Initial Plug and Seal Design for the Dutch Repository Concept

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In the Dutch repository concept, that is geological disposal in Boom Clay, plugs are proposed to be used to hydraulically seal off disposal drifts after the emplacement of waste packages and to restrict any movement of backfill. This paper presents an initial scoping of the design requirements for plugs and seals in this context and initial scoping calculations are carried out for the specific conditions expected in the Dutch geological context. It is intended to provide an initial design and approximate sizing and a commentary on the key issues, so that detailed design and performance assessment may be carried out. The design of the plug system has been split into two parts, (i) a compacted bentonite seal, designed primarily to restrict the hydraulic flow, and (ii) a concrete plug, designed to restrict any movement of the backfill. Two outline designs have been produced, one where the tunnel lining is removed to allow the concrete plug to bear on the lining and the second where the lining is not removed and frictional resistance is the main support. The initial sizing of the concrete plug leads to a plug length of 2.85 – 4.8 m for the design where the tunnel lining is not removed and 0.99 – 1.67 m where the tunnel lining is removed, depending on the tunnel radius (1.1 to 1.85 m). This length could be further reduced by the addition of shear reinforcement. The bentonite seal has been designed so that the swelling pressure is able to re-seal the EDZ and provide good sealing. Numerical modelling has shown the length required to prevent significant axial flow is between 0.5 and 1.0 m.

1 Introduction

To control water flow and restrict material movement in tunnels, such as mines, or in the case of a geological disposal repository, plugs and/or seals can be used. As part of the backfill of the repository, plugs are likely to be required. In the Dutch repository concept, plugs are proposed to be used to hydraulically seal off disposal drift after emplacement of waste packages and to restrict movement of backfill.

Based on the required functions of the plug system, two main components for a plug system in Boom Clay are summarised as follows: a concrete plug and a bentonite seal. The concrete plug should mechanically support the bentonite seal and backfill, and transfer the loads into the surrounding host rock. The bentonite seal cannot prevent leakage unless it has reached sufficient saturation, so the concrete plug must prevent leakage until this time (Dahlstrom, 2009; Malm, 2012). After this point, the requirement of the concrete plug to be watertight is no longer necessary. The concrete plug must carry the hydrostatic water pressure as well as the effective stresses.

The backfill is likely to provide a low permeability environment itself, but to reduce any risk of erosion of the backfill, the seal should consider only allow a low gradient to exist in the backfill.

The bentonite seal shall prevent axial flow from the deposition tunnel, and heal cracks that may initiate on the upstream side of the concrete plug and therefore prevent leakage. The bentonite seal is designed to have a low hydraulic conductivity, it should swell and seal all passages and it must be able to withstand a high hydraulic gradient. The bentonite seal should have good contact between the clay host rock and the bentonite seal. In order to cut off water flow through the EDZ, the bentonite seal can be inset in a slot into the host rock or may be able to reseal the EDZ via swelling behaviour. The hydraulic cut off is achieved by lowering the hydraulic conductivity of the clay around the seal to a value lower than the undisturbed in-site hydraulic conductivity (Van Marcke et al., 2013). In addition, the bentonite seal should also heal cracks that may initiate on the upstream side of the concrete plug, and thereby prevent leakage from the deposition tunnel.

2 Conceptual design of the plug geometry

Two types of conceptual plug design are studied in this paper, some basic calculations are carried out to determine the plug length and strength, from the hydraulic and mechanical point of view. The two plug systems are shown in Figure 1(a), where in Design A the concrete plug is installed inside the tunnel lining, whereas in Design B the tunnel lining is removed for the concrete plug to be installed. In both designs the tunnel lining is removed in the location of the bentonite seal, to ensure good connection between the bentonite and the Boom Clay. It is anticipated that the EDZ would be able to be sealed via swelling pressure of the bentonite, but local over-excavation in this area would allow additional reduction of hydraulic conductivity.

(a) (b)

