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The impact of hydraulic gradients and boundary conditions on the microstructural stability of clayey backfills with special respect to the risk of piping and erosion

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Abstract

Disposal of hazardous waste like high-level radioactive waste (HLW) is made by confining it in canisters surrounded by dense, ductile "buffer" clay for placement in deposition holes at a few hundred meters depth in crystalline rock. The concept favored by authorities in Sweden, Finland and Canada implies that the holes are bored from blasted or bored tunnels to be tightly backfilled by stacking compacted blocks of clay in the center and filling the remaining space between the blocks and the rock with blown-in clay pellets. The problem with this is that water flowing in from the rock can cause piping and erosion of the pellet filling, which can turn it into mud and disturb the placement of canisters and buffer clay. The controlling parameter is the rate of inflow of water per inflow point, which is determined by the structure and hydraulic conductivity of the rock. The paper describes a simple model of the mechanisms in penetration of water into the pellet fill and provides a basis for estimating the required rate of backfilling for avoiding critical conditions. The study indicates that such conditions will be caused irrespective of the rate of water inflow per point if the backfilling rate is low.

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Keywords: Backfilling, Clay, Hydraulic gradient, Microstructure, Piping, Radioactive waste

1 Introduction

Disposal of hazardous waste products containing mercury, arsenic, solidified organic pesticides, or radioactive substances, can be made in abandoned mines or – for high level radioactive waste (HLW) like spent reactor fuel – in specially created deep underground repositories. The waste can, depending on the risk level, be mixed with smectite-rich clay [1] or contained in clay-embedded metal canisters placed in rooms and drifts, or in large-diameter holes bored from drifts [2]. A common engineered barrier to migration of contaminating hazardous elements is low-permeable clayey soil filled in the waste-containing rooms, drifts and in shafts leading down to the underground disposal site. Groundwater will enter from the rock and expose it to hydraulic gradients that can cause piping and erosion depending on the inflow rate and rate of backfilling. The risk of such degradation makes it necessary to predict the impact on the microstructural constitution of hydraulic gradients generated by the successively increased water pressure on the backfill being placed. The paper describes the involved mechanisms and demonstrates what impact that hydraulic gradients can have, focusing on disposal of HLW.

2 Backfilling of tunnels in repositories

2.1 Concepts

Deposition tunnels of repository concepts like KBS-3V have to be tightly backfilled for not serving as groundwater conduits in the repository, which means that their hydraulic conductivity must not exceed that of the surrounding rock.

Since the average conductivity of crystalline rock that can be used for hosting a repository is very low, backfills containing smectitic clay material have to be used [3]. The earliest and most simple way to bring the soil on site is to move it there by tractor blades to form a slope by layer wise placement and compaction but it is recently proposed to fill the drift with assemblies of tightly fitting compacted blocks of expansive clay and to blow in pellets of dense smectite-rich clay in the space between the blocks and the rock walls and roof (Figure 1). The clay blocks can be transported and placed by robots in 6-8 m long sequences in the tunnels, interrupted by insertion of HLW canisters in large-diameter deposition holes with a spacing of 6-8 meters. Each canister placement will take about one day, meaning that the pellet backfill over this length is exposed to water inflow from the contacting rock for at least one day.

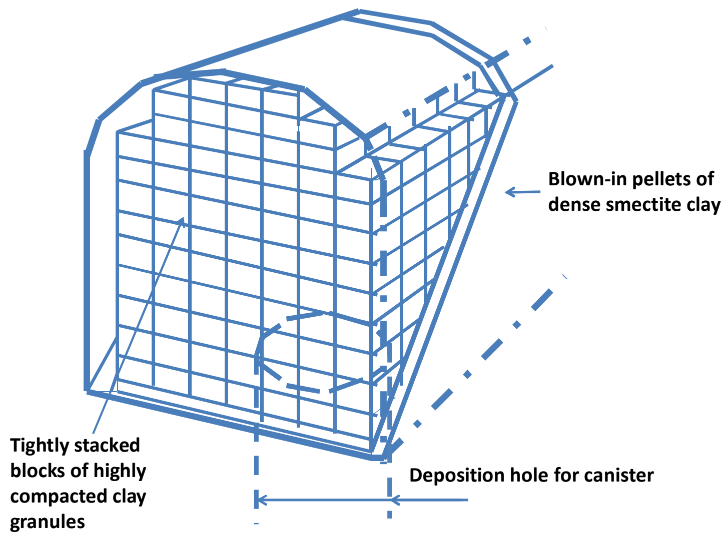

Figure 1. Cross section of tunnel with hole for placement of a HLW canisters according to SKB's concept KBS-3V. The pellet fill has a sloping front.

2.2 Role of tunnel backfill in a repository

The purpose of deep geological disposal of HLW is to 1) make the migration paths of possibly released radionuclides from the repository to the biosphere long, 2) locate the repository in low-permeable environment, 3) utilize the mechanical strength of rock for creating stable rooms, 4) make unauthorized intrusion into the repository difficult, 5) avoid risk of prospection of water for household and industrial purposes. In countries like Sweden the host rock will be granite or gneiss, which have high mechanical strength but also relatively high hydraulic conductivity because of the content of water-bearing fractures. In addition to these natural fractures there are additional, numerous fractures caused by the excavation of drifts, tunnels and shafts. Disturbance by blasting and stress changes of the rock around a tunnel leads to a continuous disturbed zone along it, i.e. the EDZ [4], [5], [6]. The matter is of great practical importance and has been subject to several national and international studies [7], [8].

