

## Value of seismic data for the risk assessment of mass transport: a case study

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**Abstract** The proper evaluation of mass transport predictions calls for mapping hydraulic conductivity ( $K$ ) fields that reproduce the natural patterns of spatial variability observed in the formation and honour all the available data. These usually include  $K$ , piezometric head measurements and other types of secondary data such as those obtained by geophysical surveys. Moreover, there may be other types of information, estimated at a larger scale than that of the model, which may affect model results. This used to be the case when obtaining boundary conditions (BC) or estimating hydrodynamic parameters using a much more extensive regional model. This paper presents a study of convective transport through a clay formation that might be a candidate for placing a hazardous waste repository. A local three-dimensional model (LM) is developed based on a regional steady state flow model (RM) of the geological formation and on data provided by five vertical profiles of acoustic impedance. BC are taken from the regional model. It is shown that the smooth patterns of spatial variability in  $K$  and BC, obtained from the RM, do not provide a realistic characterization of trajectories and travel times through the formation. The use of seismic data, in the absence of direct measurements of formation properties within the LM area, proves to be a way to obtain a first estimate of the natural heterogeneity effect, providing insights to conducting further field research.

### INTRODUCTION

In order to obtain realistic mass transport predictions it is necessary to map hydraulic conductivity ( $K$ ) fields whose patterns of spatial variability reproduce those observed in the geological formation. This is generally done by applying geostatistically-based approaches that make use of direct measurements (hard data) of hydrodynamic parameters and flow and/or transport variables. If this is done within a stochastic framework, model results are characterized in a probabilistic manner. However, obtaining the hard data usually requires destructive actions in the formation and can be expensive. These reasons limit and often make their collection impossible. Another way to collect data is the use of seismic surveys. These are less costly, non-destructive and can provide a wealth of information which may reflect the formation heterogeneity at different scales. These data (secondary data) are usually related to hard data through empirical relationships, or through scattergrams when enough direct measurements are available. It is desirable to take account of such secondary information in the process of mapping hydrodynamic parameters, incorporating them with the available hard data.

This paper presents a study of convective transport through a clay formation which might be a candidate location for placing a nuclear waste repository. This case study was proposed by the Spanish Nuclear Waste Management Company (ENRESA) and is

designed using data from real formations in Spain. So far the main purpose of the research conducted has been to determine how seismic information can contribute to a better characterization of flow and transport models from the point of view of placing a deep underground repository. The objectives include both gaining insights on the flow patterns as a vehicle for transport of contaminants to the accessible environment, and identification of zones where more field research is needed.

The clay formation is a layer embedded in a more extensive geological formation for which an earlier regional steady state flow model (RM) exists. The calibration of this model has led to parameters that vary very smoothly. The clay formation is one of the deepest layers in it. Due to this fact there are very few direct measurements of the clay properties. Using data from the RM and additional information from five seismic lines, a more detailed local three-dimensional model (LM) was built. Then the effect of heterogeneity, provided by the seismic data, was evaluated and compared to results yielded by the smooth parameters taken from the RM. The smoothing effect of boundary conditions (BC) defined by the RM model was also analysed.

## FROM THE REGIONAL MODEL TO THE LOCAL MODEL

The RM is made up of seven layers of spatially variable thickness discretized in a horizontal regular grid ( $37 \times 23$ ) with block size of  $2000 \times 2000$  m. The calibration of this model is based on a reduced set of piezometric measurements from outside of the LM area. The BC conditions for the RM are based on hydrological considerations that, together with the geological interpretation, define the boundaries for the seven layers of the model.

