COST Action TU1208

Civil Engineering Applications of Ground Penetrating Radar

This lecture is part of the TU1208 Education Pack

Electromagnetic modelling of historical bridges for advanced interpretation of GPR data

Author: Mercedes SOLLA (ES)

COST is supported by the
EU Framework Programme Horizon2020

Thank you to Loredana Matera for contributing to the editing and layouting of this lecture.

Lecture Layout

- **I. Description of the problem**
  - Bridges are complex and heterogeneous structures
  - Bridges cause complex patterns of reflections in GPR data
  - FDTD modelling can be used to assist data interpetation

- **II. Case studies**
  A. **San Antón** Bridge: FDTD model with basic geometry
  B. **Traba** Bridge: FDTD model with realistic geometry
  C. **Monforte** Bridge: FDTD model with different media properties
  D. **Lubiáns** Bridge: integration of GPR and NDT data

- **III. Conclusions**

- **References and biography of the Author**

I. Description of the problem

Fig. 1. Non-homogenous filling within the San Albert Bridge during the restoration tasks performed in 2006 and irregular shape of ring-stones in the Carixa Bridge.

- Ancient masonry arch bridges require special attention and maintenance. Non-destructive testing (NDT) methods can be used to preserve their historical character.

- Ground-penetrating radar (GPR) is capable to provide an overall internal image of a bridge, with a good compromise between resolution and penetration depth.

- Complex patterns of reflections are present in GPR radargrams collected over bridges, due to their heterogeneous structure.

COST is supported by the
EU Framework Programme Horizon2020

I. Description of the problem

Fig. 1. Non-homogenous filling within the San Albert Bridge during the restoration tasks performed in 2006 and irregular shape of ring-stones in the Carixa Bridge.

- Finite-Difference Time-Domain (FDTD) modelling is a useful tool to achieve a better understanding of radar-wave propagation and scattering phenomena occurring in structures. It facilitates the interpretation of GPR experimental data by means of a comparison with synthetic data.
- Advanced approaches are needed to build realistic models of bridges.

II. Case studies

- In this part of the lecture, different modelling strategies are illustrated, to support the interpretation of data measured on historical bridges.

- The Finite-Difference Time-Domain (FDTD) algorithm is used. Models and simulations are done by using the open-source software gprMax (www.gprMax.com).

- The modelling strategies are explained via the presentation of four different case studies, of increasing difficulty.

COST is supported by the
EU Framework Programme Horizon2020

II. Case studies

Case Study A: San Antón Bridge

The purpose of this study was to investigate the capability of FDTD modelling to simulate GPR responses collected over bridges and support the interpretation of field data. A basic two-dimensional model of the bridge was implemented, with a simplified geometry.

Case Study B: Traba Bridge

In this study, a more realistic model of the structure under test was built, by using the orthoimages of the bridge provided by photogrammetry or laser scanner. The orthoimages were binarized into black (masonry) and white (air) colours. Heterogeneity in masonry was also modelled.

An additional purpose of the study was to investigate how to reduce the computation time.

II. Case studies

Case Study C: Monforte Bridge

The synthetic model was elaborated from the orthoimages. The advance here consisted in considering the existence of more than two different media when codifying the orthoimages.

Case Study D: Traba Bridge

The purpose of this study was to create an advanced FDTD model by exploiting information provided by complementary NDT approaches. Photogrammetric or laser scanning data were used to create realistic models, as in the case studies C and D; additionally, to characterize the different media and estimate their dielectric properties, infrared thermographic data and field GPR data were jointly considered. Image processing was also used, as well as suitable approaches to simulate heterogeneity and layering.

II. Case study A

San Antón Bridge: field data

QUESTIONS:

- Hidden arch?
  - ☐ Filled or empty?
- Structural element?

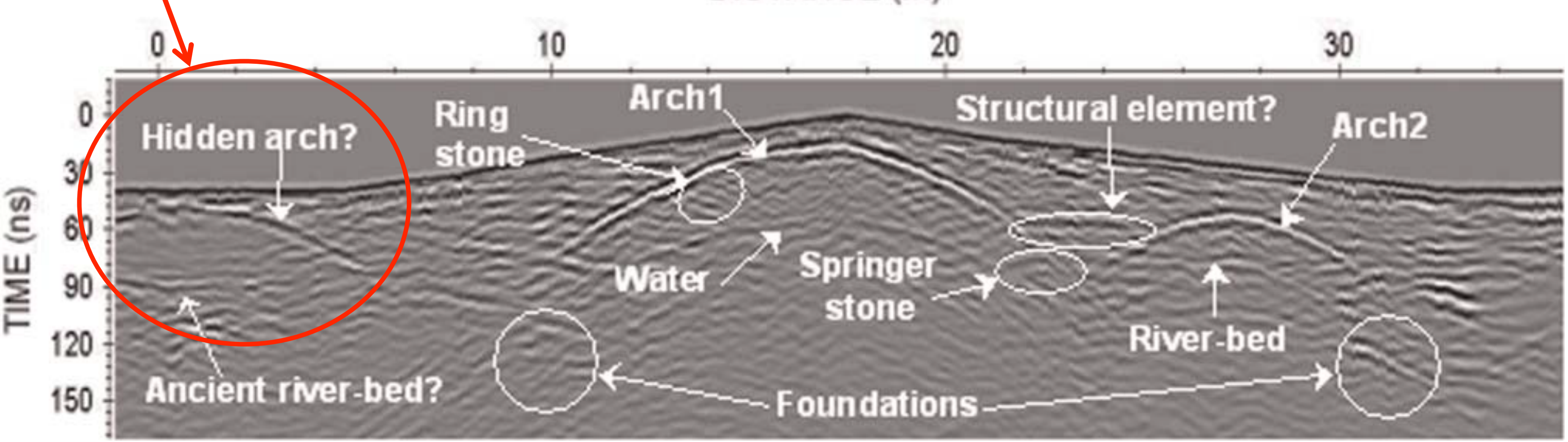


Fig. 2. Interpretation of the 250 MHz measured data and doubts in the interpretation.

II. Case study A San Antón Bridge: field data

- The interpretation of field data in Fig. 2 reveals the presence of internal structures previously unknown:
  - Three large upward arch reflections are visible. But, the bridge has only two visible arches. The third reflection is probably generated by an arch that cannot be seen due to later constructions.
  - Observing the arch reflections, it is important to notice the polarity inversion of the third reflection compared to the two reflections originated by visible arches. This suggests that the third arch is not empty and is filled with a material where the propagation velocity is lower than in the granitic masonry of the arch. The filling itself does not produce reflections, this means it is rather homogeneous.
  - Below the unexpected arch reflection there is an additional reflection, most probably due to the bed of a river channel which existed in former times.