The excavation disturbance has strong impact on the structural constitution of the rock and increases the hydraulic conductivity very significantly to a distance of several decimetres from the periphery of the opening in question. Careful blasting can reduce the depth of damage to a few decimetres except in the floor where it extends to about one meter even if careful blasting technique is employed. The nature of the EDZ of blasted drifts around drifts and tunnels is illustrated by Figure 2.

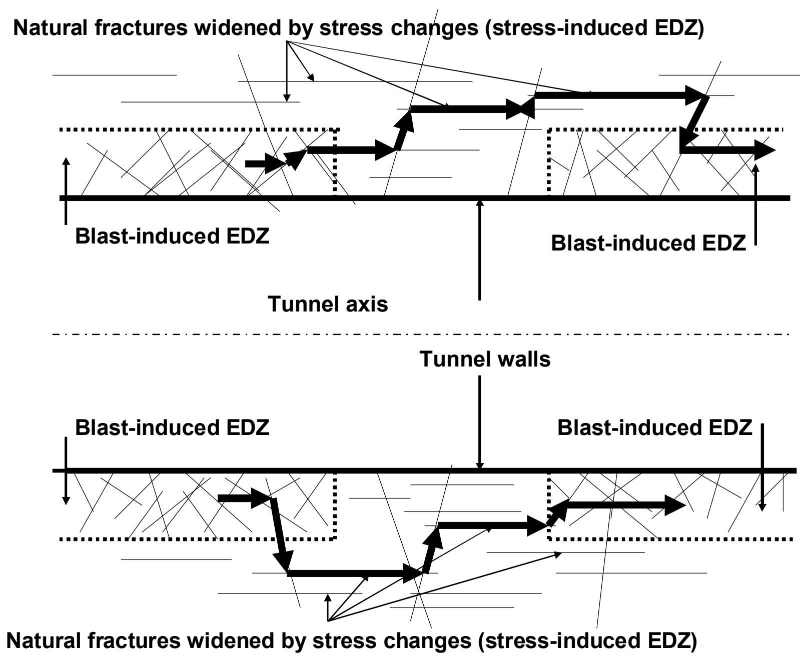

Figure 2. Conceptual model of the creation of an EDZ along a blasted tunnel by hydraulic connection of local blast-induced EDZs and longitudinal natural fractures widened by stress changes. Major flow paths after filling the tunnel with material that is less conductive than the rock are represented by fat arrows.

Large-scale hydraulic field tests for determining the hydraulic properties of the EDZ surrounding a 5x5 m^2 drift made by careful blasting and with a length of more than three blast rounds provide evidence. The tests took place in granitic rock in an abandoned iron ore mine at Stripa in mid Sweden [9]. The primary horizontal rock stresses were 15 and 30 MPa and the minor vertical and amounting to 10 MPa. The tests were made by use of ventilation technique [9], [10]. It was concluded that there are two concentric EDZs: a blast-disturbed zone extending to 0.5-1.0 m depth from the tunnel wall being 1000 times more permeable than the virgin rock, and a surrounding 3 m deep stress-induced disturbed zone. The latter was found to be 10 times more permeable in the axial direction than the virgin rock, and 5 times less permeable than the virgin rock in the radial direction. Outside the stress-disturbed zone the rock was found to maintain its virgin hydraulic conductivity.

The high axial conductivity of the EDZ can lead to quick transport of radionuclides released from leaking canisters. By definition, the backfill in blasted drifts and tunnels must be less permeable than the surrounding rock, which means that for an average hydraulic conductivity of the virgin rock of E-11 m/s and an axial conductivity of the blast-disturbed EDZ of E-8 m/s the conductivity of the backfill must be lower than this value. This pervious EDZ component can be cut off by constructing keyed-in concrete plugs that extend sufficiently deep into the floor, walls and roof, which implies that the surrounding stress-generated EDZ determines how tight backfill must be. Taking the Stripa tests as an example this EDZ component has an axial conductivity of E-10 m/s, which would hence require that the hydraulic conductivity of the backfill is lower than this value. It can be achieved for sufficiently dense backfills of expanding clay like Friedland clay, which contains mixed-layer illite/smectite, or clays dominated by smectite minerals as illustrated by Table 1.

Table 1. Hydraulic conductivity of water saturated and matured backfills*. Salt water is represented by 3.5 % $CaCl_2$ solution [8].

Density kg/m^3	Friedland clay, dist. water	Friedland clay, salt water	Smectite-rich clay, dist. water	Smectite-rich clay, salt water
1800	5E-10	E-9	2E-11	E-10
1850	2E-10	5E-10	E-11	5E-11
1900	E-10	2E-10	2E-12	E-11
1950	5E-11	E-10	E-12	5E-12
2000	2E-11	5E-11	2E-13	E-12
2050	5E-12	E-11	E-13	5E-13

* Tests with a hydraulic conductivity 30-50 m/m.

2.3 Impact of inflowing water on the microstructure of clay

2.3.1 General

Backfill placed in contact with rock will be exposed to water given off from the rock, by which saturation will ultimately be achieved. The successive filling of the voids with water is accompanied by compression of the air in them causing delay in saturation of the backfill and blow-out of trapped air causing piping. The rate of water saturation of the backfill depends on the rate of water inflow in the backfilled tunnel, which is a function of the bulk hydraulic conductivity of the rock and the groundwater pressure, as well as of the initial water content of the backfill.

