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Technical Article

Underground Waste Repositories in Exhausted Coal Mines - Recent Developments

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Abstract. Due to the general lack of appropriate surface waste dumpsites in North-Rhine-Westphalia (Germany), placing filter ashes and desulphurisation residues from power plants in underground coal mines has become an attractive alternative. The residues can be injected as a hydraulic suspension into exploited coal seams. In this paper, we summarize the fundamental geotechnical aspects that define the hydrochemical barriers for underground repositories. The environmental advantages and disadvantages of this concept are discussed. Laboratory and field investigations as well as modelling are presented in order to establish the environmental reliability of such repositories.

Key words: underground repository; exhausted coal mines; risk analysis; hydrogeology

Introduction

The subsurface disposal of industrial residues in coal mines beneath densely populated urban areas is important in North-Rhine-Westphalia, Germany. The residues from electric power plants consist of filter ashes (fly ash) and desulphurisation residues. These are being injected underground because suitable surface storage areas are no longer available. Furthermore, long-term enclosure of potentially toxic pollutants at the surface requires expensive technical measures and constant monitoring of the landfill area. On the other hand, existing geological barriers surrounding an underground repository can ensure some of these measures. Appropriate geological host rock conditions are found in underground mines in the Ruhr Region. The waste material is being used for construction and for backfilling cavities behind longwall facings. This process diminishes surface subsidence and renders the ventilation of the underground pits more effective. From the viewpoint of waste disposal as well as mining, underground deposition is thus economically reasonable. However, this procedure is only acceptable if the environmental compatibility is guaranteed; the materials should not endanger the biosphere or hydrosphere. Human, animal, and plant life must be unconditionally protected. The use of mines as repositories therefore requires a clear demonstration that contaminants that might reach the surface after thousands of years will not cause any harm.

The storage of non-radioactive, toxic residues is regulated by the German Waste Law, which requires an environmental impact assessment. Following the legal technical definitions and regulations, the placement of residues in mines has the character of a final repository. Accordingly, a maintenance-free and secure long-term deposition is necessary. The risk analysis must address geological safety aspects, geotechnical safety during the operating phase, and long-term safety.

Geological safety aspects

Any formation selected as a host rock has to satisfy the natural barrier requirements for a given geological time span (Kroll 1993). The geotechnical and hydraulic characteristics of the host rock must be predictable on both a spatial and temporal basis. The spatial aspect is satisfied if the host rock is not transsected by shear or fault zones or other geological heterogeneities.

Long-term safety of a selected host rock requires that the geotectonical region does not show any seismic activity or recent seismic-tectonic strain and stress. This can be determined through geological analysis of

- Recent crust movements;
- Historical and recent natural or induced seismic activity at this location and its surroundings; and
- The tectonic stress situation in the surrounding area, in order to estimate possible activity and/or the seismic potential of tectonic elements.

Geotechnical safety during the operating phase

Contamination of the environment must be avoided during processing as well as at the final repository. Also, during the active deposition of waste underground, workers handling the material must be protected. Pollutants cannot be spilled, nor any workers exposed to the waste materials during transport and deposition of waste.

The technical procedure to deposit the residues into the provided host rock area is based on long-standing experience. Ash from coal fired power plants have been used as back-filling materials in mines for a long time. Deposition of residues by injecting a hydraulic suspension into the open void space of the broken rock mass excludes any contact with the working personnel. At the surface, the ashes are mixed with mine cuttings, cement, and water to form a hydraulic suspension. This fluid is transported by pipeline down to the level of the underground repository and finally injected into the broken rock mass through injection tubes. The necessary void space originates from the mining process itself. The coal seam is broken by a rotating rock crusher and transported by belt drives to the surface. Behind the longwall face, a previously installed safety shield supports the load of the overburden layers. After exploitation, the shield moves forward and the overburden collapses into the generated void space, as shown in Figure 1. The mining process creates new fractures within the overburden, which increases the hydraulic permeability of these sediments. The layers underlying the repository do not experience such effects and can be considered undisturbed. The broken rock mass consists of blocs of different dimensions. Approximately 20% of this highly heterogeneous sub-region are therefore voids, which can now be filled by the hydraulic suspension. Due to the pressure of the overburden, the broken rock mass and the injected waste suspension are transformed into a concrete-like compact agglomerate. The area that the waste was injected into corresponds to a hypothetical underground repository, surrounded by porous fractured sediments.