II. Case study A

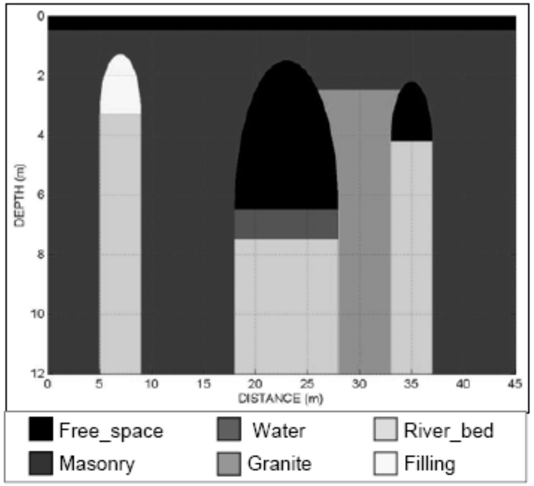
San Antón Bridge: basic model

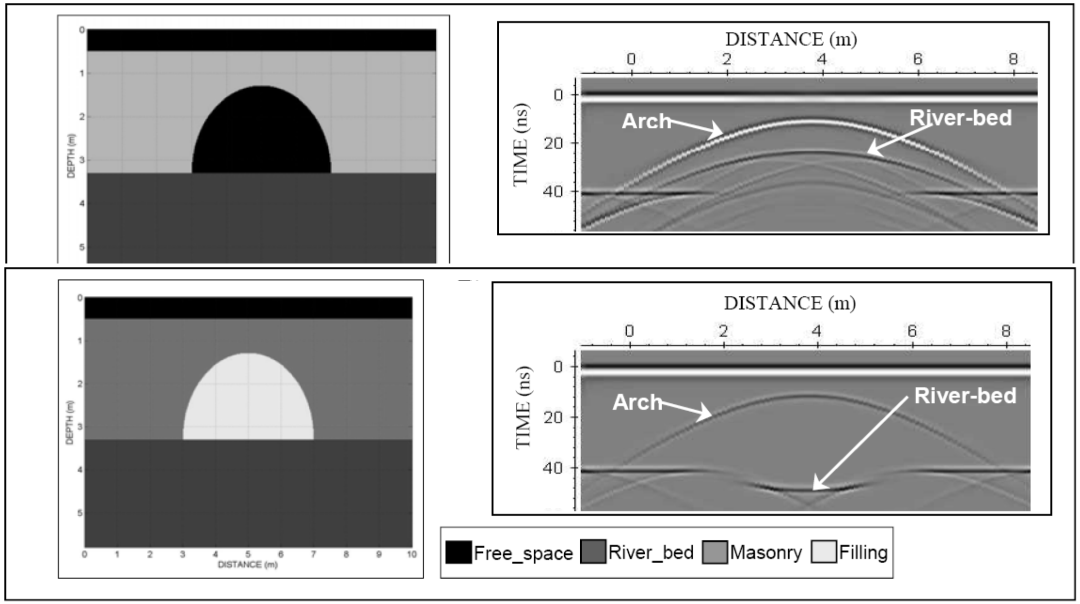
- There are no historical references in the literature, concerning the third arch.
- Two dimensional FDTD models were developed, to achieve a better understanding of the GPR wave propagation and scattering phenomena and ease the interpretation of experimental data. For example, simulations were carried out to study the effect of air or soil filling on the signal polarity (the purpose was to understand whether the third arch was empty or filled).
- The FDTD models were built based on the measured external geometry of the bridge.

II. Case study A San Antón Bridge: basic model

FDTD models

“basic geometry”





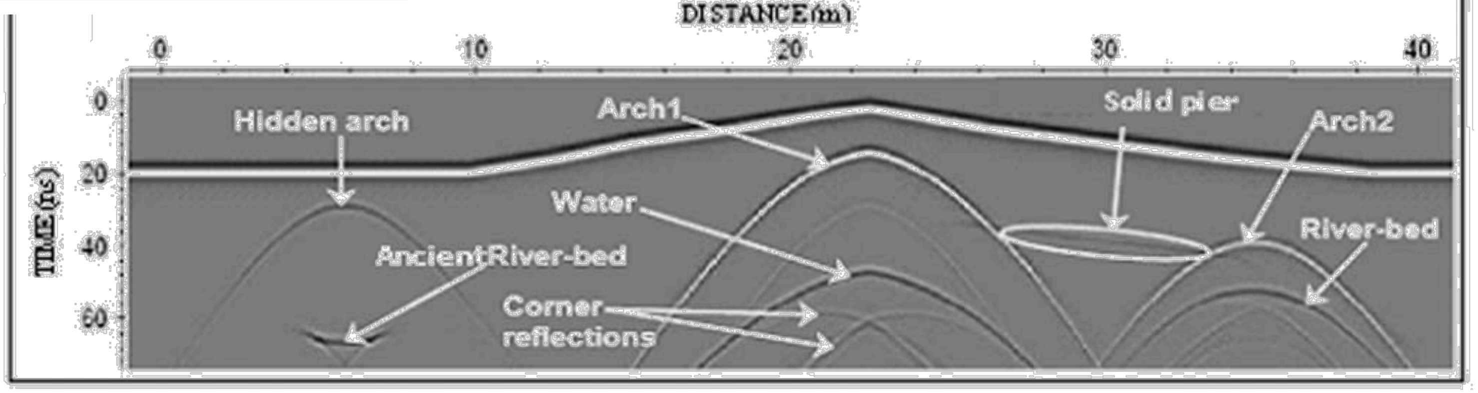


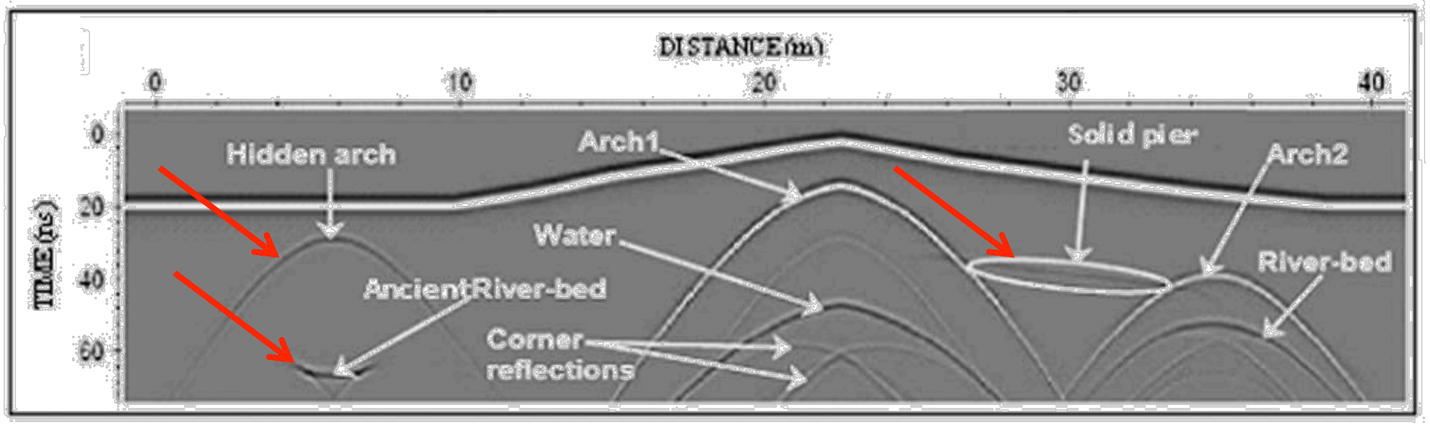
Fig. 3. Interpretation of the 250 MHz synthetic data.