2.3.2 Bench-scale tests

The impact of inflowing water on the pellet fill that is one of the backfill components shown in Figure 1 has been investigated in large-scale experiments with artificial inflow points for measuring the inflow rate and generated pressure under different, controlled inflow rates. Laboratory experiments with pellets filled in large narrow boxes equipped with single inflow points into which low-electrolyte water was injected at constant rate have been conducted, followed by large-scale tests simulating the conditions in real tunnels and drifts. Figure 3 illustrates the observed flow pattern in the pellet fill. The conclusion was that very low inflow rates (<<0.1 l/min) gave slow uniform wetting while inflow rates higher than 0.1 l/min resulted in quick wetting and outflow to and away from the surface of the slope (Table 2).

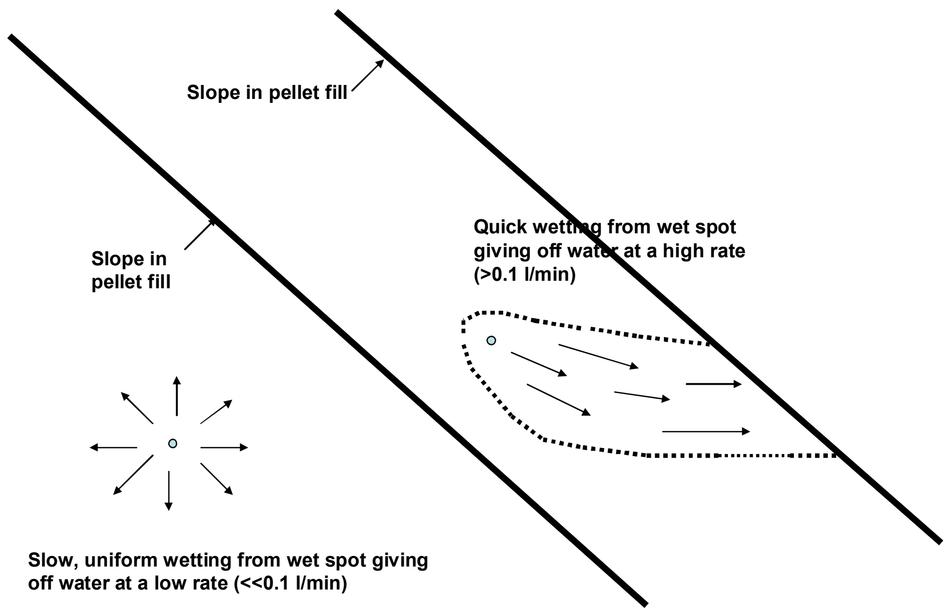

Figure 3. Recorded wetting of smectite pellet fill for different inflow rates from a single inflow point. Left: uniform wetting of the pellet fill for inflow rates <<0.1 l/min. Right: Rapid wetting for inflow rates exceeding 0.1 l/min (After Clay Technology AB).

Table 2. Observations of flow pattern for three flow rates (Clay Technology AB).

Inflow rate, l/minutes	Character of water distribution	Time to breakthrough at slope, h	Sorbed water before breakthrough, l	Duration of test, hours
0.01	Uniform around inflow, upward trend	50	32 (uniform, diffusion-type)	54 (Plexiglass box broke)
0.1	Downward trend	3 (one major channel)	18 (small channels)	Piping
1	Wetting trend initially downwards, then uniform	0.3 (one major channel)	66	Piping

The large-scale tests were made using an artificial steel tunnel filled with compacted clay blocks surrounded by blown-in clay pellets according to Figure 1. Water was let in at different, constant rates from a point located about 2 m from the slope in the pellet fill. The experiments lasted for one to several days and showed that inflow rates lower than 0.1 l/minute gave very slow penetration while inflows exceeding 0.2 l/minute gave quick penetration of water. It was found that piping forming a successively widening channel, ultimately took place irrespective of the inflow rate, turning the fill to a slurry that flowed out on the floor.

Figure 4 shows a case with injection of water of 0.25 liter per minute in one part and 0.1 liter per minute in the other half that was separated from the first. The higher inflow gave piping in a few hours followed by substantial softening of the fill that became slurry-like. The lower inflow gave piping in 12-24 hours.

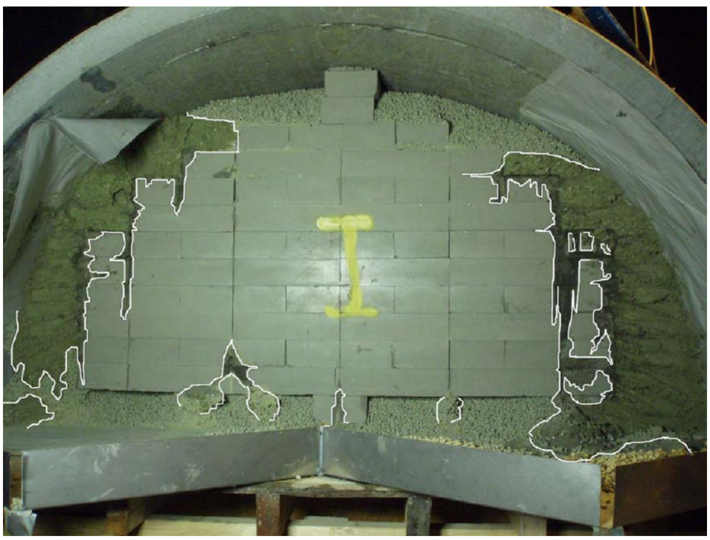

Figure 4. Test for measuring uptake and transport of water in the pellet filling surrounding a clay block assembly. Water was injected at a rate of 0.25 liter per minute in the right part through a nozzle located at the point where the uppermost white line starts, and 0.1 liter per minute in the separated left part through a nozzle hidden by the plastic sheet. In the right part water flowed downwards from start while in the left part it initially tended to flow upwards [11].