During the operating phase, groundwater quality should not be affected. Drifts and shafts are kept dry by pumping, so contact with groundwater is minimal. When the mine is exhausted, the pumping will be stopped and the water level will rise again. The groundwater rise will slow down when the deepest ventilation drift is reached and will increase again until the next mining horizon is flooded. Empirical values from exhausted mining fields in this region indicate that a rate of approximately 1m/14days can be anticipated in the shafts (Kories 1994). Since the coal pit has been drained for a long time period, the host rock is only partially saturated. Steep hydraulic gradients will therefore exist, causing water to flow through the rock matrix. The transient propagation of the saturation front through the host rock is therefore the most important load case, and must be addressed by any risk analysis of this concept. Additionally, the long-term safety of a given underground repository also depends on regional groundwater flow patterns within the regional geological framework.

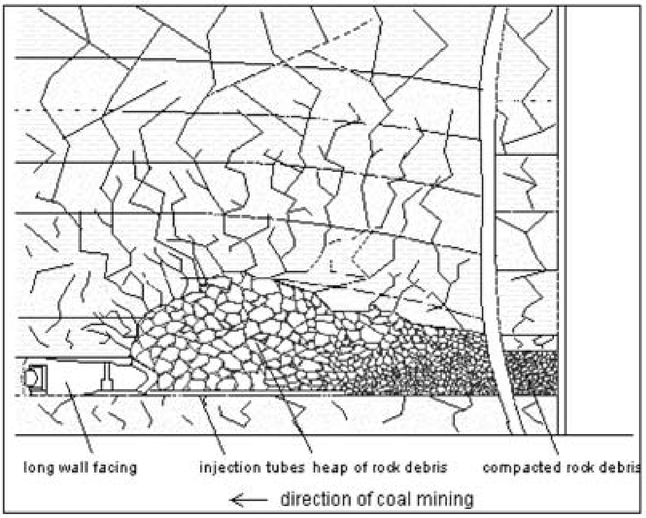

Figure 1. Broken strata can be injected with ash slurry

Long-term safety

Two possibilities exist for environmentally-safe deposition of low pollutant waste and residues (Obermann and Rüterkamp 1991): emission-neutral placement and absolute enclosure. Emission-neutral implies that the waste and residues in the repository area will not deteriorate the groundwater quality beyond natural background levels, even if pollutants are dissolved from the repository body. This characteristic of a residue is examined in batch tests (Paas 1997) with the groundwater. Certain minerals, construction debris, and ashes from coal-fired power plants are typically emission neutral.

If the residue cannot be established to be emission neutral, complete enclosure has to be verified. No pollutants that could affect the surface biosphere may leave the repository area in life-endangering concentrations for at least 1,000 years. In this case, a multi-barrier concept is considered. The multi-barrier concept distinguishes between different hydraulic and geochemical barriers. The host rock embedding the waste body is considered to act as internal hydraulic barrier, whereas the surrounding rock (e.g., shale and siltstone) acts as an external hydraulic barrier. In order to fulfil the prerequisites on safety and reliability, the waste body must be located at an adequate depth (e.g., 1,000 m below the surface) and the surrounding rock must have low permeability and sufficient thickness. Geochemical barriers also retard contaminant mobility due to adsorption within the rock matrix and on fracture surfaces.

The most likely path by which dissolved contaminants may return to the biosphere is via slow groundwater flow after the mines are depleted and pumping of groundwater has been stopped. The country rock has been the subject of considerable hydrogeological and geochemical investigations over the past few years (Jäger et al. 1990). Groundwater may flow with much higher velocities through fractures and fissures than in the porous matrix. Depending on the interconnectivity of the fractures, relative fast pathways may be present between the waste repository and the biosphere. In such cases, dilution, chemical reactions, and sorption may still ensure safe long-term waste disposal.

The high requirements on underground repositories are justified considering that mistakes made in the subsurface cannot be repaired. After the groundwater recovers, the area is no longer accessible.

Risk assessment

If the host rock is a fractured aquifer, faults, fractures and fissures control its hydraulic behaviour. Within a fractured system, advection may occur at much higher flow velocities than within the undisturbed porous matrix. Theoretical and experimental investigations, which were performed in connection with the burial of radioactive waste, indicated that matrix diffusion is important as a retardation mechanism affecting solute transport processes in fractured rock (Neretnieks 1980). The physical process of matrix diffusion is particularly relevant for those dissolved species that show only weak sorption and would migrate at or near groundwater velocity from a deep burial repository towards the surface (Bradbury and Green 1985).

