exact procedure for estimation of influences of the surroundings on determining of the ideal value of velocity. It should be pointed out that the mistake made by settling the average value of velocity V_0 influences the quality of the estimated radius to a very high degree. Direct estimation of the radius from raw data leads to being unfamiliar with the exact coordinates of the peak of the hyperbola (x_0 and t_0), since the process of fitting is not conducted. The core of the problem in the given case involves 4 unknown variables: the radius of a pipe R, velocity of EM waves' propagation V_0 and coordinates of the hyperbola's peaks x_0 and t_0. Applying the generalized Hugh's transformations [5] it becomes possible to form a system of 4 equations which satisfy the hyperbola. The above mentioned unknown variables are expressed in the frames of these equations. In order to solve them, it is necessary to define a statistical and/or physical condition (by analysis values of differentials using the coordinates, for example) for interpretation of raw data with the aim of gaining the optimal set of 4 points which represent the data in the best possible way. According to spatial allocation of velocity, presence of noise and undefined correlation between estimated parameters, radius estimation error does not satisfy the desired accuracy interval. To be precise, the noise contained in starting data is so strong that it makes the method not robust enough. Procedures of following radius estimation on the basis of the fitted curve are based on the method of minimizing the sum of square algebra or orthogonal distances from the second degree curve to the N given points [6]. The very procedure of fitting eliminates coordinates of the hyperbola's peak (x_0 and t_0) as unknown variables, so that the problem becomes more defined. The basis of the procedure described in paper [1] is solving linearised problem of minimizing algebra distances square, based on scaling (transformation) of restrictions and analysis of generalized vectors of proper values [7]. Good characteristics of algorithm are simplicity and good results for samples with small noise ratio. Generally, the biggest influences on pipe radius estimation accuracy have noise level in raw data and error in determination of average velocity V_0. Noise influence is obvious in fitting procedure, and velocity error ΔV_0 represents systematic error in the fitting results interpretation process. According that, data acquisition process by GPR is done under real conditions with unknown and unhomogenous layers of soil above the pipe, it turns out that the change of the propagation velocity of EM waves is stochastic, and that sampled points from hyperbola will contain considerable amount of noise. Therefore, linearized model based on minimizing algebra distances square isn't the best possible solution for presented problem wirh high sensitivity of the pipe radius estimation process.

4. ABSOLUTE RESIDUAL MINIMIZING METHOD

Absolute residual minimizing method, generally, represents iterrative refitting procedure pondering residuals with biggest differences. That method is developed in order to eliminate problem shown in previous chapter. Basic fitting procedure is done using modified Levenberg-Marquardt method of minimizing non-linear problems, based on minimizing of algebra distances – residuals.

$$\mathbf{F}(\mathbf{a};\mathbf{x})=\mathbf{a}\cdot\mathbf{x}+\boldsymbol{\varepsilon}=ax^2+bxy+cy^2+dx+ey+f=0 \quad (1)$$

$\mathbf{a}=[a\ b\ c\ d\ e\ f]^T$ – coefficient vector

$\mathbf{x}=[\ x^2\ xy\ y^2\ x\ y\ 1]$ – design vector

$\boldsymbol{\varepsilon}$ – error vector (residuals)

In order to force the condition out of the second degree polynome **F(a;x)** that, when fitting, gives the solution in the form of hyperbola