2.3.3 Conceptual model

Taking the observations from the quoted tests as a basis of a conceptual model for water penetration into a filling of smectite pellets it is believed that the mechanisms leading to water uptake of the backfill are strongly related to its microstructural constitution. Figure 5 represents pellets of smectite-rich clay exposed to a point of inflow of water from adjacent rock. For low inflow rates, initially generating a low pressure, a small hydraulic wedge is formed but remains stable by being blocked by the confining pellets that sorb water by diffusion and thereby expand. Many more small wedges tend to be formed in different directions but they all stagnate because of the tightening of the expanding pellets surrounding them. The water pressure is thereby raised and a larger hydraulic wedge evolves and propagates as indicated in Figure 6. The consequence is that the high-pressure case evolves after sufficiently long time independently of the inflow rate.

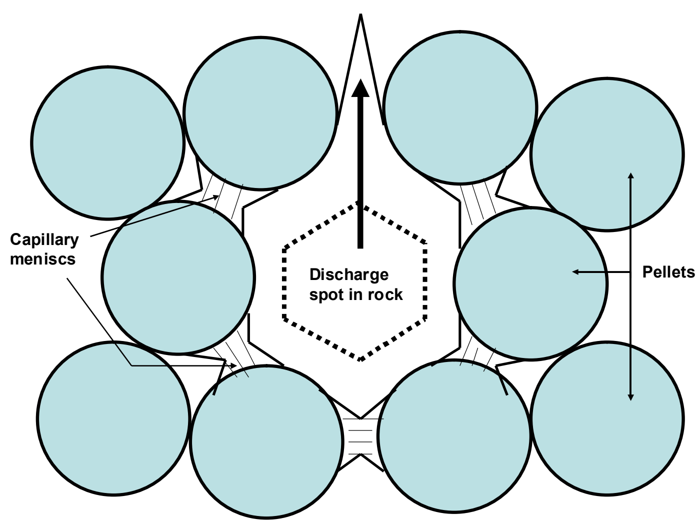

Figure 5. First phase of wetting of the pellet fill at low inflow rate and pressure.

Figure 6 shows the case with high water pressure causing a propagating hydraulic wedge that displaces pellets and propagates with little resistance only. The flow path becomes a channel that propagates if the inflow is high enough to maintain a pressure at its tip that causes wedging. Gravity will tend to orient the channels downwards (cf. Figure 3), hence directing penetrating water to the lowest part of the pellet fill. Wetting of the pellets confining the channels takes place by diffusive water migration making their boundaries successively tighter. This means that all water entering from an inflow point is successively directed to one main channel which becomes eroded and widened. It will self-seal once the water flow has ceased, which occurs if the whole backfill is confined by tight bulkheads.

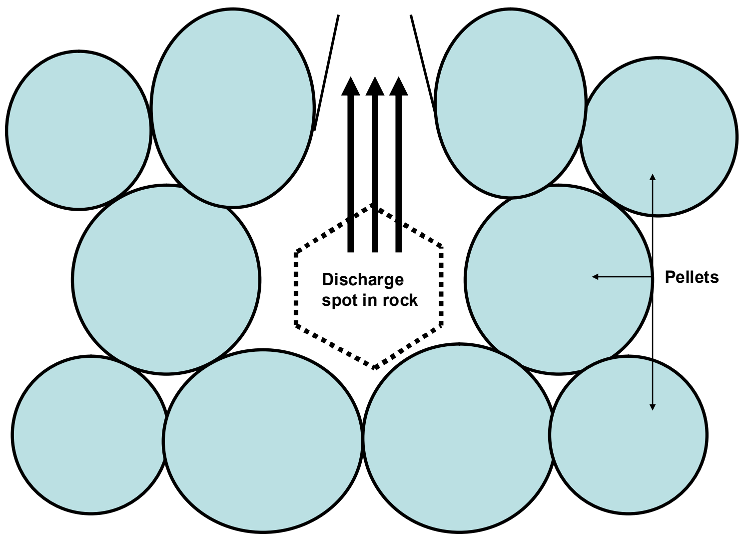

Figure 6. Wetting of the pellet fill at high water pressure.

3 Conditions for water uptake by clayey backfill

3.1 Rock constitution and hydraulic performance

The basis for creating a conceptual model for the wetting and saturation of the backfill is the frequency and spacing of discharge points of the rock surface. This makes it necessary to consider the rock structure and the role of the EDZ around blasted tunnels.

The inflow points are located where the water-bearing fractures appear in the rock walls and predominantly where such fractures intersect since these crossings represent continuous flow paths (Figure 7). In the present study it is assumed that all water inflow takes place in and along such crossings.

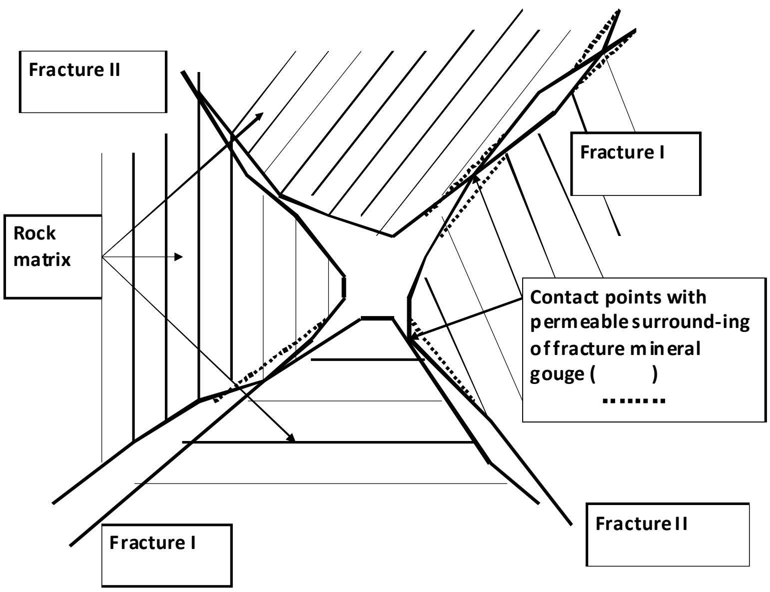

Figure 7. Crossing of fractures (I and II) form a channel that serves as flow path.