Quantitative risk assessment can be conducted using numerical simulation models to predict local and temporal development of groundwater flow and solute transport in the vicinity of an underground repository in a sedimentary host formation. Such models must consider the following physical processes:

- Diffusion of contaminants into the rock matrix;
- Adsorption of contaminants in the matrix;
- Fast fracture flow within the fracture network;
- Slow flow in the matrix.

For the numerical description of a realistic flow system, the following problems have to be solved (Wendland and Schmid 1995):

- A stochastic fracture network should reflect natural fracture patterns and must consider natural fracture length and spacing distributions;
- The network must be generated in a 3D-domain considering a random 3D-distribution of fractures;
- Any arbitrary cross section of the 3D-fracture network will intersect fracture traces, which can be investigated using a 2D-model of the problem.

In this work, we briefly describe the experimental and numerical effort carried out at the Ruhr-University of Bochum to develop a computational tool and to provide physical parameters as input for a numerical model.

Derivation of Parameters

A numerical model for a fractured host rock requires the derivation of effective aquifer parameters such as the permeability of fractures and matrix, statistical fracture data, and effective diffusion and sorption coefficients.

Determination of diffusion coefficients

The determination of diffusion coefficients was performed using diffusion cells. Diffusion was measured through different rock samples of 52 mm diameter and 5 mm thickness. The rock disks were fixed into perspex holders, which were mounted vertically in the diffusion cell. One half of the diffusion cell contained the reservoir of the diffusing species, and the other (active cell) was initially kept at zero concentration (Figure 2).

The chosen experimental array induces one-dimensional diffusion through the rock sample. The data were evaluated considering Fick´s 2nd law (Lever et al. 1985). The experiments performed at different temperatures generally lasted a few weeks, with steady-state diffusion being reached after 1-3 weeks (Figure 3). All experimental data could be fitted reasonably well to the model and yielded consistent effective diffusivity coefficients ranging from $7 \cdot 10^{-9}$ cm^2/s to $2 \cdot 10^{-8}$ cm^2/s (Himmelsbach et al. 1995).

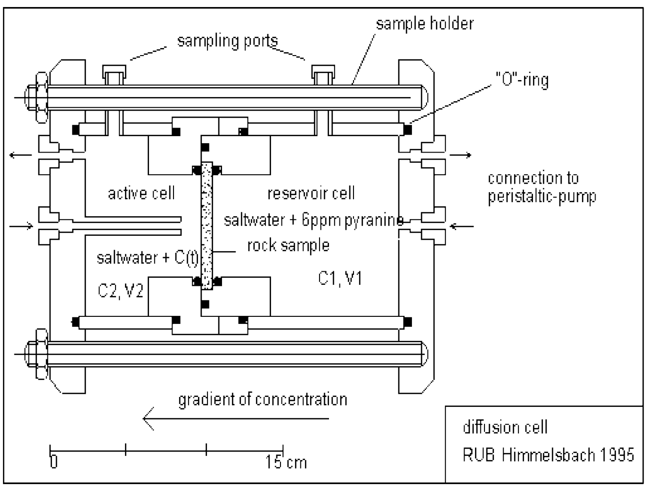

Figure 2. Schematic sketch of the diffusion cell

Evaluation of heavy metal sorption

Two migration experiments using cadmium and lead, as solute, and pyranine, as tracer, were performed in the laboratory to investigate the migration behaviour of heavy metals. The array consisted on a sandstone block with a length of 24 cm, a height of 24 cm, a width of 21 cm and a single fracture in the middle of the block. A small plastic ribbon having a thickness of 350 µm separated both halves of the block, setting the fracture aperture to a definite value. The matrix porosity was determined using mercury porosimetry. Since the tracer experiments should investigate advective-dispersive fracture flow affected by matrix diffusion, any superposition of this process due to an unsaturated matrix had to be avoided. The sandstone block was therefore saturated with artificial formation water that corresponds to the depth of a disposal site (Himmelsbach and Wendland 1999). During the tracer experiments, the formation water was pumped at a flux rate of 4.57 ml/h through the fracture plane (Figure 4). The tracer injection lasted 1 min and was performed through the septum at the lower injection point.

