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Radar Inspection of Structures

Inspection par radar des structures

Radaruntersuchung von Bauwerken

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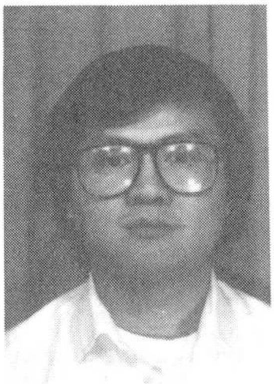

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SUMMARY

Subsurface radar is being used increasingly during the investigation and appraisal of a wide range of existing buildings and structures. The technique has been used regularly to obtain details of construction features and defects. The use of radar techniques to estimate the moisture content and porosity of construction materials poses a severe test of the method. The paper discusses briefly alternative methods of measurement and a number of dielectric models which have been employed as a basis for interpreting measured data.

RÉSUMÉ

Le radar est de plus en plus utilisé dans le cadre des études et évaluations d'une vaste gamme de structures et de bâtiments existants. La technique est régulièrement utilisée pour obtenir des détails sur les caractéristiques et les défauts de construction. L'utilisation d'un radar pour évaluer la teneur en eau et la porosité des matériaux de construction peut représenter un test sévère de la méthode. Cet article aborde brièvement les différentes méthodes de mesures et un nombre de modèles diélectriques qui ont été utilisés pour former la base de l'interprétation des données mesurées.

ZUSAMMENFASSUNG

Tiefenradar kommt bei der Untersuchung und Beurteilung von verschiedenartigen bestehenden Gebäuden und Bauwerken zunehmend zum Einsatz. Das Verfahren wird regelmässig zur Ermittlung von Detailaspekten des Baus und von Fehlern benutzt. Die Bewertung des Feuchtigkeitsgehalts und der Porosität von Baustoffen kann das Radarverfahren schwer auf die Probe stellen. Das Referat behandelt in Kürze alternative Messmethoden und eine Reihe von dielektrischen Modellen, die als Grundlage zur Ausdeutung von Messdaten eingesetzt werden.

1. INTRODUCTION

1.1 The use of subsurface radar has grown considerably in recent years, both as a geophysical tool and for the investigation and assessment of civil engineering structures and buildings. Most commercial radar surveys are carried out using impulse radars. These work by transmitting impulses of electromagnetic energy and receiving energy backscattered (reflected) at discrete interfaces within the medium being surveyed. In general energy is reflected at changes in permittivity, but very thin conductive layers may produce reflections similar to those associated with electrical permittivity variations [1].

1.2 The relative permittivity (ε_r) of dry solids is generally in the range 2 - 8, air has a value of unity and water about 80, in the frequency range of interest. The presence of moisture in a porous media has a large influence upon its effective relative permittivity. For example 'dry' mature concrete $\varepsilon_r \approx 6$, whereas in a saturated mature concrete $\varepsilon_r \approx 12$. This paper discusses briefly alternative methods of measurement and a number of analytical dielectric models which have been employed as a the basis of interpreting measured data.

2. MEASUREMENT TECHNIQUES

2.1 Two different measurement techniques are available employing :

i) air-launched pulses propagated from horn antennas mounted away from the surface being irradiated. This equipment tends to operate at frequencies between about 1 - 3 GHz. Its non-contacting nature allows data to be gathered at high speed and the method has been widely used for pavement thickness evaluations [2].

ii) ground-coupled antennas where the equipment is in contact with the medium being surveyed. Centre operating frequencies range from about 10 MHz to 2 GHz, although frequencies above 500 MHz are most commonly employed on buildings and structures. Ground coupled antennas are sensitive to changes in the permittivity and conductivity of the surface layer of the medium being surveyed. The performance of antennas showing marked variations in some instances.

2.2 Material properties can be evaluated by either reflection or transmission. Air-launched pulses are most commonly used for reflection measurements. As might be expected, such measurements only provide information on the relative permittivity of the material in the surface zone. The transmission technique involves passing a pulse through the media, recording the transit time for a pulse reflected from the rear wall. Accordingly the value of relative permittivity established is an average value for the full depth of member in question. Consider the case of a concrete slab. Millard et al [3] report comparisons of ε_r obtained by reflection and transmission techniques.