The role of EDZ is of great importance in this context since it makes the difference between blasted and bored tunnels obvious. While blasting produces frequent fractures to a depth of at least a couple of decimeters from the contours of the tunnels, the disturbance caused by tunnel boring machines is negligible [8] leaving the structure of virgin rock unchanged.

3.2 Water-bearing features

3.2.1 Fractures in rock

For the sake of simplicity and clarity we will use here a terminology that has been applied in the stone industry and tested for characterization of rock intended for constructing repositories for hazardous waste. It distinguishes between large-scale weaknesses in the form of major fracture zones (1^{st} and 2^{nd} order discontinuities), smaller fracture zones (3^{rd} order discontinuities) and discrete water-bearing fractures (4^{th} order discontinuities), [7], [8]. The strategy of locating HLW tunnels in rock with only the last-mentioned type of weaknesses is followed here.

3.2.2 Inflow in TBM tunnel

Identification of water-bearing fractures is easily made in bored tunnels as exemplified by Figure 8, which shows all significantly water-bearing fractures in the “Prototype” tunnel in an underground laboratory at Äspö, southwestern Sweden. It had 5 m diameter and 90 m length and was TBM-bored at 450 m depth in granitic rock [8]. The water pressure close to the tunnel was measured and found to be about 1.5 MPa. One identifies a more or less subhorizontal fracture set (green), a steep significantly water-bearing set oriented NW/SE (blue), and a steep and less wet set oriented NE/SW (red). The inflow in the outer part (Section 3530 to 3580) was 75 l per day and meter, and 500 l per day and meter in the inner part (Section 3585 to 3600). The measured conductivity of the rock matrix next to the backfill, corresponding to the EDZ of the bored drift, was E-10 to E-9 m/s.

Backfilling with 30% smectite-rich clay and 70% crushed rock was not possible in the wettest part but could be made in the rest of the tunnel.

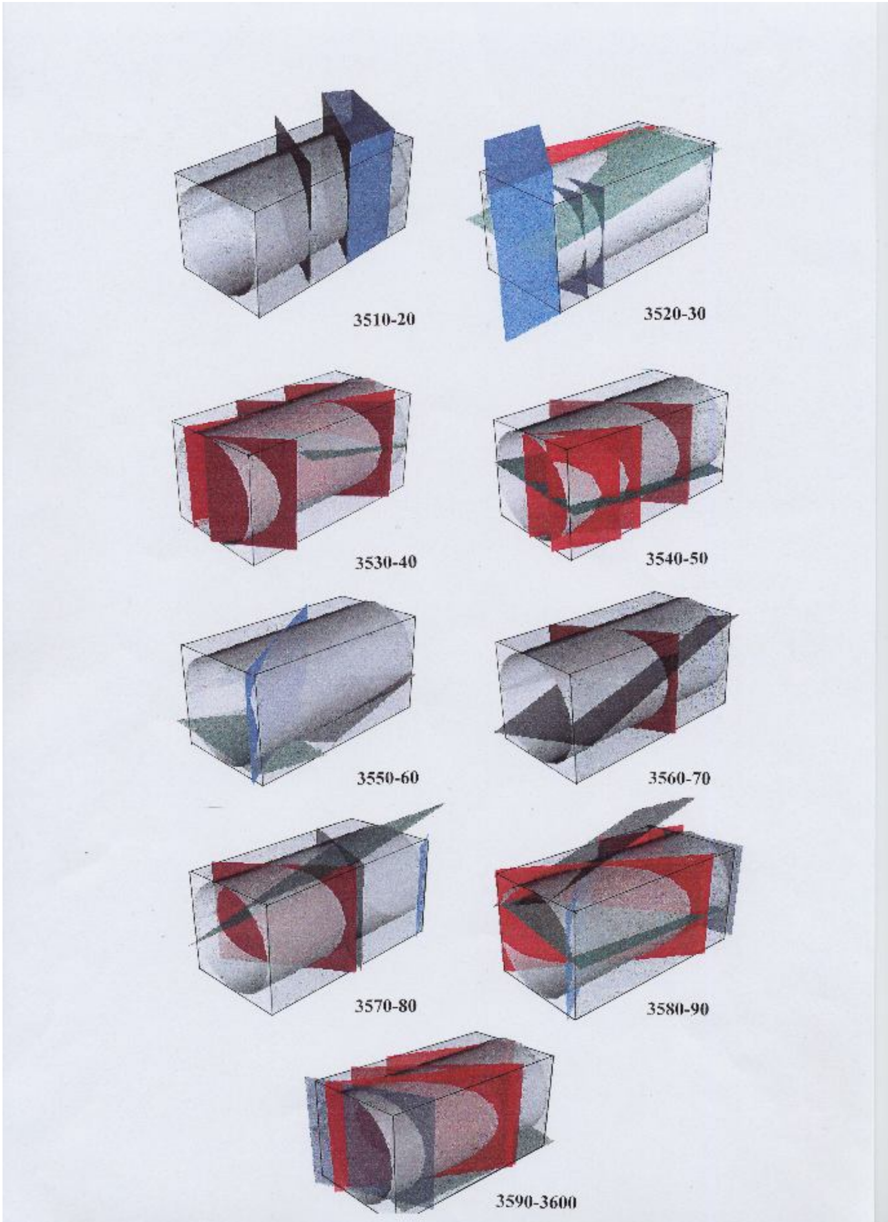

Figure 8. Major water-bearing discontinuities in the Prototype drift illustrating the frequency of intersections of 4th order discontinuities, representing “channels”. The interaction of several of these features in the innermost part, i.e. from 3580 to 3600, made up a major fracture zone with strong inflow of water [8].