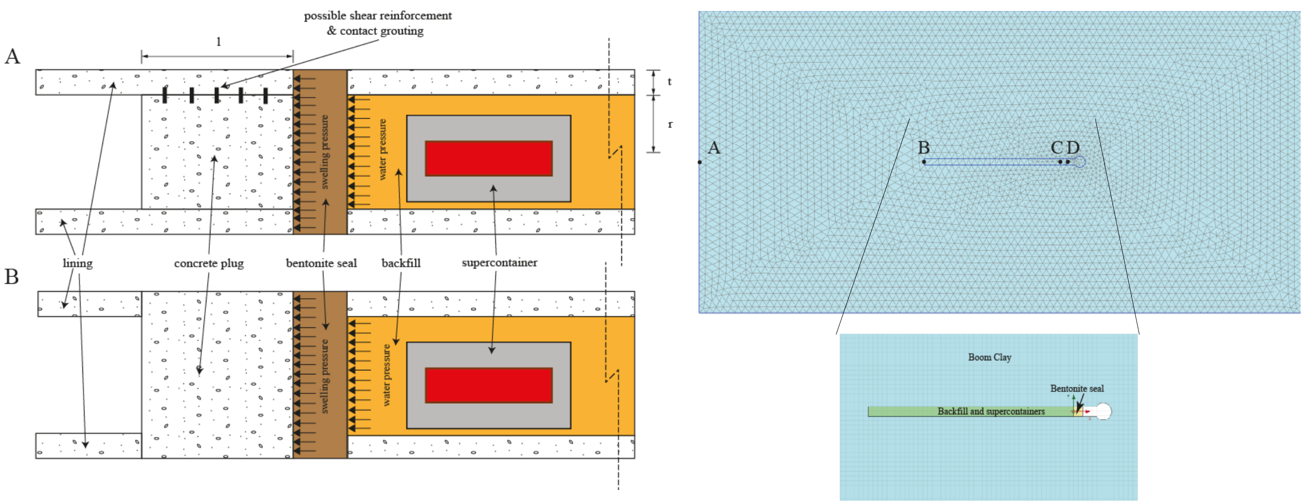

Figure 1. (a)Two types of conceptual plug system design; A: with the concrete plug installed inside the tunnel lining, and B: with the tunnel lining removed locally where the concrete plug is installed and (b) The mesh and details of the deposition tunnel and plug system used for the hydraulic simulation

In Design A the mechanical loads must be withstood via friction between the tunnel lining and the plug, whereas in Design B the plug can transfer loads via compression into the lining (and subsequently the rock). In both cases, the concrete is designed to be unreinforced to reduce the possibility of metal corrosion and for the same reason neither design A nor design B has access tubes. Moreover both designs do not require alteration to the tunnel construction via tapering or substantial over-excavation.

3 Mechanical stability

For the first type of plug design (shown in Figure 1(a) type A), the failure of this parallel-sided plugs is governed by the interface shearing between concrete plug and lining. The following equation can be applied to calculate the circular plug length *l*, of radius *r* (Auld, 1983),

$$l \geq \frac{\sigma r}{2 p_{pe}} \tag{2.1}$$

where σ is the applied stress, in this case the total stress, is assumed to be 7 MPa. This is the sum of the estimated swelling pressure in the backfill of 2 MPa (Fälth and Gatter, 2009) and a pore-water pressure of 5 MPa at the depth of 500 m (Arnold et al., 2015; Verhoef et al., 2011); and p_{pe} is the permissible punching shear stress of the rock or concrete interface. It may be possible to reduce this length by incorporation of shear reinforcement (as shown in Figure 1(a) type A), but this has not been considered in this scoping calculation.

For the design of the type B plug, the resistance force is provided by the interface shearing between concrete plug and host rock and support from the lining. In addition the plug itself must be able to support the generated shear within the plug. It was found due to the thickness considered for the lining (~0.5m) that the punching stress through the plug is the dominant mechanism. This can be considered via the following equation (Auld, 1983),

$$\sigma_p = \frac{\sigma \pi r^2}{2\pi r l} \leq p_p; l \geq \frac{\sigma r}{2 p_p} \tag{2.2}$$

where σ_p is the punching stress and p_p is the permissible punching stress of the concrete.

Utilising EN1992-1-1 (European Committee for Standardisation, 2004) to derive the appropriate concrete strength measures and using concrete class C55/67, the permissible punching shear stress of the rock or concrete interface, p_{pe}, is 1.35 MPa and p_p is 3.87 MPa.

For design A, applying equation (2.1) and considering the inside radius of the tunnels r = 1.85 m for LILW and (TE)NORM disposal gallery and r = 1.1 m for HLW/spent fuel disposal gallery (Verhoef et al., 2011), would give a plug length of 4.80 m and 2.85 m, respectively.

For design B, and applying equation (2.2) gives the plug length of 1.67 and 0.99 m for radius of the tunnel of 1.85 m and 1.1 m, respectively.

4 Hydraulic seal of the plug system

Two-dimensional plane strain analyses have been performed with PLAXIS 2D AE (Plaxis, 2014) to investigate the hydraulic performance of the seal component of the plug system. The objective is to investigate the length at which flow is reduced to a minimum and pressure gradients in the backfill are reduced to reduce erosion.

The simulation domain is approximately 200 m long and 100 m high, with the mesh and geometry near the deposition tunnel and plug system shown in Figure 1(b). The domain is discretised using 15-node triangular elements and refined in close vicinity of the tunnel (Figure 1(b) top). The hydraulic boundary conditions are as follows: the water head at the outer Boom Clay boundaries are fixed to 500 meters, the inner boundary of the open tunnel and the outer sealing boundary are free draining, i.e. fixed of 0 m head.