Specimen Thickness (mm)	Storage Condition	% Saturation	Estimated ε_r	
			Reflection	Transmission
150	Dry	31	5.8	5.8
400	Dry	41	6.0	8.0
300	Wet	100	10.0	10.2

It will be seen that moisture gradients within porous media can produce erroneous estimates of ε_r as the surface zone is not representative of the body of the media. This can have a significant effect on the estimated propagation velocity and, hence, the estimated thickness of layers. There is a corresponding influence upon any estimates which might be made for the moisture content of the media.

2.3 Another potential source of error is the increase in reflectivity of an interface brought about by the conductivity of the media. In general this is likely to be a small influence at the frequencies employed, unless the effective conductivity at the frequency is large (1 GHz, $\sigma > 0.1$ S/m; 2 GHz, $\sigma > 0.25$ S/m) - refer Figure 1. The DC electrical conductivity of concrete is reported to range from 0.2 S/m for wet concrete to 0.001 S/m for dry concrete. There is little available data concerning the relationship between

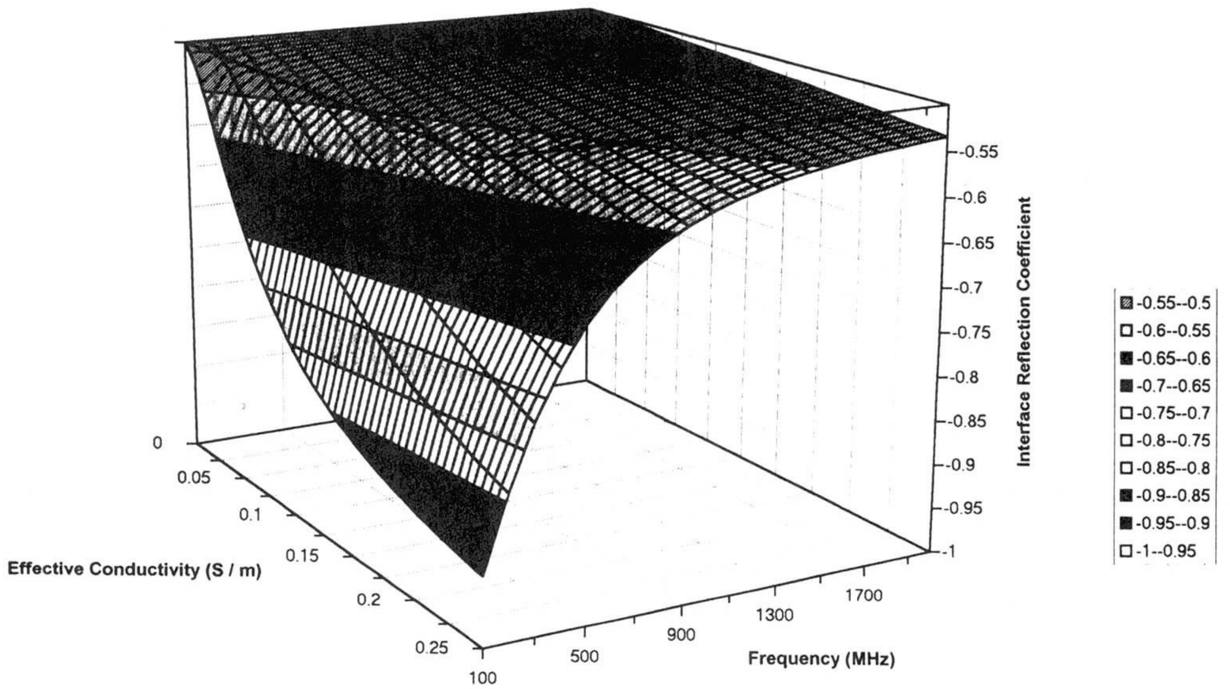

Figure 1 : Interface Reflection Coefficient versus Frequency and Conductivity of Medium 2 (Concrete) for Relative Permittivities, Er1 = 1, Er2 = 9
NB. Conductivity of Medium 1 (Air) = 0