The number of water-bearing fractures intersecting the tunnel in Figure 8 was 12 in the inner 15 m long part of the tunnel, i.e. the wettest part, and 24 in the outer 80 m long part. The number of inflow spots taken as fracture crossings seen in the tunnel walls was approximately the same as the number of fracture intersections. Using these data one finds that the inflow per point was about 500 l per day, or 0.35 l per minute in the inner part and about 15 l per day, or 0.01 l/min, in the outer. One concludes that the failed backfilling in the inner part of the tunnel is explained by a higher point wise inflow than 0.1 l per minute.

3.3 Modelling of the hydraulic performance of near-field rock

3.3.1 Rock structure controls the flow paths and inflow into the pellet fill

Assuming that the water-bearing fractures in the rock make up an orthogonal network and that water flow takes place along the intersections of the fractures the flowpaths in the rock can be visualized as in Figure 9. For a spacing of the fractures that is larger than the tunnel diameter no flow paths intersect the tunnel. In practice the spacing of fractures varies and ranges from a couple to several meters. For the Prototype tunnel in Figure 8 the spacing of fracture crossings representing inflow points in a backfill ranged between 1.25, each with an inflow of 0.35 l/min, and 3.33 m, each with an inflow of 0.01 l/min.

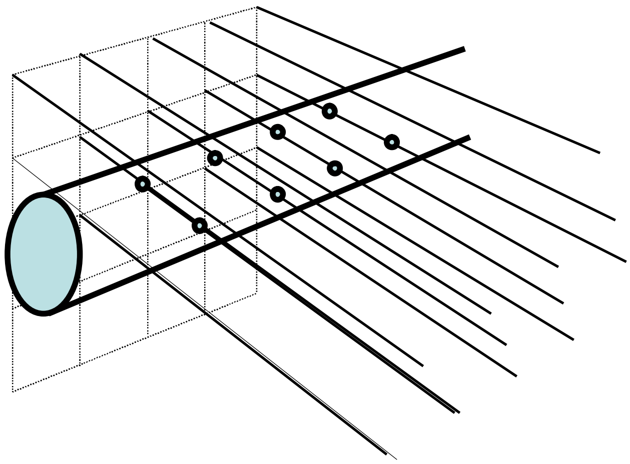

Figure 9. Example of channels formed by intersecting water-bearing fractures grouped in cubical symmetry. The tunnel in the figure happens to fit between two sets of fractures such that only one, sub horizontal, set intersects the tunnel.

The inflow rate per point can be related to the average hydraulic conductivity *K* of the rock surrounding the tunnel if the frequency of inflow points is known. *K* can be determined by "ventilation" tests implying that air with known low humidity is pumped through the tunnel, dried and again pumped through in a cyclic fashion. The amount of water taken up by the air is measured until equilibrium is reached and used for evaluating the conductivity by applying ordinary flow theory and recorded water pressures at different distances from the tunnel [7],[10].

For a bulk hydraulic conductivity of E-10 m/s and a frequency of inflow points of one per meter length of the Prototype tunnel the measured inflow of 0.01 l/min per meter tunnel in the outer part would give an inflow of 0.1 l per minute where there is only one channel per meter tunnel length and 0.05 l/minute if there are two points as in Figure 9. Since the inflow is directly proportional to the bulk hydraulic conductivity, a bulk hydraulic conductivity of E-9 m/s and one inflow point per meter tunnel length would give an inflow from it of 0.1 l/minute. For two inflow points it would be 0.05 l/minute per point and 0.025 l/minute if there are 4 points per meter tunnel length. For the lower bulk hydraulic conductivity of E-11 m/s one inflow point per meter tunnel length would give an inflow into the tunnel from this point of 0.01 l/minute. Extending the calculation to consider more cases one gets the diagram in Figure 10.