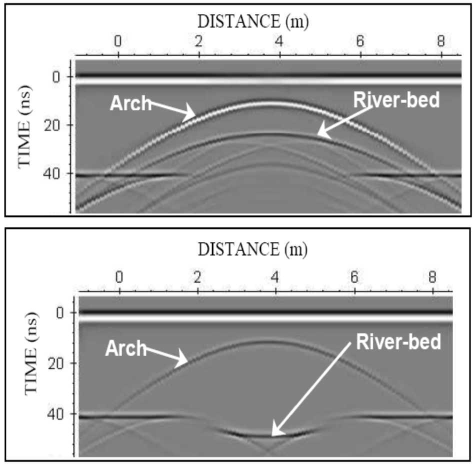
COST is supported by the
EU Framework Programme Horizon2020

II. Case study A

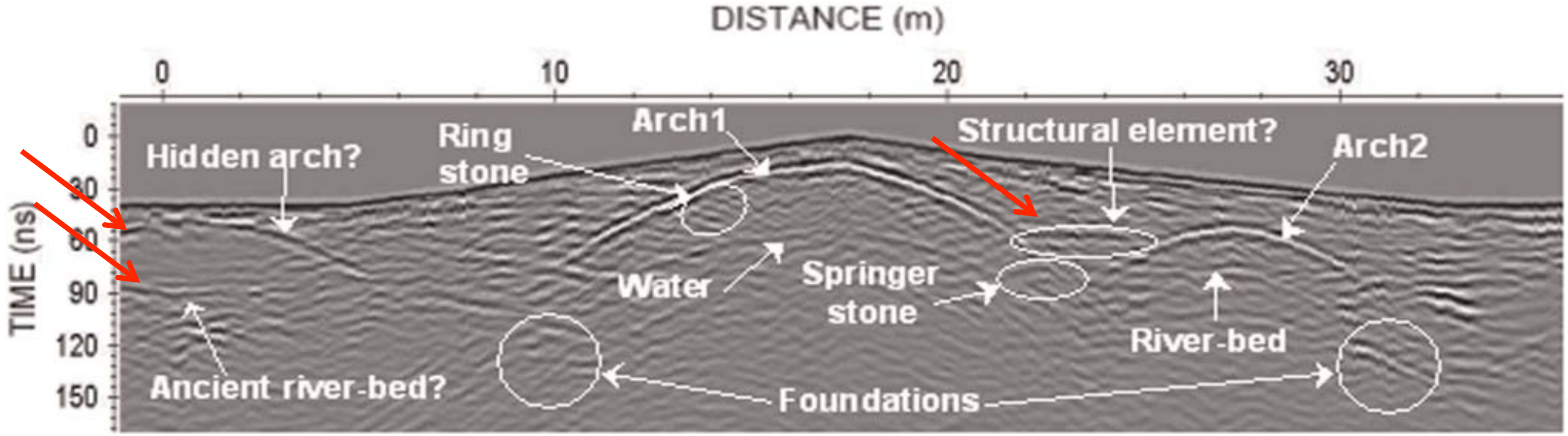
San Antón Bridge: basic model

Fig. 4. Comparison of Synthetic and Measured Data.





Synthetic data



250 MHz measured data

COST is supported by the
EU Framework Programme Horizon2020

II. Case study A

San Antón Bridge: basic model

QUESTIONS:

- Hidden arch?
  - □ Filled or empty?

There is a third hidden arch
Inversion of the signal polarity: Filled
Flat reflection from the river-bed: Filled

- Structural element?

Macize or solid ashlar

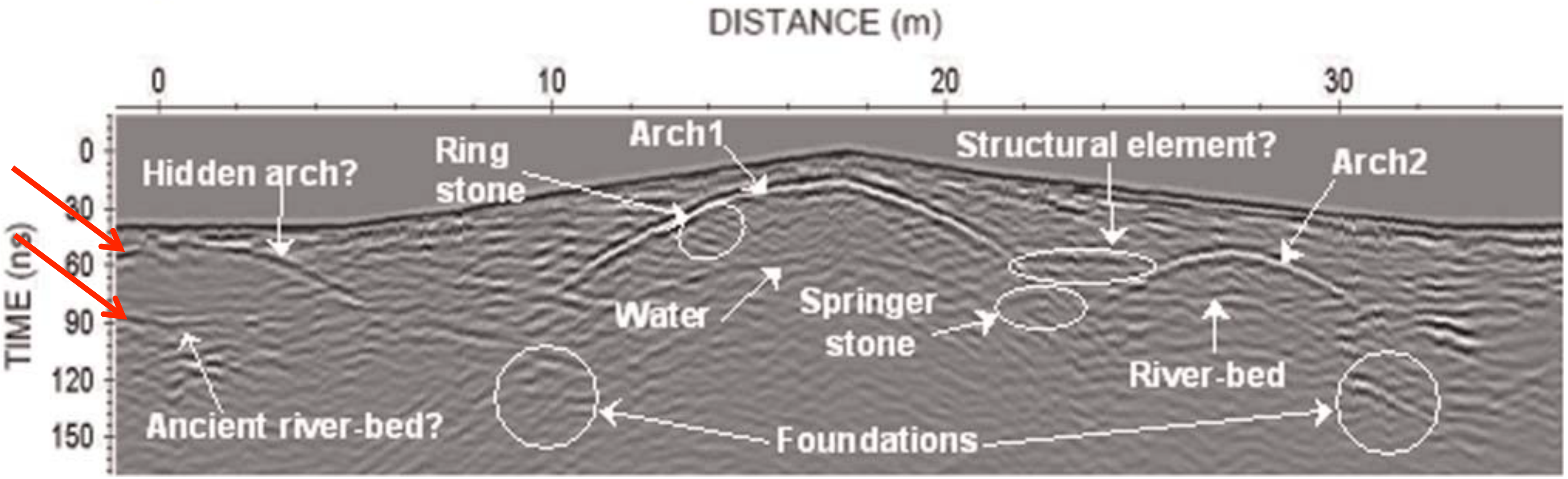


Fig. 5. Final interpretation of the 250 MHz measured data.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study A San Antón Bridge: basic model

- The synthetic data show reflection patterns similar to the field data (Fig. 4).
- In complex structures, such as masonry bridges, without a comparison of actual profiles and simulation results, it can be difficult to interpret the experimental data and obtain information about previously unknown structural elements (such as hidden arches, Fig. 5).
- Some limitations of this approach were found:
  (1) the geometry of the bridge, and particularly the arches, should be more accurately defined; and ,(2) the complete simulation in Fig. 3 took a significant amount of time (about three days!).
- More information and further results are in [1].

II. Case study B

Traba Bridge: field data

Fig. 6. Orthophoto of the upstream wall of the Traba Bridge produced by laser scanning methods.

QUESTIONS:

- Void in a pier?

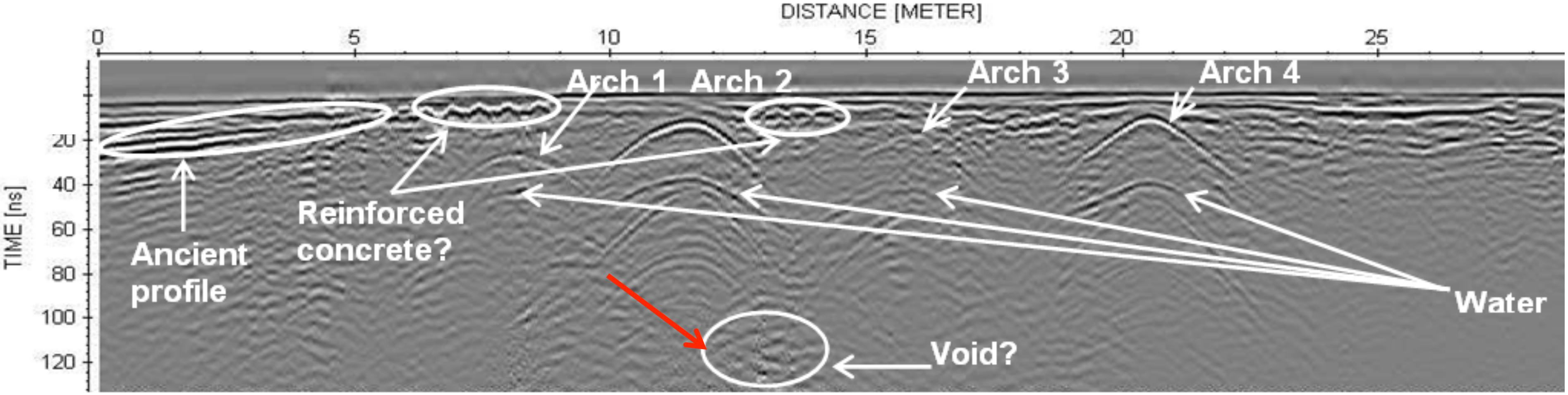


Fig. 7. Interpretation of the 250 MHz measured data and doubts in the interpretation.