During the first tracer experiment, pyranine and cadmium were injected simultaneously. A second experiment was performed with pyranine and lead. The breakthrough curve of cadmium was nearly the same as for pyranine (Figure 5). The time elapsed until first detection as well as the time elapsed to reach the peak concentration were also nearly the same. Hence, under high-saline pore water conditions, cadmium is highly mobile and shows no retardation effect. Under the same hydrochemical conditions, with a salt content three times greater than seawater, lead was absorbed to such an extent that no breakthrough curve could be measured.

In-situ experiments

In-situ experiments (Zobel 1998) have been done to evaluate, under natural conditions, the applicability of the physical parameters obtained in the laboratory. For these migration experiments, heavy metals and a tracer were injected into the rock surrounding a potential underground repository. Three boreholes located in a mining drift were used.

Considering the relative short distance between the boreholes, the migration of solutes through the disturbed zone is marked by fast-appearing breakthrough curves (Figure 6). The recovery rate after 12h increased up to 38% for the tracer, indicating that the solutes have been injected directly in a fracture network. The breakthrough curve for cadmium was almost the same as that for the tracer

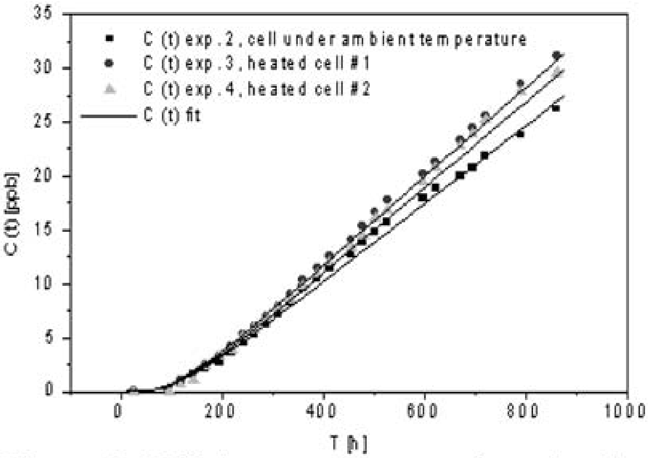

Figure 3. Diffusion experiments performed under different temperatures

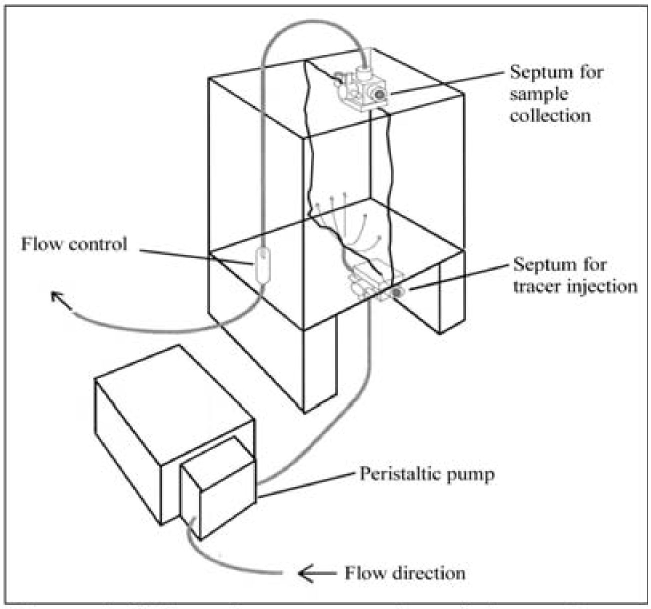

Figure 4. Schematic representation of the sandstone block

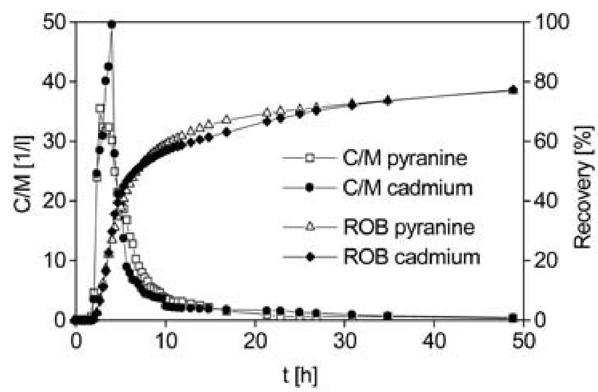

Figure 5. Measured breakthrough curves (C/M) and recovery rate (ROB) for cadmium and pyranine at the outflow point of the sandstone block

pyranine, without any retardation. The experiment confirmed that cadmium is very mobile, while lead is retained by adsorption.