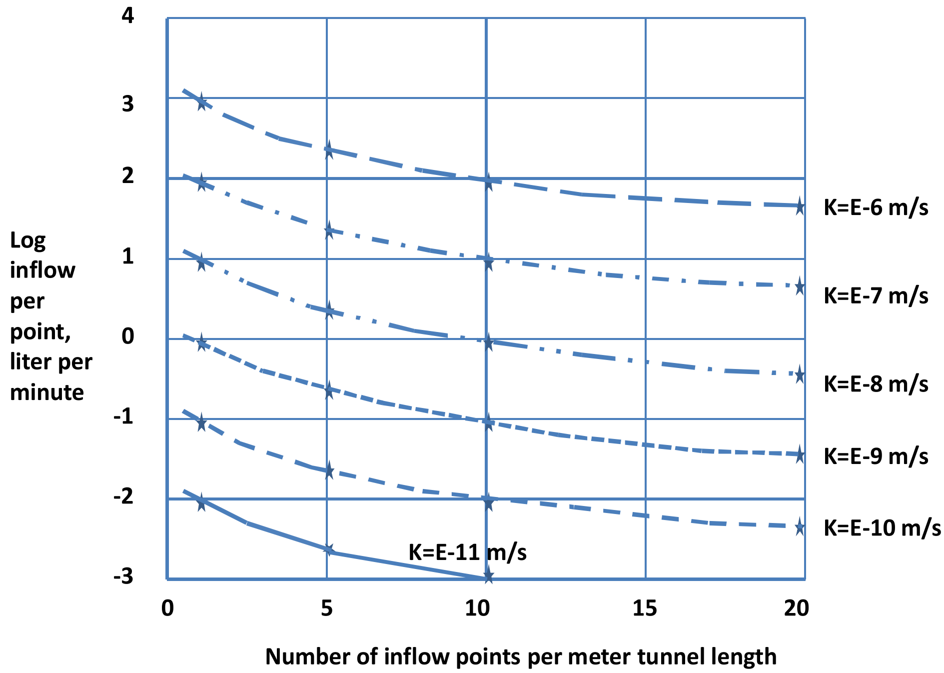

Figure 10. Inflow per point in liters per minute in log scale as function of the bulk hydraulic conductivity of the rock and number of inflow points per meter tunnel length.

The bulk hydraulic conductivity of the rock ranged between E-11 and E-10 m/s where the outer part of the Prototype tunnel was located. The number of inflow points in this part was 0.8 per meter tunnel length, which gives an inflow per inflow point of 0.01 to 0.1 l/min according to the diagram in Figure 10. This means that water would penetrate the pellet fill so slowly that backfilling at a rate of 6 m/day would not cause problems. Had the average hydraulic conductivity of the rock been E-9 to E-10 m/s the inflow from a single point per meter tunnel length would be 0.1 to 1 l/min creating critical conditions. Backfilling of TBM tunnels located at 450 m depth in rock with higher average hydraulic conductivity than E-9 m/s would definitely cause difficulties.

3.3.2 The role of the EDZ in wetting of clayey backfill

Figure 11 illustrates the hydraulic role played by the EDZ of blasted tunnels with respect to the risk of piping and erosion. The reason is that the rock from the periphery to a depth of a couple of decimetres to about 1 meter becomes rich in blast-generated fractures, as illustrated by determination of the hydraulic conductivity of the EDZ [7]. Counting the fractures in holes bored from the periphery as illustrated by Figure 11, the number of blasting-induced inflow points is at least 100 times higher than in virgin rock, which is compatible with the fact that the hydraulic conductivity of the EDZ is about 100 times higher than that of virgin rock. This suggests that the inflow per point will be reduced to 1/100 of that of a TBM tunnel and that backfilling of blasted tunnels may be successful even in rock with an average hydraulic conductivity as high as E-8 m/s as indicated by the diagram in Figure 10.

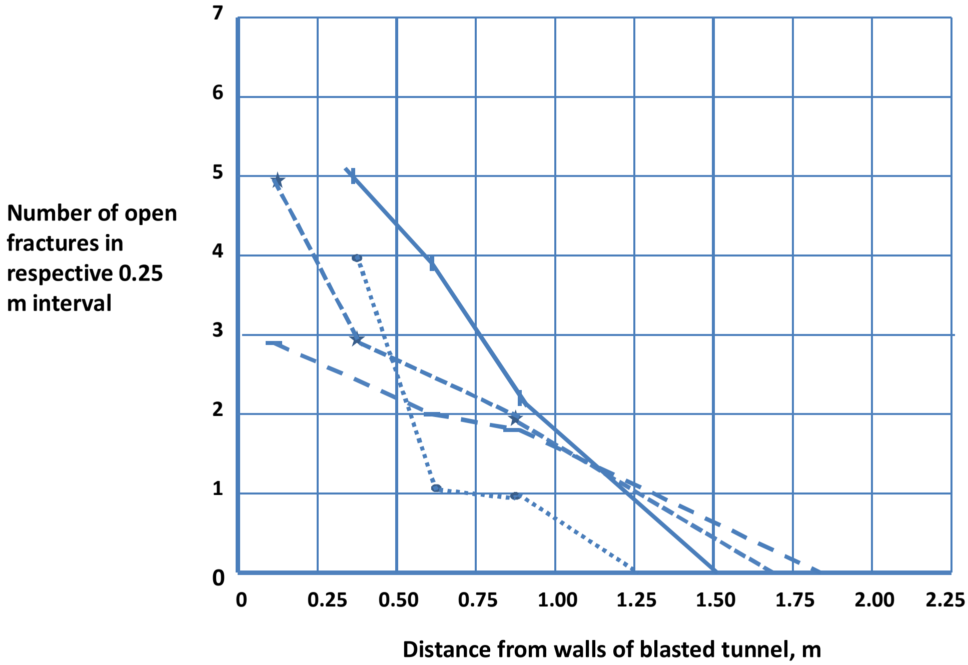

Figure 11. Example of presence of water-bearing fractures in the EDZ of blasted tunnel in granitic rock for different distances from the tunnel contour, determined by mapping of cores taken perpendicularly to the contour [7].

3.4 Conceptual model of the impact of inflow on pellet fills

3.4.1 Rate of inflow

Figure 12 generalizes the spot pattern in a tunnel to be backfilled. The sloping pellet fill shown in the figure moves intermittently to the right by which the front becomes located at different distances from the respective inflow points. Naturally, a very small distance from a spot discharging much water is more critical than when the backfilling has proceeded far beyond it, which implies that backfilling of a TBM tunnel must be quick when passing such spots. For a blasted tunnel with many more spots with lower discharge of water, the conditions are less critical but some wet spots will still be there and the backfilling should be quick when passing them.