The model calibration yields constant hydrodynamic parameters over extensive areas varying only due to lateral changes in lithology. The reference clay layer is the fifth member in the RM counted from the upper layer. Its upper limit is between 120 and 220 m deep within the LM area. The calibrated value of hydraulic conductivity ( $K$ ) in this layer is  $10^{-7}$  m day<sup>-1</sup> for clay. In the same layer, lateral changes to detritic materials appear with  $K$  equal to  $6 \times 10^{-2}$  m day<sup>-1</sup> and gypsum with  $10^{-2}$  m day<sup>-1</sup>. The overlying layer  $K$  is  $5 \times 10^{-6}$  m day<sup>-1</sup> and the underlying layer value is  $2.5 \times 10^{-3}$  m day<sup>-1</sup>.

Figure 1 shows the piezometric head distribution for the different layers and with more detail for the fifth layer. The inner rectangle on it (Fig. 1(b)) shows the LM area. Inside the latter there are five lines representing the spatial location of five seismic profiles available in the clay formation. The LM general features are:

- Regular grid of  $44 \times 48$  blocks of size  $500 \times 500$  m.
- Total thickness of 200 to 300 m. This is the area where the clay formation reaches its greatest thickness.
- Vertical discretization based on the acoustic impedance profiles that lead to definition of five different layers. Two additional layers overlying and underlying the formation are added to place prescribed head boundary conditions. The prescribed head values are taken from the RM model. The BC along the lateral limits of the LM rectangle (Fig. 1(b)) are also limits of prescribed head and are taken from the RM.
- There are lateral changes of lithology within the LM area. Presence of gypsum in the SE corner, and of detritic materials in the NW and NE corners.

### MAPS OF EFFECTIVE POROSITY AND HYDRAULIC CONDUCTIVITY

The five impedance ( $Z$ ) profiles shown on Fig. 1(b) provide the information to define the vertical discretization within the LM. The spatial distribution of this seismic attribute has been used to map porosity ( $\Phi$ ) and hydraulic conductivity ( $K$ ). Due to the lack of  $K$  and piezometric measurements in the LM zone, we have taken an empirical relationship between the parameters  $Z$  and  $\Phi$ . Following different authors as Tosaya & Nur (1982), Kowallis *et al.* (1986) or Klimentos (1991), it can be assumed that  $Z = a + b\Phi$ . The  $a$  and  $b$  coefficients are determined using the values of a laboratory test conducted for several samples taken from a borehole in the LM area. Assuming that the effective porosity ( $\Phi_{eff}$ ) is a constant fraction of the total porosity  $\Phi$ ,  $\Phi_{eff}$  is mapped for the LM as shown in Fig. 2.

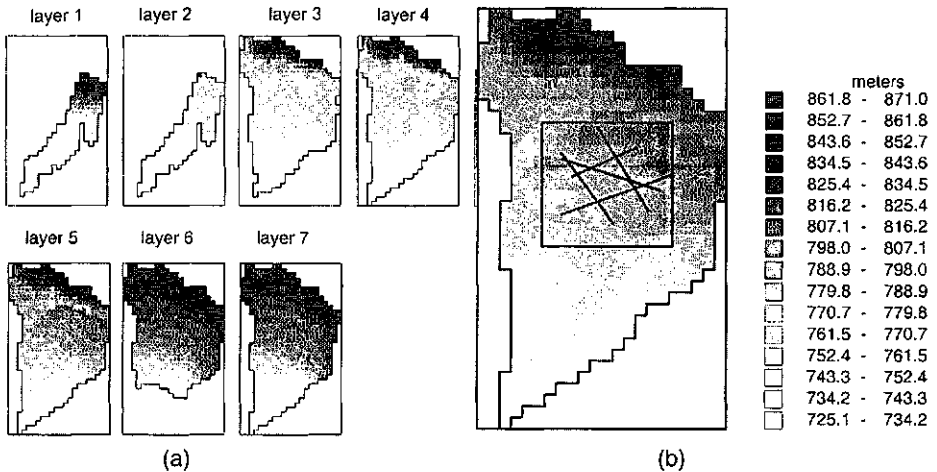


Fig. 1 (a) Piezometric head in regional model layers from upper to lower layer, and (b) local model boundary and seismic lines for clay layer. Layer 5 in RM corresponds to clay layer.