The domain is divided into 3 different property areas with different hydraulic properties, (i) those of the host rock (Boom Clay), (ii) backfill and supercontainers, and (iii) the bentonite seal (Figure 1(b) bottom). The fluid flow has been modelled here using a steady state Darcy flow equation. The mechanical behaviour and displacements in the domain have not been included in the simulations. Since the backfill material for the Dutch disposal project has not been fully specified, two values of hydraulic conductivity are used in the simulations representative of foamed concrete, the proposed backfill material, or sand. The hydraulic properties of the different materials are: k = 10^{-9} m/s and 10^{-10} m/s for backfill, 10^{-13} m/s for bentonite and 10^{-12} m/s for the Boom clay. In order to find the optimal bentonite seal length, the hydraulic response of five different length seals, L={0.1, 0.5, 1.0, 2.0, 5.0} m, are studied.

Figure 2(a) shows the pore water pressure head distribution in the calculation domain with backfill hydraulic conductivity, k=10^{-9} m/s (left-hand side) and k=10^{-10} m/s (right-hand side), for various seal lengths. An increase in seal length, reduces the low pore water pressure head zone. The reduction in the backfill hydraulic conductivity also results in a reduction in the low pore water pressure head zone. Figure 3 shows the pore water pressure head profile along the line AD (see Figure 1(b)) with backfill hydraulic conductivity k=10^{-9} m/s and k=10^{-10} m/s, for various seal lengths. As can be seen, the pore water pressure head at points B and C increase with increasing length of the bentonite seal. Overall, the pore water pressure head gradient is mainly taken by the bentonite seal, only a small part is taken by the backfill, which reduces the likelihood of erosion.