COST is supported by the
EU Framework Programme Horizon2020

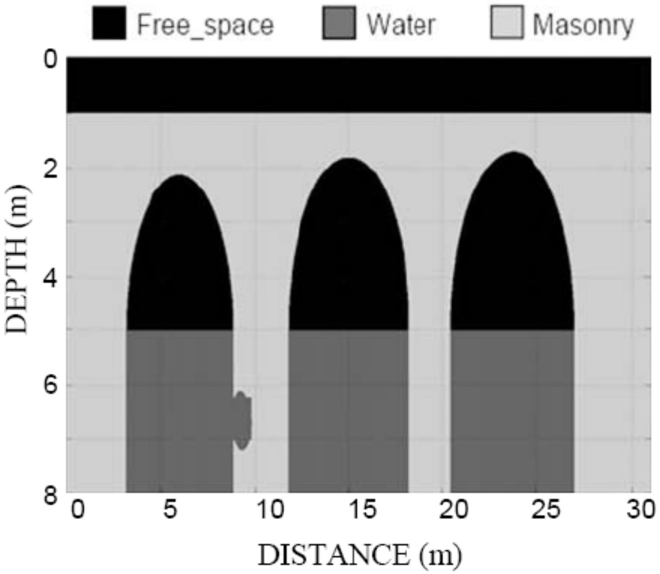
II. Case study B

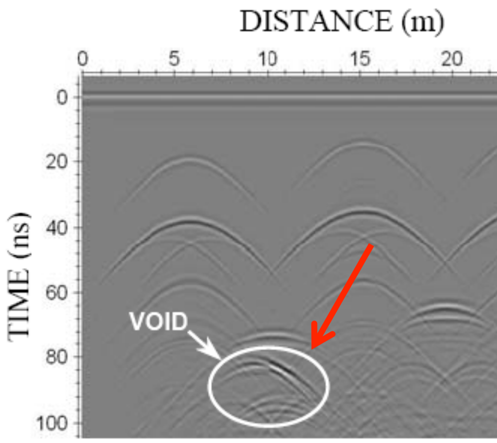
Traba Bridge: field data

- Fig. 7 shows reflections due to the arch-air and air-water interfaces. A severe attenuation of the signal in the first and third arches is observed. This effect is probably due to the presence of construction materials different than the original ones.
- Over the two restored arches, a reflection pattern is noted, composed by a series of small hyperbolas most likely generated by reinforced concrete.
- During an underwater inspection carried out a few days after the survey, a cavity in the central pier of the bridge was found. This fault could be correlated with an anomaly identified in the same pier and interpreted in Fig. 7 as a probable void location.
- Fig. 8 shows the synthetic data produced when simulating a cavity through the use of a basic geometry.

II. Case study B

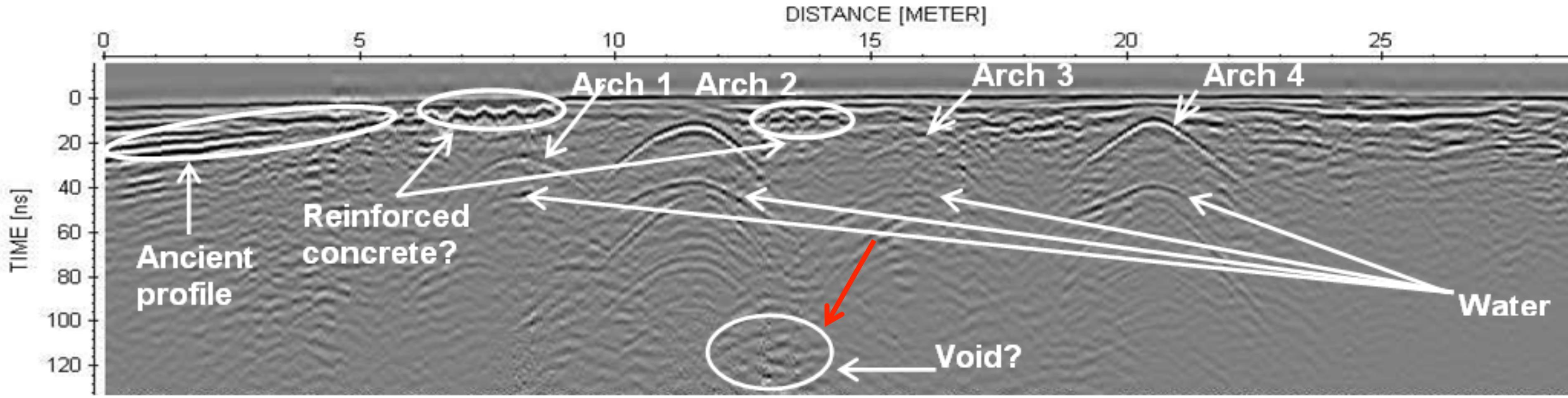
Traba Bridge: basic model





Synthetic data

Fig. 8. FDTD model: basic geometry



Measured data

COST is supported by the
EU Framework Programme Horizon2020

II. Case study B

Traba Bridge: realistic model

- To develop a more accurate and realistic FDTD model, 3D data of bridges obtained by laser scanner were used as inputs to create the model. The model was elaborated from the binarized orthophoto (Fig. 9) and the electromagnetic properties were randomly assigned by simulating a heterogeneous masonry.

Photogrammetry: Real geometry

Binarized image: FDTD model

Fig. 9. Binarized image used as input to create the synthetic model.