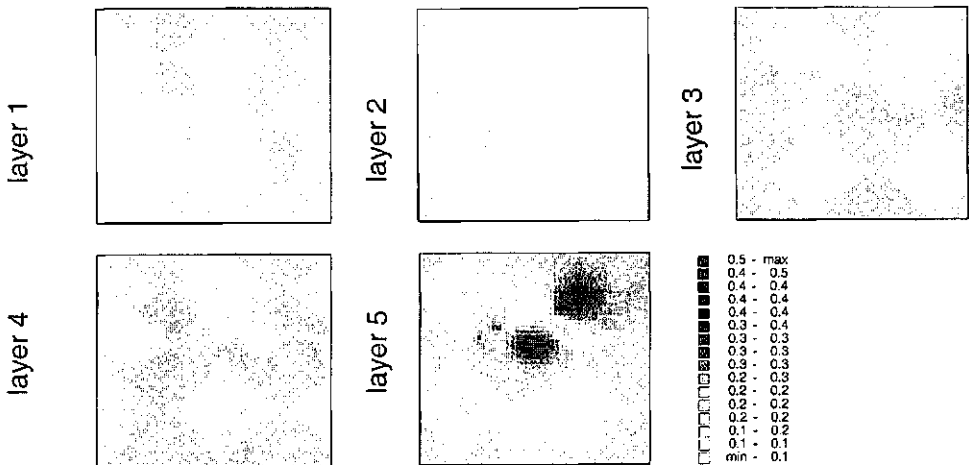


Fig. 2 Effective porosity distribution in local model layers.

Among the properties of reservoir rocks, perhaps permeability is the most difficult to predict. It depends on porosity, pore size and shape, clay content, stress, pore pressure, fluid type, saturation and other factors. However, the essential behaviour of  $K$  can often be expressed by the simple Kozeny-Carman relation that states  $\kappa = B\Phi^3/S^2$ , where  $\kappa$  is permeability,  $S$  the specific surface area and  $B$  a geometric factor.

A more general expression, successfully applied in real cases, includes a percolation threshold porosity  $\Phi_c$  and allows the exponent of  $\Phi$  to increase to a value of seven as  $\Phi$  decreases (Mavko & Nur, 1997). These considerations have led to rewriting the Kozeny-Carman expression as one equation:

$$\log_{10} K = \begin{cases} \left( 3 + (n-3) \frac{\Phi - \Phi_c}{\Phi_e - \Phi_c} \right) \log_{10} (\Phi - \Phi_c) + \log_{10} C & \Phi < \Phi_e \\ 3 \log_{10} (\Phi - \Phi_c) + \log_{10} C & \Phi \geq \Phi_e \end{cases} \quad (1)$$

where  $n$  is the lowest value to be reached by the  $\Phi$  exponent,  $C$  is a constant and  $\Phi_c$  is a threshold under which  $\Phi$  exponent starts to increase linearly, reaching  $n$  for  $\Phi = \Phi_c$ . The coefficients to be determined in equation (1) are  $n$ ,  $\log_{10}C$ ,  $\Phi_c$  and  $\Phi_e$ . With the criteria of reproducing the value of  $K$  calibrated in the RM, these coefficients have been computed for three different hypotheses of  $K$  variability. These are:

H-I:  $\sigma_{\log K} = 1.04$ ;    H-II:  $\sigma_{\log K} = 0.37$ ;    H-III:  $\sigma_{\log K} = 1.30$

In all three cases the coefficients have been calibrated with the requirement that the geometric mean of  $\log_{10}K$  matches the value  $-7$  calibrated in the RM.

Figure 3 shows the maps of  $\log_{10}K$  for case H-I.