Numerical Developments

In order to predict the local and temporal development of groundwater flow and solute transport in the neighbourhood of an underground repository, both the equations describing the flow and the transport mechanisms (Bear 1972) have to be approximated numerically. To accomplish this, we developed a computer code (Schmid et al. 1995) based on the finite element method, for numerical simulation of a coupled model, including porous and fracture flow. We considered single-phase (water) flow with a single dissolved solute moving through a homogeneous porous medium. The flow field is independent of the solute concentration. A fracture-matrix model, which describes the rock masses by coupling discrete fractures and porous matrix, was used for simulating flow and solute transport in a randomly generated fracture system (Wendland and Schmid 1995). For the discretisation of complex geological structures, elements of different dimensions can be combined in a 3D-model: one-dimensional elements for channels, two-dimensional elements for open fractures, and three-dimensional elements for the porous matrix blocs.

In this model, the essential transport processes occur by advection in the fractures. Retardation effects are attributed to diffusion/dispersion and sorption in the porous rock. A problem one has to deal with is the numerical coupling of the fast advective transport in the fractures with the slow diffusive process in the matrix. Solving the advection-diffusion equation by the traditional Galerkin approach becomes inefficient.

In order to avoid spurious oscillations, a fine discretisation is needed, requiring a huge amount of storage and computation time. For the efficient numerical solution of the advective-diffusive equation, the symmetrical streamline stabilization (S^3) scheme is applied in order to stabilize the high advective transport in the fractures. It combines the Galerkin method with the least-squares method, leading to oscillation-free results due to an inherent upwind effect (Wendland and Schmid 2000).

3D finite element model

In order to investigate the applicability of numerical simulations for the safety analysis of underground repositories, the computer code was verified using the experimental breakthrough curves obtained for the sandstone block (see the section on evaluation of

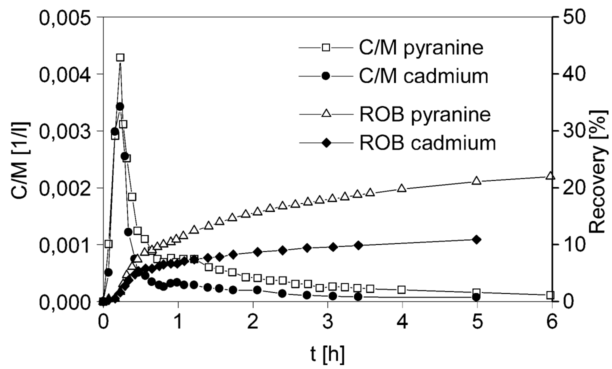

Figure 6. Breakthrough curves for the in-situ migration experiment

heavy metal sorption). Due to sealed areas within the single fracture, an irregular flow pattern in the fracture plane was expected, mandating a 3D-model of the transport process.

In a first attempt (Himmelsbach and Wendland 2000), a numerical model based on the parallel plate approach was constructed (Figure 7). The resulting mesh used for the simulation has 9108 nodes, which are interlaced to 8668 3D-elements describing the matrix and 435 2D-elements for the fracture. A good agreement between measured and calculated breakthrough curves (Figure 8) was obtained because the essential diffusion, sorption and porosity coefficients for the porous matrix had been previously determined in the laboratory. An inverse simulation with these unknowns would not allow a unique solution. The comparison of measured and calculated breakthrough curves verified the numerical model, assuring its applicability for large-scale problems. In a second approach (Wendland and Himmelsbach 2002), the natural roughness of the fracture surface was added to the model by assigning spatially variable apertures to the fracture plane. The apertures (Figure 9) were generated by a geostatistic method, considering a log-normal density distribution and a given correlation length. Finally, a sensitivity analysis was performed to assess the influence of different statistical parameters on the transport behaviour. The results indicate that the solute migration appears to be controlled by the statistical mean aperture of the single fracture.