II. Case study B

Traba Bridge: realistic model

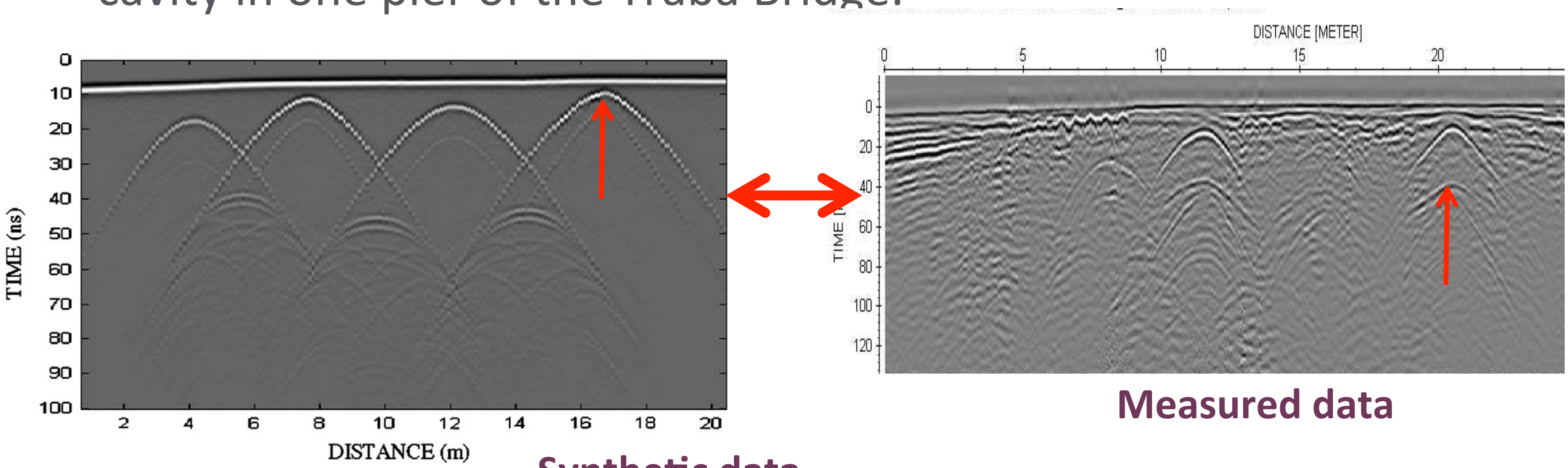
- When structures of fine geometry need to be modeled, the spatial discretization step has to be very small, in order to achieve a fine staircase approximation of the real continuous boundary. This approach results in huge computer memory requirements and very long computation time.
- The new gprMax uses a mixed model of parallelization, based on a hybrid MPI and OpenMP programming, which allows to calculate different GPR traces with different nodes of a cluster.
- More details are in [2].

COST is supported by the
EU Framework Programme Horizon2020

II. Case study B

Traba Bridge: realistic model

- The synthetic radargram (Fig. 10) shows all the reflections produced by the structural elements of the bridge, including irregular arch geometries, presence of multiple reflections, corner reflections, and reflections from the foundations and filling between arches. The complex reflection pattern can hinder the detection of some interesting reflectors, such as the presence of a cavity in one pier of the Traba Bridge.



Measured data

Synthetic data

Fig. 10. Results of realistic FDTD models and comparison with field data.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study C

Monforte Bridge: model with different media

- Fig. 11 shows a processed 500 MHz field radargram, with a homogeneous area (arch ring thickness) over the intrados of the vault. The filling-stone interface was not clearly identified because of the amount of diffractions generated at this interface by multiple sources such as a probable ring separation, the usual irregular geometry of the ring stones in the interior of the structure, and the heterogeneous filling over the arch.

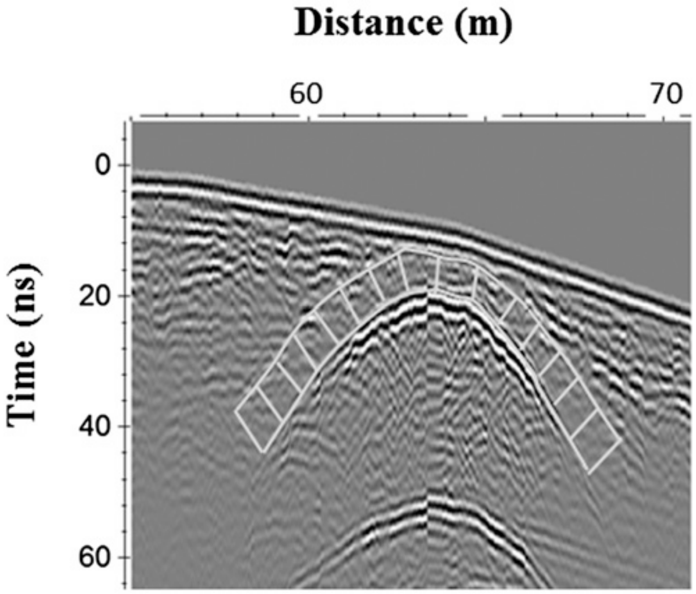


Fig. 11. 500 MHz measured data showing the homogenous area corresponding to the arch ring thickness.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study C

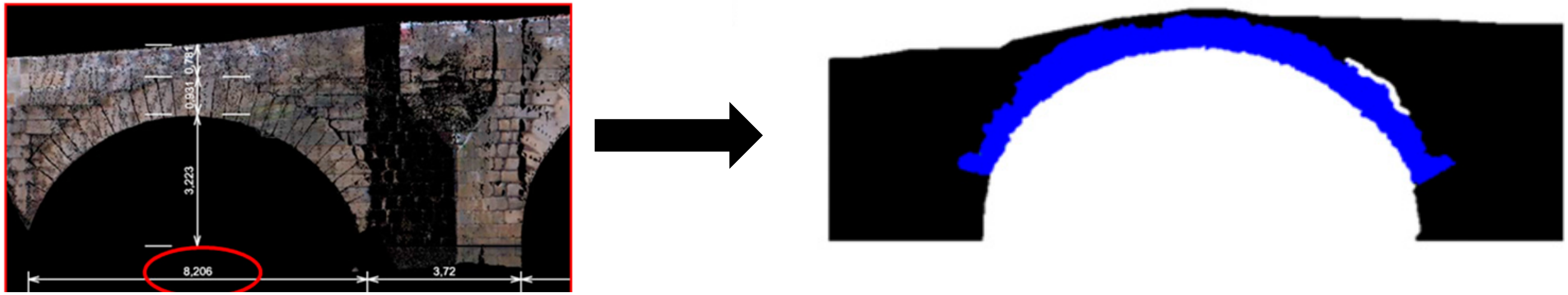
Monforte Bridge: model with different media

- The approach used to create the models was similar to the one adopted in the previous study. But here, more than two media were introduced in the model.
- The main purpose of the study was to investigate the capability of GPR to evaluate the arch ring thickness, which is a parameter influencing the arch stability.
- A careful interpretation of the complex pattern of reflections in the radargrams, aided by FDTD modelling, also allows for the detection of inner structural damages, such as delaminations and arch ring separation.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study C

Monforte Bridge: model with different media



Orthoimage

Processed image

Fig. 12. Processed image used as input to create the synthetic model.