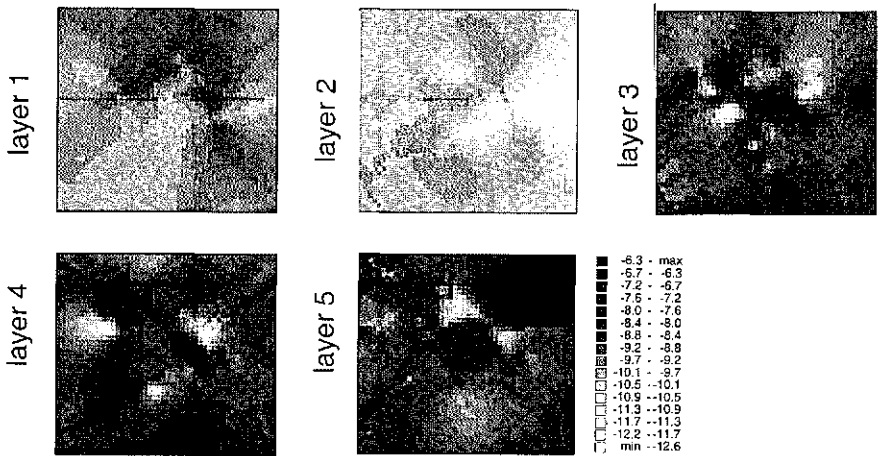


Fig. 3 Maps of hydraulic conductivity in local model for case H-I ( $\sigma_{\log K} = 1.04$ ).

An exhaustive and well organised revision of relations among geophysical and hydrogeological parameters can be found in Cassiraga (1999).

## IMPACT OF $K$ HETEROGENEITY

The smooth variation of the prescribed head boundary conditions (BC) defined by piezometric head from the RM influences the piezometric head in the inner layers, diminishing its local variability. The farther the layer is from the boundary, and the higher the value of  $\sigma_{\log K}$ , the more local variability is observed in head.

In order to analyse the effects of heterogeneity (derived from the seismic data) on mass transport, the following experiment has been conducted. From each node of a regular grid ( $21 \times 19$ ) defined on the mid plane/surface equidistant from the upper and lower layers in the LM, a particle is released and its trajectory and travel time to reach the clay boundary are computed. Only the convective mechanism of transport is accounted for, as in Capilla *et al.* (1995, 1998). When using homogeneous parameters from the RM the trajectories are almost vertical, all particles leave the formation through the lower limit and the travel time distributions follow smooth patterns similar to that of the clay thickness.

However, when transport is simulated for a heterogeneous  $K$  field, flow patterns change and have an important impact on mass transport predictions. Figure 4 shows the horizontal projections for the 399 trajectories simulated. Their general direction is from the upper to the lower layer and goes from northeast to southwest. The deviation from the vertical occurs in the lower layers due to two different facts. The second layer, from above, has lower  $K$  thus maintaining the highest vertical gradient in the upper layers. Next to this, there are zones in the lower layers with higher conductivity, where the pressure gradient becomes very horizontal, and so trajectories, allowing longer particle travel times. The travel times to the lower boundary layer are presented in Fig. 5. The grey dot locations show the horizontal projection of the releasing node and the grey is related with the travel time value.

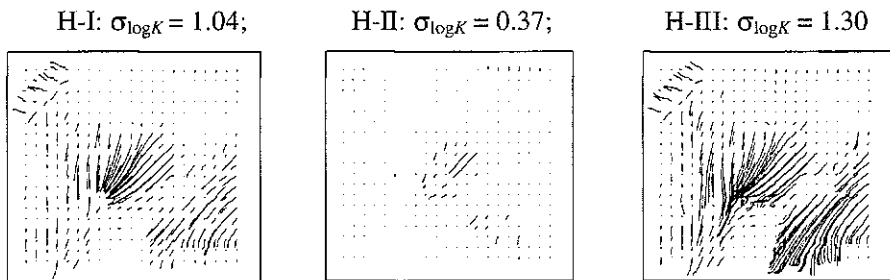


Fig. 4 Horizontal projections of trajectories from mid-plane to lower formation limit.