Fracture network generation

The generation of a fracture network depends on the scale of the model. Fractures can either be incorporated deterministically as discrete fracture sets or stochastically, if the scale of observation becomes larger (Kulatilake et al. 1993). The considered study

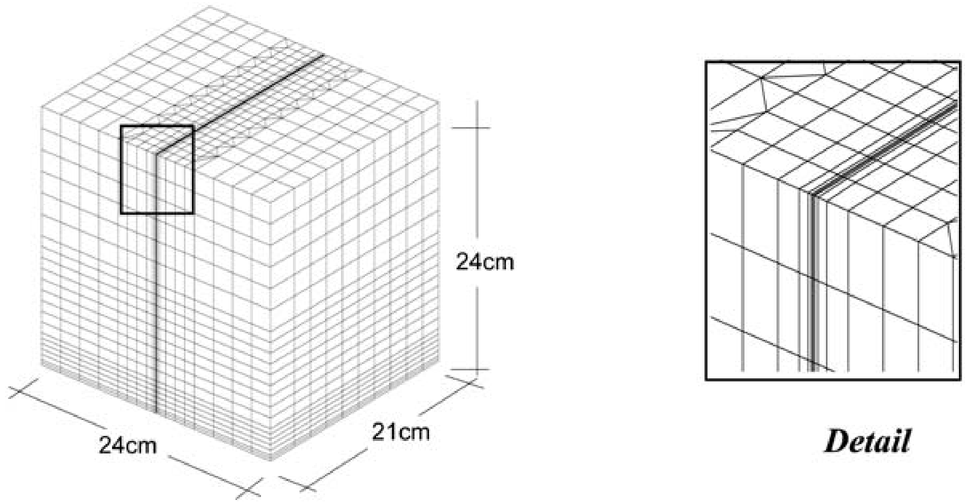

Figure 7. Spatial discretisation of the sandstone block pattern in the fracture plane was expected, mandating a 3D-model of the transport process.

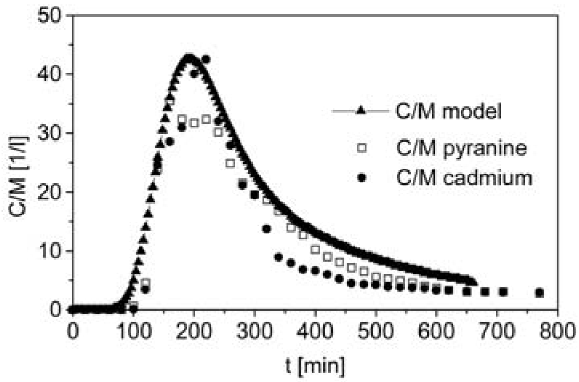

Figure 8. Simulated breakthrough curves compared to measured values at the outflow point of the sandstone block

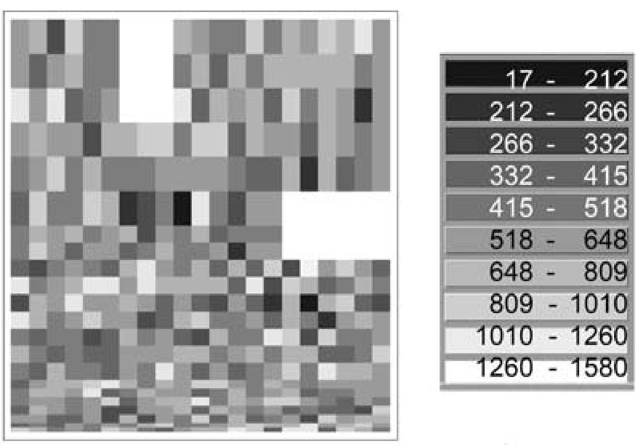

Figure 9. Stochastic aperture distribution for a single fracture in the sandstone block (bright = large aperture; dark = small aperture). Legend in µm.

required a stochastic approach because the number of fractures was too large for deterministic generation. This involved an evaluation of field-measured statistical fracture parameters:

- Direction and dip of main fracture patterns and their spherical variance;
- Statistical fracture length distribution;
- Statistical fracture spacing distribution;
- Mean fracture aperture and its distribution.