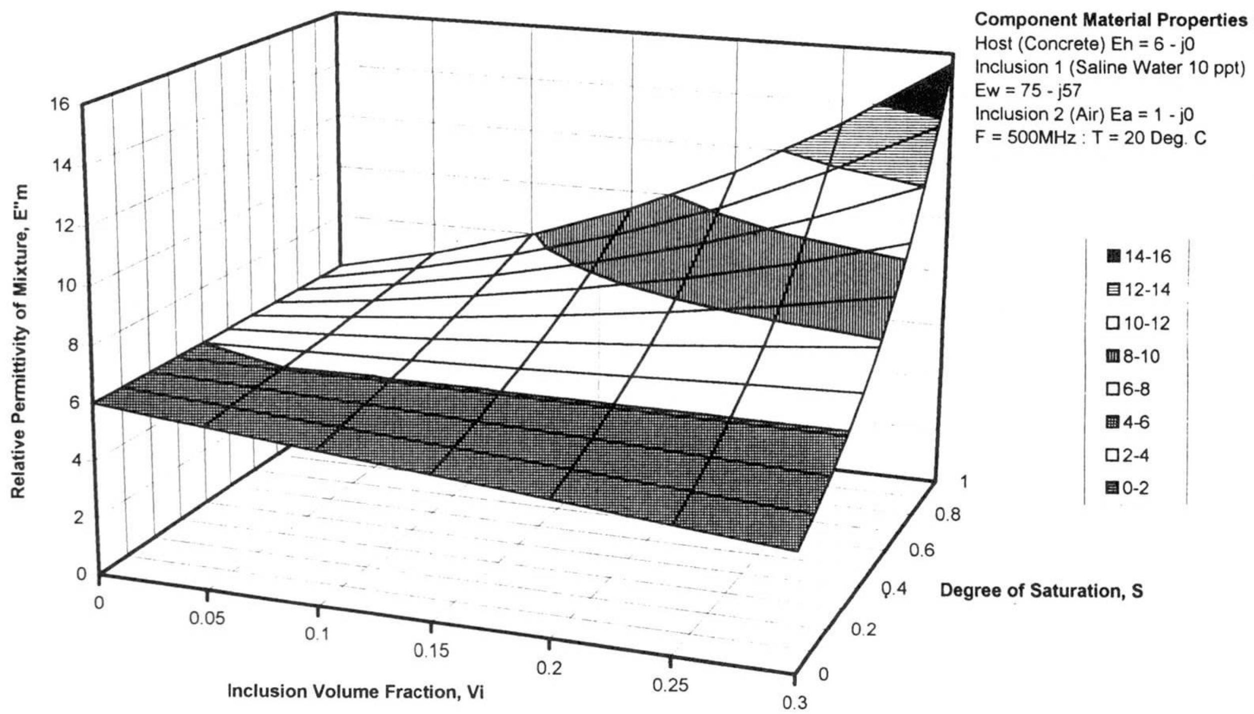

Figure 2 : Relative Permittivity of Mixture Based on Three Phase Spherical Inclusion Dielectric Model (after de Loor) Concrete : Water : Air [E* = Em]

DC and effective conductivity at microwave frequencies for construction materials, although effective conductivity is known to increase with frequency.

3. DIELECTRIC MODELS

3.1 The short length of this paper only permits the briefest consideration of the formulation and use of analytical dielectric models. This is a topic of considerable practical interest, the objective being to determine the dielectric properties of a heterogeneous mixture of two or more substances of known permittivities. Factors influencing the average permittivity of a mixture include the permittivities of the individual substances, their volume fractions, spatial distributions and shapes of the constituents and their orientation relative to the electric field vector of the incident electromagnetic waves. The substance having the highest volume fraction is generally regarded as the host medium, with the other substances being inclusions.

3.2 Many types of dielectric models have been developed and several comprehensive reviews of the topic have been presented in the literature [4,5]. For our current purposes these might be broadly classified into simple volumetric models and geometric dielectric models.

3.3 A volumetric model considers only the volume fraction of the constituents. For a two phase mixture these models generally take the form

$$\varepsilon^{\alpha}_{m} = \varepsilon^{\alpha}_{h} + V_i (\varepsilon^{\alpha}_{i} - \varepsilon^{\alpha}_{h}) \qquad \text{(E1)}$$

where the subscripts m, h and i denote the permittivities of the mixture, host and included material. V_i denotes the inclusion volume fraction. A linear mixture model is produced when $\alpha = 1$. When $\alpha = 0.5$ the dielectric model is known as the refractive model (since $\sqrt{\varepsilon}$ = refractive index of medium). Two phase models would arise only in a dry material (construction material solids + air) or a completely saturated material (construction material solids + water). In practice such materials occur rarely and most porous materials are partially saturated (construction material solids + air + water), which requires a three phase model.