Particle trajectories deviate more from the vertical flowpaths in RM as the  $K$  field becomes more heterogeneous. Travel times generally increase due to the combined effect of the lower  $K$  in the second LM layer and the longer trajectories within the lower layers.

In this case study, the local fluctuations of prescribed head BC are mainly associated with the spatial variability of  $K$ . In order to estimate the impact of BC smoothness, alternative prescribed head conditions have been simulated for the upper and lower layers. The differences between prescribed head conditions taken in the RM and the new BC are simulated as a stochastic process. Its geostatistical properties

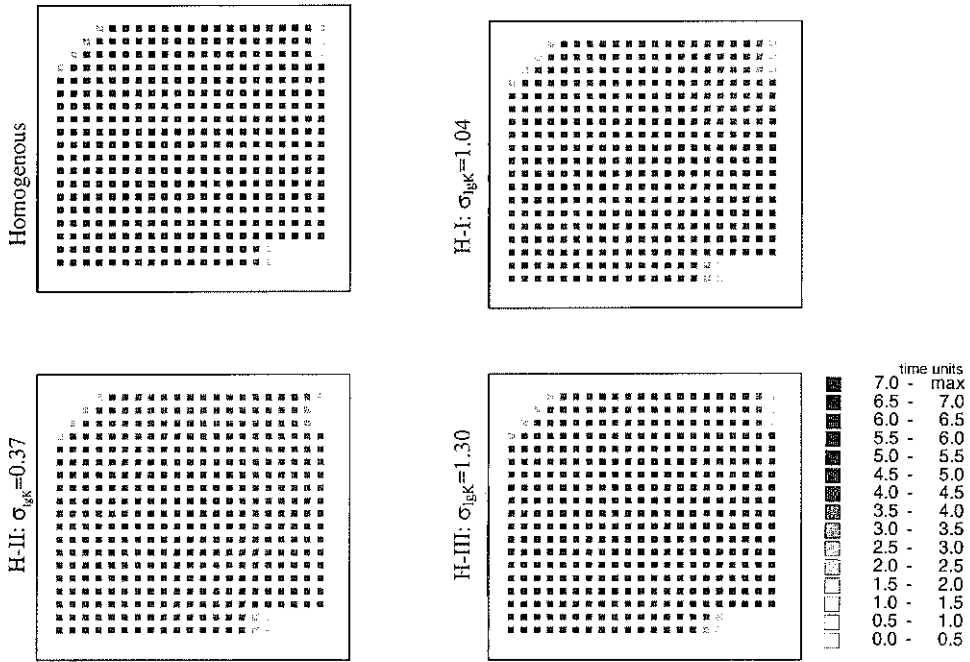


Fig. 5 Travel times from mid-plane to lower formation limit.

are obtained from the structural analysis of head differences in layer 3 (inner layer) between H-I results and those for homogeneous parameters. Under these conditions trajectories adopt higher curvatures and travel times can locally increase or decrease, often by a non-negligible magnitude.

### CONCLUSIONS

It has been shown how seismic data can be used to estimate the patterns of spatial variability when no other data are available. Introducing  $K$  fields that reproduce real heterogeneity patterns has a strong impact on convective transport predictions. This shows that proper modelling of heterogeneity may be essential in real situations.

Boundary conditions have a non-negligible impact on mass transport predictions that locally can be as important as that due to  $K$  heterogeneity. Both types of spatial variability should be studied jointly as stochastic processes.

The next phase of this study should incorporate direct measurements of piezometric head and  $K$  in the formation (not yet available) as well as the calibration of impedance- $K$  relationship. The incorporation of seismic data should always rely on direct measurements of formation properties.

Among the uncertainties in the clay formation, the lower  $K$  values in the second layer and its local maxima in the lower layer, require more field research due to their strong impact in model predictions.

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