The statistical parameters can be evaluated by fitting statistical distribution models to observed field data. This can be done considering Gaussian, log-normal, or exponential distributions. Figure 10 shows an example depicting the fracture-length distribution for a sandstone outcrop where the considered log-normal distribution yields the best results. The obtained statistical information, which is consistent with real fracture patterns, can be used to generate a three-dimensional random fracture network (Huewel 1995). Figure 11 shows such a 3D fracture domain.

The most difficult part is to generate a three-dimensional finite element mesh coupling the fractures to the rock matrix surrounding them. Due to the irregular distribution of fractures in space, it has been impossible up to now to generate useful elements as required by the finite element method. To avoid this problem, we restricted ourselves to a two-dimensional model. This is obtained by intersecting the fracture system generated in the space by a representative vertical plane. The intersection between the generated fractures and the vertical section appears in the flow model as one-dimensional traces. Discretising these one-dimensional elements and generating regularly distributed points on the matrix, a triangulation algorithm can generate the required FEM mesh.

Conclusion

Coal mines in the Ruhrgebiet region are located in the most densely populated urban area of Germany. The productive Carboniferous sequences are overlain by Cretaceous porous and fractured aquifers, which are widely used to supply water for the northern part of the Ruhrgebiet. To sustain these water resources, any use of mines for subsurface disposal of industrial residues must insure that these aquifers will not be affected by aqueous solutions after mining ceases. In other words it must be shown that these aqueous solutions will not reach the biosphere or, if they do, they will be diluted and sorbed to such extent that their effect can be neglected.

The developments presented were necessary in order to construct a numerical model of an underground repository site for wastes of low toxicity. Future work must focus on the realistic definition of a hydrogeological model describing the vicinity of the disposal site. The future model should include both sedimentary units of the Carboniferous host rock, the sandstone and siltstone layers. However, only the sandstone layers will be simulated as fractured aquifers, while the siltstone layers will be treated as conventional anisotropic porous aquifers. Only the combination of both types of sedimentary units will reflect realistic aquifer conditions and will be useful in estimating, for example, travel times in the vicinity of the flooded repository. With regard to the general uncertainty of model input parameters, multiple simulations of different scenarios, reflecting different boundary conditions and aquifer properties, have to be performed. The different resulting scenarios will help us to understand the sensitivity of the model to the different aquifer input parameters.

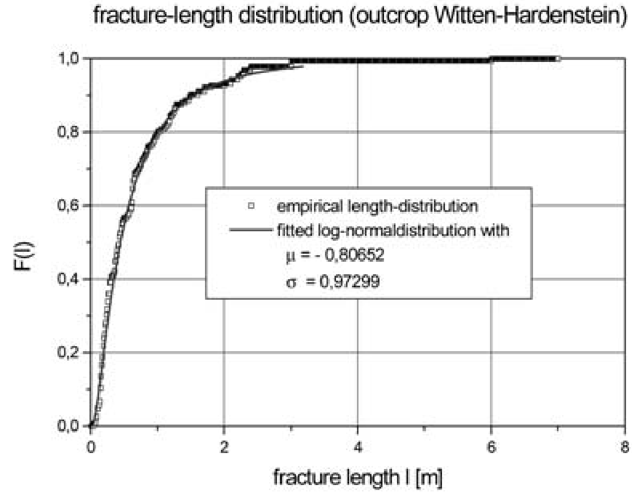

Figure 10. Fitting a log-normal probability function to empirical outcrop data

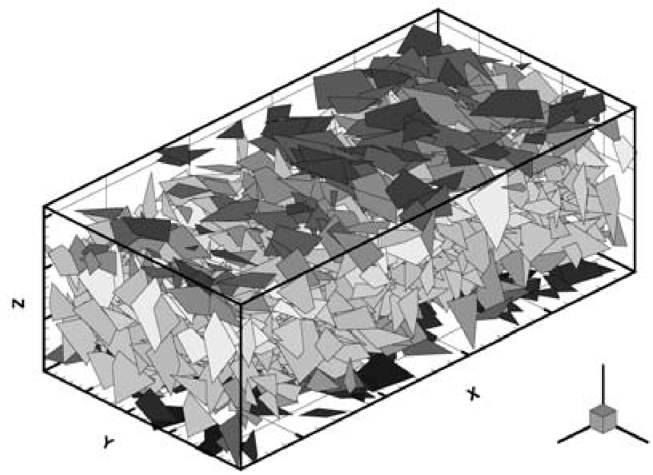

Figure 11. Randomly generated fracture network

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