3.4 Geometric dielectric models seek to provide a representation of the physical nature of material in question. Such models have a greater range of applicability than simple volumetric models. They are generally much more complicated formulations with attendant difficulties in achieving numerical solutions, particularly when consideration is given to the complex permittivity of mixtures containing water. Figures 2 and 3 illustrate the relationship between relative permittivity and dielectric loss factor of a mixture versus inclusion volume fraction (V_i) and the degree of saturation (S). Figures 2 and 3 were derived using Model 2 (see below). The model is based upon spherical inclusions within a concrete host. The difficulty of solving the 'inverse-problem', that is the estimation of the components of the mixture from a determination of relative permittivity and dielectric loss factor, will be appreciated. Such a determination gives a contour line on the surface, further information is needed to achieve a unique solution. Halabe et al [6] have applied similar methods to concrete bridge decks.

3.5 Figure 4 illustrates the relative permittivity of a concrete member estimated by various three phase dielectric models assuming an inclusion volume fraction (V_i) of 5%. This would correspond to a poorly compacted concrete. Spherical inclusions have been assumed for geometrical models. For Models 1 and 2 the spherical inclusions are of identical size. Model 5 provides for a continuous size distribution. The dielectric model details are as follows :

Model No.	Model Type
1	Polder-Van Santen-de Loor Formula. $\varepsilon^* = \varepsilon_h$ [7]
2	Polder-Van Santen-de Loor Formula. $\varepsilon^* = \varepsilon_m$ [7]
3	Feng and Sen Formula [8]
4	Linear Volumetric Model [see equation (E1)]
5	Refractive Volumetric Model [see equation (E1)]

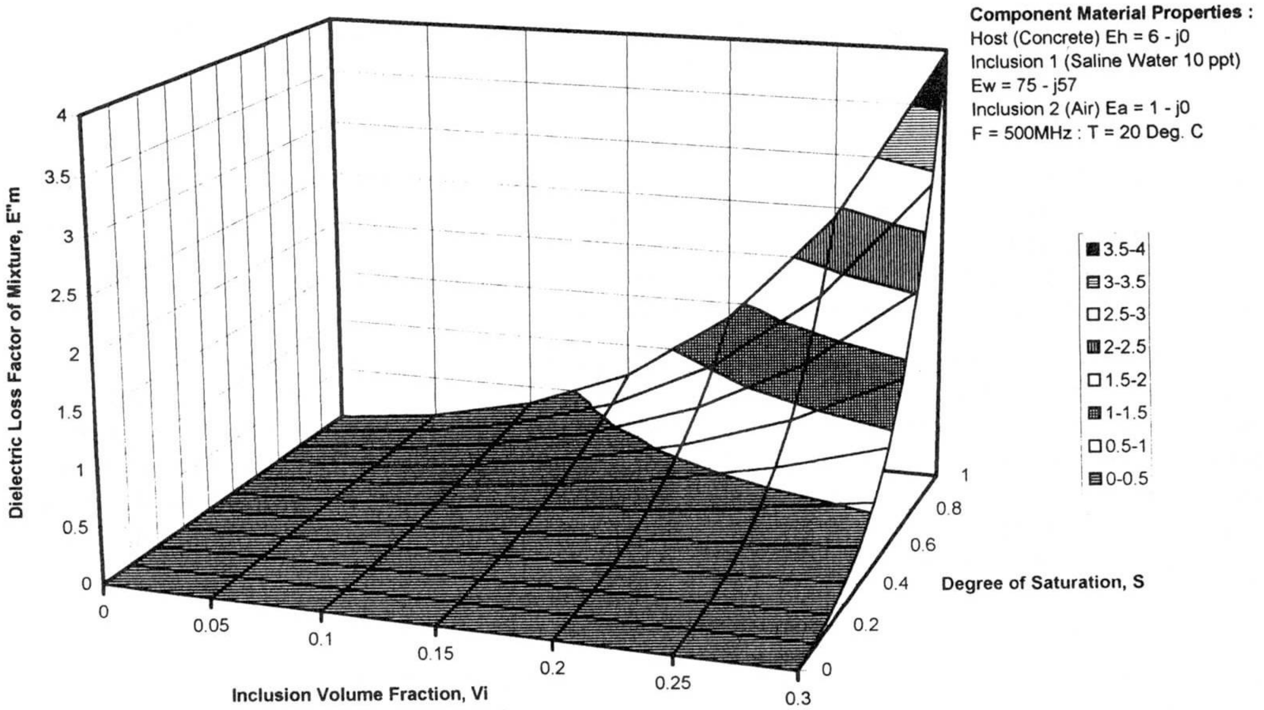

Figure 3 : Dielectric Loss Factor of Mixture Based on Three Phase Spherical Inclusion Dielectric Model (after de Loor) Concrete : Water : Air [E* = Em]