$$b^2-4ac>0 \quad (2)$$

As well as the condition that the hyperbola axis is always orthogonal to the surface, correspondent allowed value intervals for polynome ceofficients are defined. Considering that allowed value intervals for polynome coefficients are defined, initial hit vector values are adopted in interval [0,1]. After initial fitting, residual values for every input data are analized as well as RMSE value (Root Mean Squared Error). Based on the value of the biggest residual, initial set of points with residuals is determined. Its value is bigger or equal to 50% of maximum residual value (Difference Limit). All points in the set are pondered for correspodent increment, which gradually decreases its influence to final result of fitting. In iterative procedure, number of pondered points from the initial set is decreasing until the next fit has better RMSE (smaller) than the previous one. Procedure of decreasing the influence of points with higher level of noise on the fitting process provides multiple decrasing of RMSE, which leads to significantly better input sample approximation and pipe radius estimation quality. After analisys of the formed method it is determined that the quality of the result depends on, besides noise, density of the input sample, and the ratio of maximum and other residuals from the initial fit. Hence, for every characteristic problem there is a need for new, optimal condition for the initial set of points forming. In order to surpass suboptimal solution, an additional optimization procedure is developed which varies the difference limits for forming the initial set of points (Difference Limit). That is how whole complete residual difference space is searched, and global optimal polynome coefficient values are estimated with high accuracy. The criteria for global optimal set of parameters selection is the smallest RMSE value, again. Process of error elimination by determining velocity ΔV_0 involves determining maximum density of probability distribution [9] of pipe radius for corresponding velocity. Procedure is based on varying velocity ±20% comparing to initial value estimated by GPR and selecting the value that provides radius distribution with highest probability density. It is final step in data interpretation process. Velocity analisys provides soil characteristics analisys as well, considering that soil characteristics are defined based on EM waves propagation velocity.

$$\varepsilon_R=(C/V_0)^2 \quad (3)$$

ε_R – dielectric constant (characteristic) of soil

C – speed of light in vacuum ≈30cm/ns

V_0 – EM waves propagation velocity (interval 1÷25 [cm/ns])

5. EXPERIMENTAL RESULTS

Example of radius estimation and velocity distribution analisys is done for the scan with known pipe diameter and depth. Figure 2 (left) shows hyperbolic reflection of full, steel, gas pipe 35.56 cm in diameter (14“) at relative depth of 107 cm and the result of data extraction from the scan.

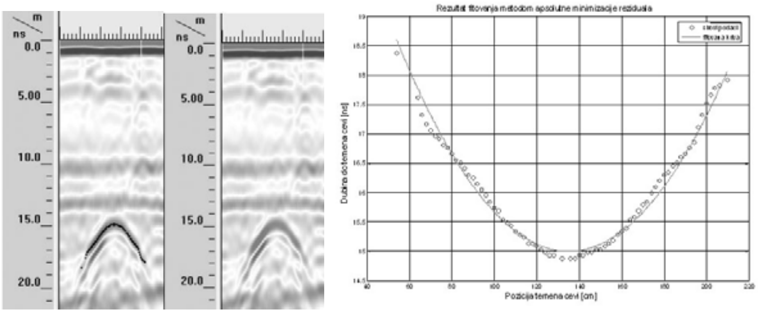

Figure 2. Example of GPR scan generation and fitting results

Initial RMSE value when fitting was 0.12233, maximum value of the residual was 0.28887 ns. Figure 4s shows initial distribution of resiuals. After applying method of absolute minimisation of residuals, RMSE value is 0.00120, and maximum residual value is 0.00658ns. It has to be mentioned that only 8 out of 72 points have residual that is not 0. Limit condition for pondering started from initial value of 0.061165 and stopped on 0.00436. Figure 2 (right) shows final fitting result of the given method. Velocity distribution analisys for known diameter shows that the velocity of points on the fitted hyperbola varries from 13.6 to 14.8cm/ns. Using normal distribution, the ideal average velocity value of V_0=14.2055cm/ns is determined. Initial value of the average velocity from point reflector (RADAN) was 14.0cm/ns. Given velocity defines depth of z_0=106.525cm, which matches the real depth. Applying (3) dielectric constant ε_R=4.46 is calculated, which corresponds to dry, sand saturated soil (sand soil – dry: ε_R= 3÷6, V_0=12-17cm/ns). Dielectric constant matches to real soil characteristics (Novi Sad gasline, 2005. august, near DTD river channel, sand soil).

6. CONCLUSION

This paper briefly describes the basic principle of using one of possible methods for initial data set extraction from hyperbolic reflection in radar scan. Further, the principle for forming and realization of non-linear algorythm for hyperbola fitting is represented, along with complete overview of all conditioning facts and ways for surpassing them. Algorythm application is succeffully shown on real scans, specific for the problem. Analisys of velocity distribution from the fitted hyperbola was done in order to obtain exact characteristic of analized soil. Further research could be directed towards minimizing orthogonal distance in fitting process, as well as new implementations of velocity analysis in order to achieve better radius estimation and more complete subterrestrial soil analysis.

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