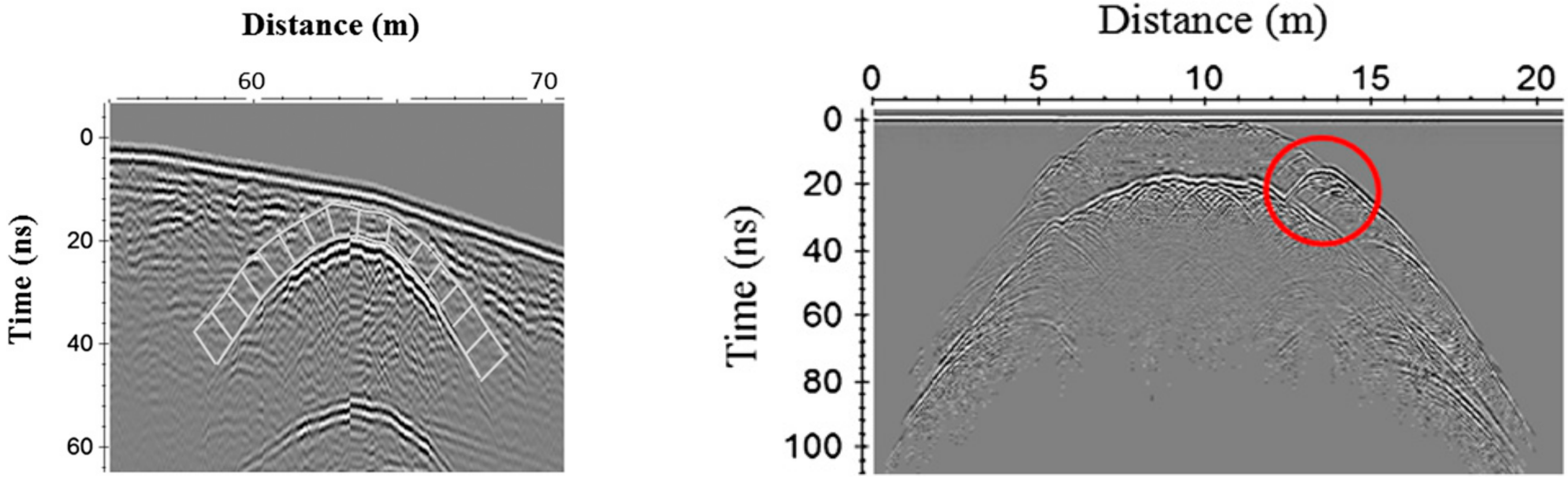
- The geometry of the models was built by using the contour of the arch ring on the orthoimage (Fig. 12). For that purpose, the orthoimage was suitably processed: regions made of different materials were identified, according to the different hypotheses of simulation; each material was represented by a different colour.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study C

Monforte Bridge: model with different media

- Regular interfaces produce a shift in the polarity of the signal, compared to the direct signal. This shift was not clearly observed in the synthetic data (Fig. 13).
- More details can be found in [3].



Measured data

Synthetic data

Fig. 13. Synthetic data produced from the simulation shown in Fig. 12.

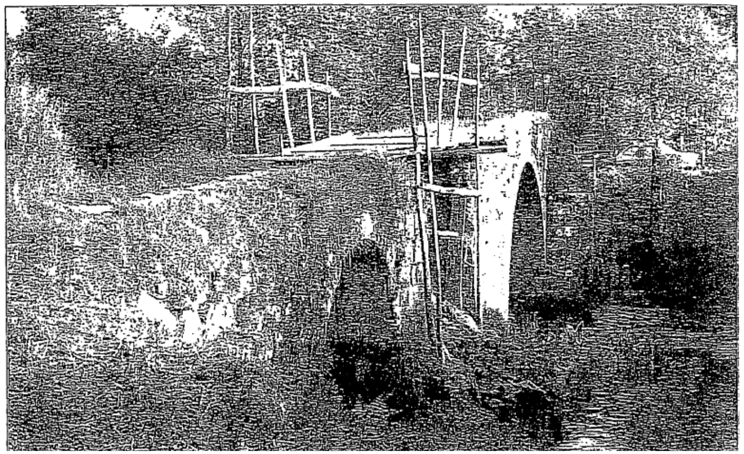
COST is supported by the
EU Framework Programme Horizon2020

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

QUESTIONS:

-Restorations?



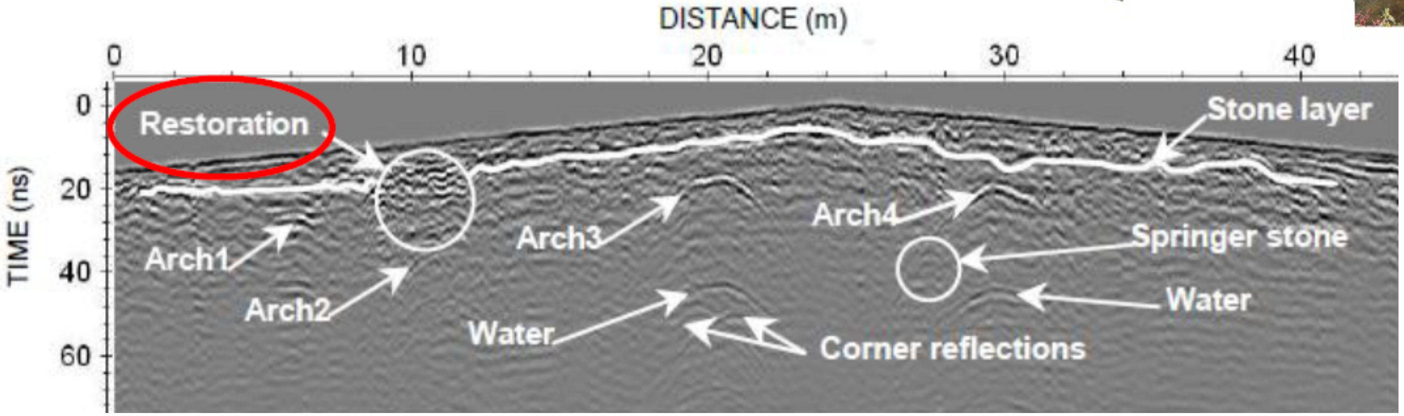


Fig. 14. Interpretation of the 500 MHz measured data.

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

- Fig. 14 shows the field data, with the reflections produced at the arch-air interfaces. A continuous reflection can be observed along the entire radargram, which allows to measure the pavement thickness. A pattern of reflections can be easily noticed, over the first arch at the beginning of the radargram, which probably indicates the existence of construction materials different than the original ones. Some authors wrote in the literature that this vault was reconstructed because of a great flood in 1984.

- It is possible that this bridge was rebuilt several times, judging by the existence of different materials in its stonework (granitic ashlar, mortar with high content in clay, and cement in the portion rebuilt in the twentieth century).

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

- An integrated approach was developed to assist in the analysis of field GPR data, with the purposes of classifying different fillings in the stonework of the restored Lubiáns Bridge and defining their distribution.
- Realistic FDTD models were created by exploiting both photogrammetric and thermographic surveys. The precise geometry provided by photogrammetry defined the structure in fine detail. Thermography was used to distinguish areas of the stonework made of different materials (corresponding to different heat-emissivity values). The execution of simulations allowed to define the composition and distribution of the filling.

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

Region	Materials	k
Pathway	Granitic flagstones & cement	[5-7;60%] & [12-13;40%]
Original	Granitic ashlar	[6-7;100%]
Rest. 18th	Granitic masonry & clay	[7-9;60%] & [11-14;40%]
Rest. 20th	Granitic masonry & cement	[7-9;60%] & [11-14;40%]

Table 1. Media characterization.

- The media characterization in Table 1 was obtained from the combined analysis of field and synthetic GPR data.
- For the geometric reconstruction of the bridge, RGB images were used to create the primary model (photogrammetry). Then, thermographic images were superimposed to the model. After defining projection planes of the areas of interest, ortho-thermograms were obtained, as shown in Fig. 15.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

Fig. 15. Results of the geomatic surveys: 3D model with RGB (a) and thermographic (b) texture (downstream view).

- The orthothermogram was used as a basis for classifying the different materials and for realizing an accurate FDTD model. Similar temperatures corresponded to regions with similar properties.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

- The first step consisted of transforming the original color palette (256 colors) to a version with up to 16 colors (Fig. 16a).
- The second step consisted of eliminating grey areas, which were zones with no assigned temperature (Fig. 16b). These grey areas were removed via interpolation with surrounding areas. Then, large regions were divided in smaller zones, according to the temperature in the original image.
- The third step (Fig. 16c) consisted of removing the vegetation (white areas). As it is impossible to know the real material behind this vegetation, the solution was to employ an interpolation technique with the surrounding areas.