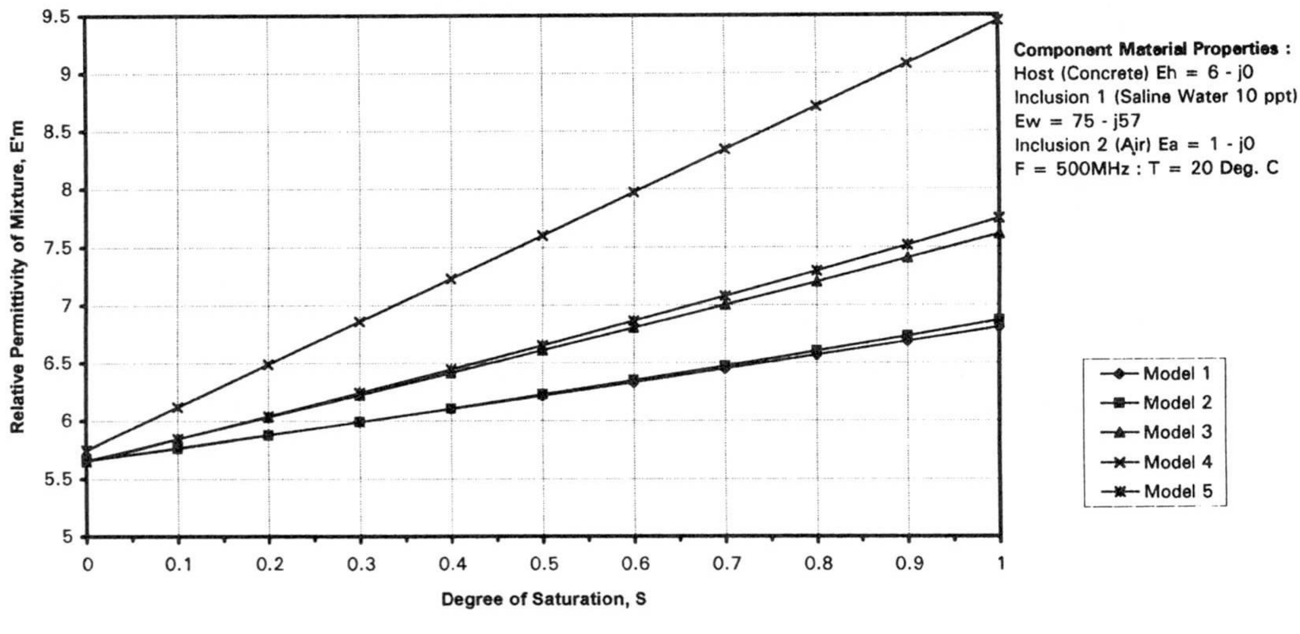

Figure 4 : Relative Permittivity of Mixture Based on Various Three Phase Dielectric Models for an Inclusion Volume Fraction, Vi = 0.05

It is clear that different dielectric models will give substantially different estimates for the degree of saturation, assuming that the inclusion void fraction were known at the measurement location !

4. CONCLUDING REMARKS

4.1 There is a need to develop dielectric models which match experimental data more closely. The effective medium type theory put forward by Feng and Sen [8] is based on grain shape and does not treat the pore space adequately. This produces computational difficulties. Endres and Knight [9] report different values for ε_r during imbibition and drainage of a porous media. They also note that fine pores have an effect on dielectric behaviour which is out of proportion to their percentage of the total porosity.

4.2 The Building Research Establishment has a programme of research into radar, current interests concern experimental measurements of structural concretes and reinforcing bars, coupled with their analytical modelling. Although it is acknowledged that further studies are required of the nature of porosity with construction materials, there is some concern that the path of ever more complicated dielectric mixture models, which seek to achieve a better representation of the physical reality of the material concerned, may not be particularly rewarding. An alternative approach may be to explore the possibilities offered by artificial neural networks.

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