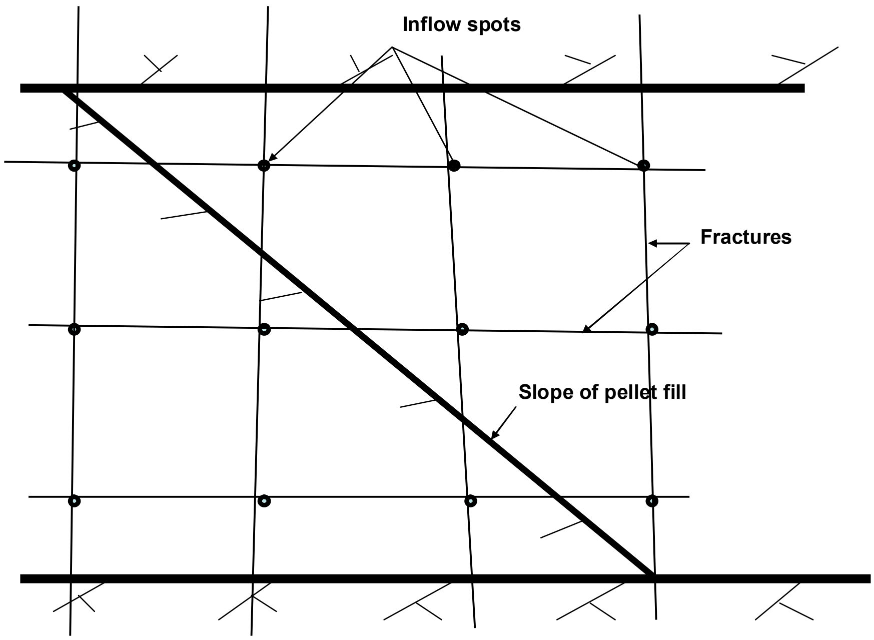

Figure 12. Generalized fracture pattern with inflow points formed by intersecting fractures. The points become located at different distances from the slope in the filling process.

Considering the diagram in Figure 10 and the spot pattern in Figure 12 one can estimate the risk of breakthrough of channels from the rock to the front of the pellet fill being placed. An inflow from a single point into the pellet fill of 0.1 l/min would imply a water penetration rate of 1 m per hour in the pellet fill if the diameter of the channel is 1 mm. If it expands to 3 mm diameter, which is still a narrow channel with only little erosion, the water penetration rate would be only 0.1 m/hour. A 0.1 mm channel would imply a water penetration rate of 10 m per hour, which shows that the penetration rate and time for breakthrough depends on the size of the channel and that the possibility to pursue backfilling of pellets without breakthrough of water can require backfilling rates of more than 1 m per hour. Naturally the spacing of the inflow points plays an equally important role. One realizes from this that, for the pellet dimensions considered, the diameter of a channel formed by penetrating water is on the order of 1 mm. This makes it possible to solve the problem of defining a safe backfilling rate for different point inflows and geometrical distribution of the points. Larger pellets imply wider voids and channels and hence more risk.

3.4.2 Erosion

The erosive effect of inflowing water is a function of the rate of flow in the channels and the resistance to shearing of the clay surrounding them. The case can be treated by applying flow models as proposed by Hellström et al [12], [13]. The successive concentration of flow to one channel evolves according to such models worked out for percolation of granular soils. This is in excellent agreement with the experiments shown in Figures 3 and 4 from which it was concluded that the large majority, or possibly all of the outflow, came from one discharge point and that it increased with time [11]. The water contained only a small amount of dispersed clay, indicating that the erosion was initially very moderate.

4 Discussion and conclusions

4.1 Wetting

The matter of foreseeing whether a tunnel can be successfully backfilled with smectite-rich pellets can be assessed by making a rock structural model for estimating the number of inflow points and calculating the inflow rate by measuring the inflow rate in the not yet backfilled tunnel. If this rate is higher than a certain critical rate, piping and erosion will be caused by which the backfilling operation can fail. The critical rate can not be determined at present but it is estimated from large-scale expeiments that it is not a material property. Instead, channel-wise percolation of water will take place at any inflow rate after sufficiently long time, i.e. when the water pressure at the inflow point is high enough. The observations led to the following conceptual model of wetting by inflowing water:

1. For low water pressure the wetting proceeds by capillary suction and surface diffusion along the pellet surfaces, associated with expansion of the pellets and release of minute particle aggregates that form clay gels that tighten the voids between the pellets. When the degree of saturation rises the pressure also goes up and finally causes breakthrough.

2. For high water pressure the wetting is dominated by inflow through a channel that is widened if the water pressure is high enough to overcome the pressure acting between the pellets. Almost all water flows in the wide channel and quickly makes its way by the influence of gravity causing downward migration of the water.

3. The conceptual model, validated by field tests, implies that the inflow into tunnels at a few hundred meter depth from discrete points in rock with common hydraulic conductivities is less than 0.1 l/min in blasted tunnels per meter tunnel length, and 0.1-1 l/min per meter length in TBM tunnels. An inflow rate of 0.1 l/min will allow backfilling of about 10 m tunnel per day without problems caused by penetrating water; blasted tunnels are concluded to be more easily backfilled than TBM tunnels.

4. Piping, implying quick penetration of water from the inflow points to the slope of the pellet fill, wets the pellet grains around the outflow point and disrupts

them by which the outermost part of the flow path undergoes successive widening and strong wetting of the pellet fill. This causes a mud flow scenario.

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