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

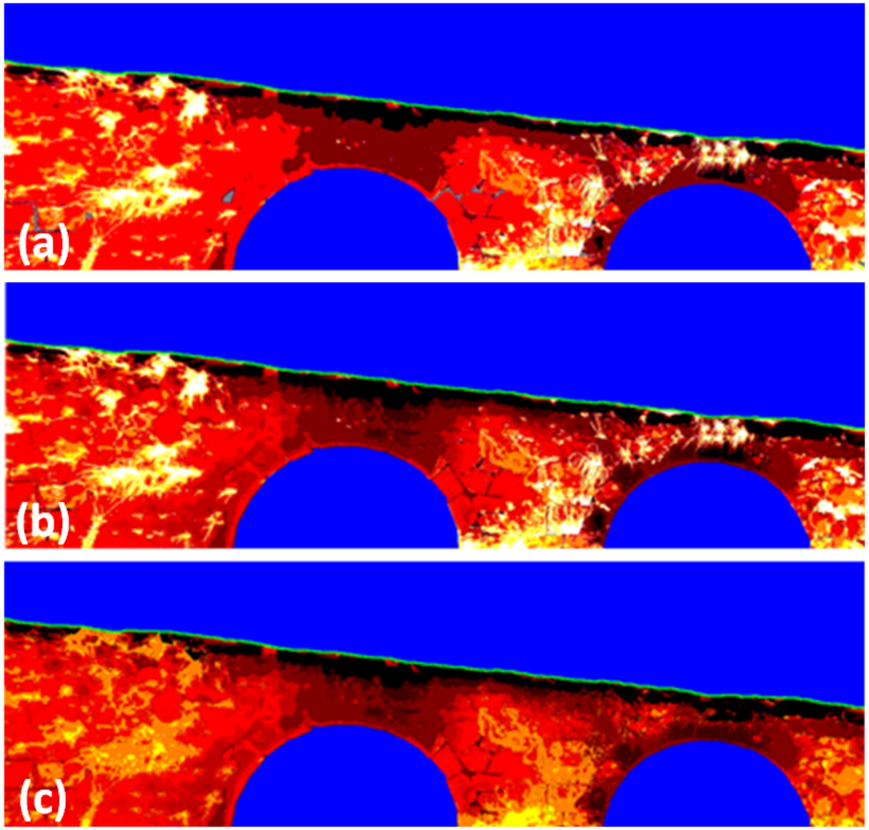


Fig. 16. Outcomes of the synthetic image generation process

COST is supported by the
EU Framework Programme Horizon2020

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

- To randomly generate layers: Pareto on/off distributions.
- Assumption (a): material layout distributions were the same for all regions. Regions formed by more than one material were modelled with a uniform distribution (each material with a custom heterogeneity setup). Fig. 18a.
- Assumption (b): A layered layout composed of stone and cement was assumed. However, layer size and material proportions did not match those of real data. Fig. 18b.
- Assumption (c): The final setup in the restored zone led to an average length of 30 cm, and the thickness was adjusted to 6 cm and 4 cm for stone and cement, respectively. The pavement structure resulted in an average length of 60 cm with a thickness of 5 cm and 3 cm for stone and cement, respectively. Fig. 18c.

COST is supported by the
EU Framework Programme Horizon2020

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods

- The comparison of measured and synthetic data allowed verifying the proper definition of the material properties and layer recreation (Fig. 19).
- More details can be found in [4].

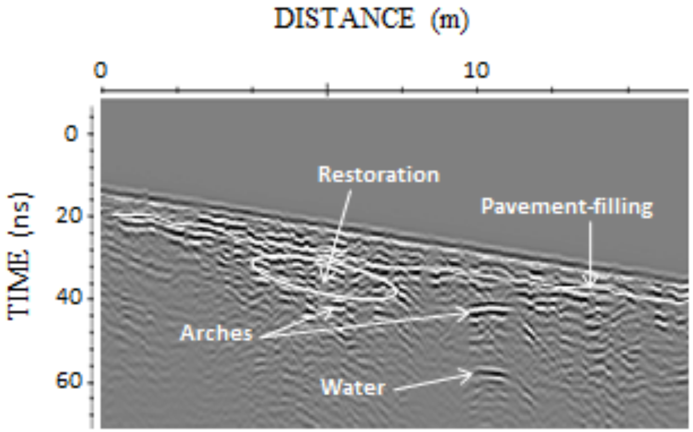


Fig. 17. Measured data showing the complex pattern of reflections produced over the restored arch.

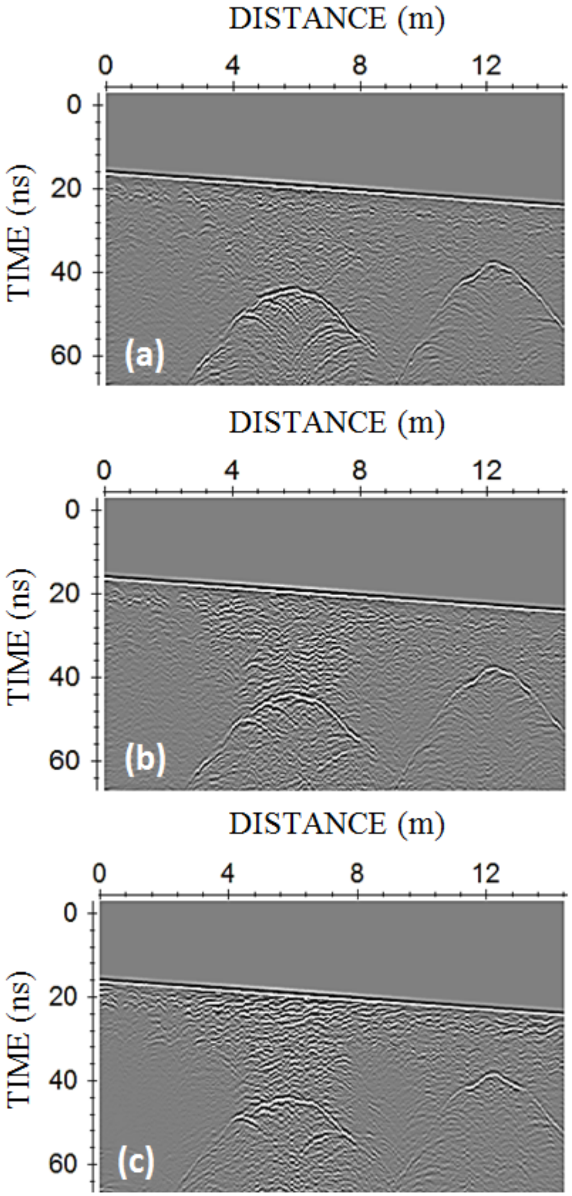
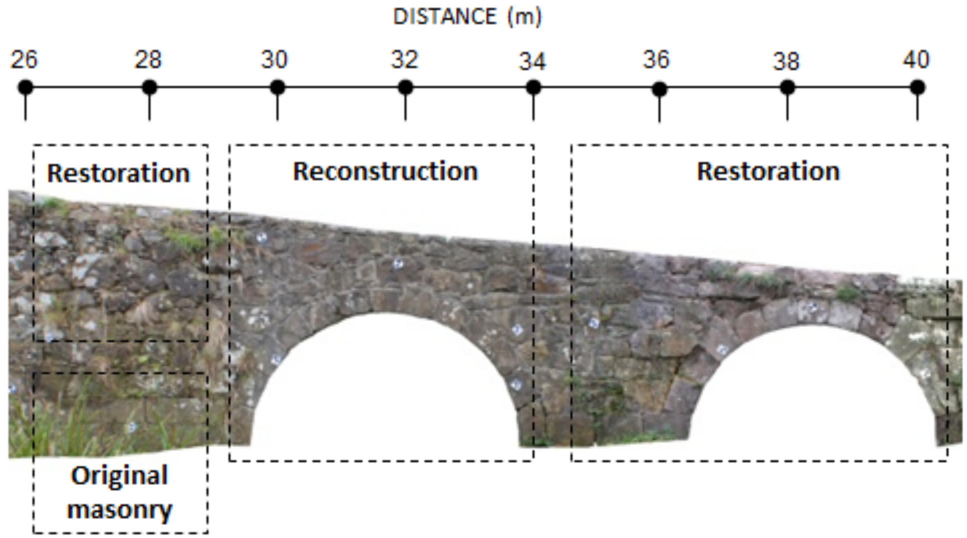


Fig. 18. Synthetic data.

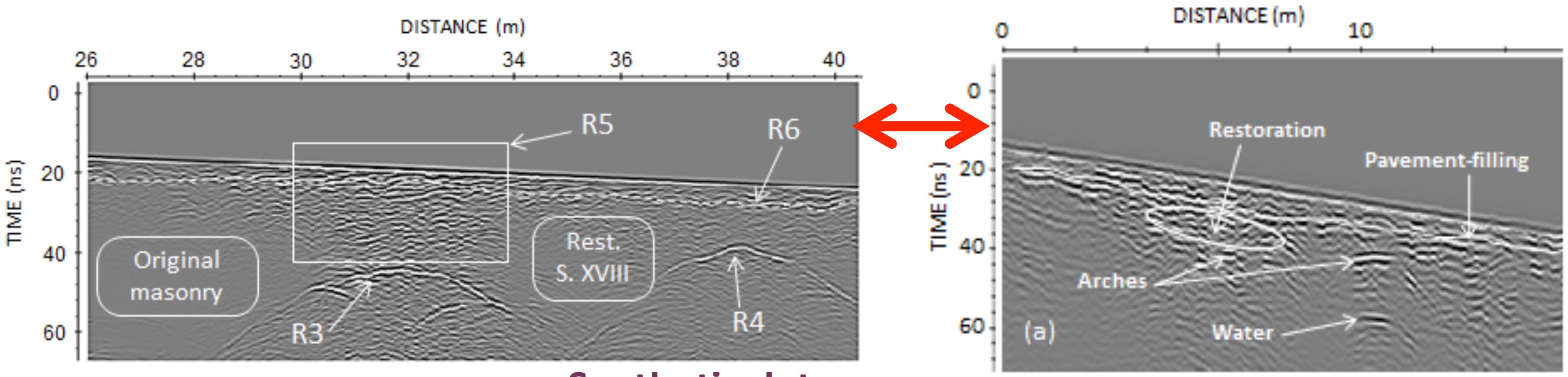
COST is supported by the
EU Framework Programme Horizon2020

II. Case study D

Lubiáns Bridge: integration of GPR with other NDT methods



Region	Filling materials	Dielectric constant (k)
Pathway	Granite flagstones	60%: 5-7
	Cement	40%: 12-13
Original masonry	Granitic ashlar	100%: 6-7
Restoration s.XVIII	Granitic masonry	60%: 7-9
	Clay	40%:11-14
Reconstructions.XX	Granitic masonry	60%: 7-9
	Cement	40%:11-14



Synthetic data

Measured data

Fig. 19. Comparison and final interpretation.

COST is supported by the
EU Framework Programme Horizon2020

III. Conclusions

- Good correlation was obtained between field and synthetic GPR data.
- FDTD modelling is an important tool for interpreting the complex pattern of reflections observed in complex and heterogeneous structures such as masonry bridges.
- Improvements are necessary in the approach for media characterization. In this context, further research will be focused on the development of more advanced and realisting models exploiting additional geophysical methods and inversion techniques.

COST is supported by the
EU Framework Programme Horizon2020

References

[1] “GPR assessment of the medieval arch bridge of San Antón, Galicia, Spain,” M. Solla, H. Lorenzo, F.I. Rial, A. Novo, 2010, Archaeological Prospection, vol. 17, pp. 223-232.

This article presents the GPR assessment of the San Antón Bridge. Interpretation and analysis of GPR reflection data were supported by FDTD numerical modelling. Results show that GPR mapping provides valuable information for detecting internal structural elements such as a possible hidden arch that remains from ancient times.

[2] “Non-destructive methodologies in the assessment of the masonry arch bridge of Traba, Spain,” M. Solla, H. Lorenzo, B. Riveiro, F.I. Rial, 2011, Engineering Failure Analysis, vol. 18(3), pp. 828-835.

This article presents the GPR assessment of the Traba Bridge. Interpretation and analysis of GPR reflection data were supported by FDTD numerical modelling. Results revealed unknown inner details such as a possible internal cavity in the central pier of the bridge.

References

[3] “Ancient stone bridge surveying by ground-penetrating radar and numerical modeling methods,” M. Solla, B. Riveiro, H. Lorenzo, J. Armesto, 2014, J. of Bridge Engineering, vol. 19 (1), pp. 110-119.

This article presents the GPR assessment of the Monforte Bridge. Interpretation and analysis of GPR data were supported by FDTD numerical modelling. The results revealed unknown information from the interior of the structure such as hidden arches, thickness of ring stones and restorations.

[4] “Evaluation of historical bridges through recreation of GPR models with the FDTD algorithm,” M. Solla, R. Asorey-Cacheda, X. Núñez-Nieto, B. Conde-Carnero, 2016, NDT&E International, vol. 7, pp. 19-27.

This article presents the GPR assessment of the Lubiáns Bridge. Interpretation and analysis of GPR data were supported by FDTD numerical modelling through the combination of photogrammetric, thermographic and field GPR data. The results allowed to define the composition and distribution of materials.

Author

Dr. Mercedes Solla (merchisolla@cud.uvigo.es) is an Associate Professor in the Defense University Center (Spanish Naval Academy) and a researcher in the Applied Geotechnologies research group at the University of Vigo. She is an active member of the COST Action TU1208 and the Vice-Leader of Working Group 4, dealing with the applications of Ground Penetrating Radar (GPR) outside from the civil engineering area and with the combined use of GPR with complementary non-destructive testing approaches.

Mercedes' research interests include GPR methodology and its applications, as well as the development of electromagnetic modelling approaches for an advanced interpretation of GPR data. She is the editor of a book on non-destructive testing and the author(co-author of more than 10 book chapters, more than 35 journal papers, and more than 80 papers in conference proceedings. For more info on Mercedes' scientific activity, please visit this website: https://www.researchgate.net/profile/Mercedes_Solla_Carracelas

COST is supported by the
EU Framework Programme Horizon2020

Thank you

TU1208 Education Pack

COST Action TU1208

Civil Engineering Applications of Ground Penetrating Radar

www.GPRadar.eu

info@GPRadar.eu

www.cost.eu

www.facebook.com/COSTActionTu1208/

COST is supported by the
EU Framework Programme Horizon2020