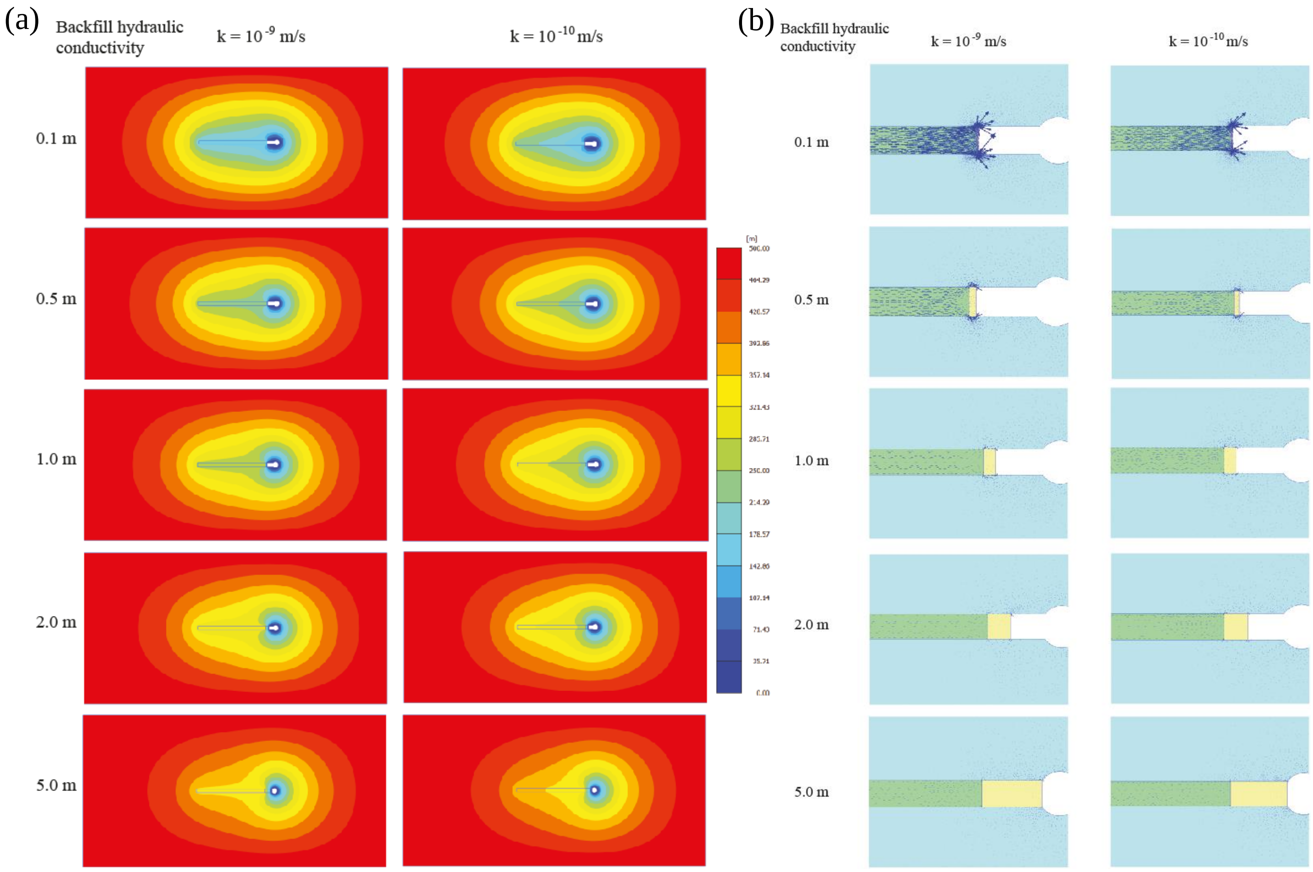

Figure 2. (a) Pressure head distribution for different sealing length, left: k=10^{-9} m/s of the backfill hydraulic conductivity; right: k=10^{-10} m/s of the backfill hydraulic conductivity and (b) Velocity distribution near the plug for different sealing length, left: k=10^{-9}m/s of the backfill hydraulic conductivity; right: k=10^{-10} m/s of the backfill hydraulic conductivity

Figure 3 also shows that with lower backfill hydraulic conductivity, the pore water pressure head gradient in the rock decreases, which indicates a lower backfill hydraulic conductivity results in better sealing, however the gradient in the backfill is greater, indicating a greater chance of erosion. Figure 4(a) shows the percentage of water head gradient taken by the bentonite seal (Point C) over the water head at end of the disposal tunnel (point B) as a function of plug length, for different backfill hydraulic conductivity. These plots shows that for different backfill hydraulic conductivity the percentage of water head at B/C have similar trend. The optimal seal length can be conducted to be between 0.5-1.0 m, since any further increasing the seal length only slightly increases the percentage of water head at B/C.

The velocity of water flow close to the disposal tunnel and the plug system is shown in Figure 2(b), for two different backfill hydraulic conductivities, and for various seal lengths. The results from calculations with $k=10^{-9}$ m/s and $k=10^{-10}$ m/s are similar, with the major flow paths in the host rock around the seal. In both cases increasing the plug length results in decreasing velocity around the plug system. As seen from Figure 2(b) the maximum flow velocity located near the top and bottom of the plug, which indicated those areas may be the weak zone, reinforcement could be useful, e.g. by extending the bentonite seal into the host rock. At seal lengths over 1 m, axial flow is virtually eliminated and almost no preferential flow around the seal is seen. Figure 4(b) shows the maximum velocity in the domain versus seal length for different backfill hydraulic conductivities and reinforces this finding. It is seen that the optimal plug length located between 0.5-1.0 m, with further increases in length not resulting in substantial decreases in flow.

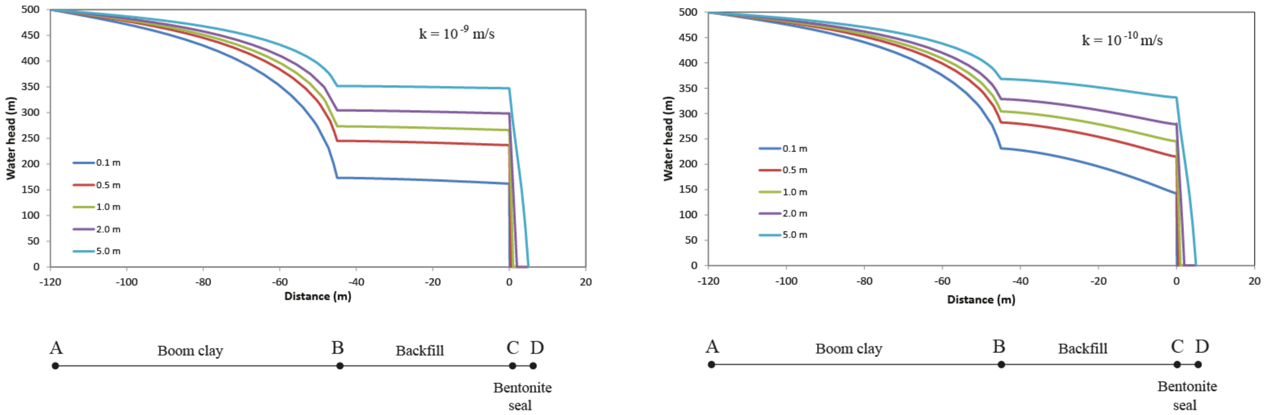

Figure 3. Pressure head distribution along the tunnel for different sealing length, left: $k=10^{-9}$ m/s of the backfill hydraulic conductivity; right: $k=10^{-10}$ m/s of the backfill hydraulic conductivity

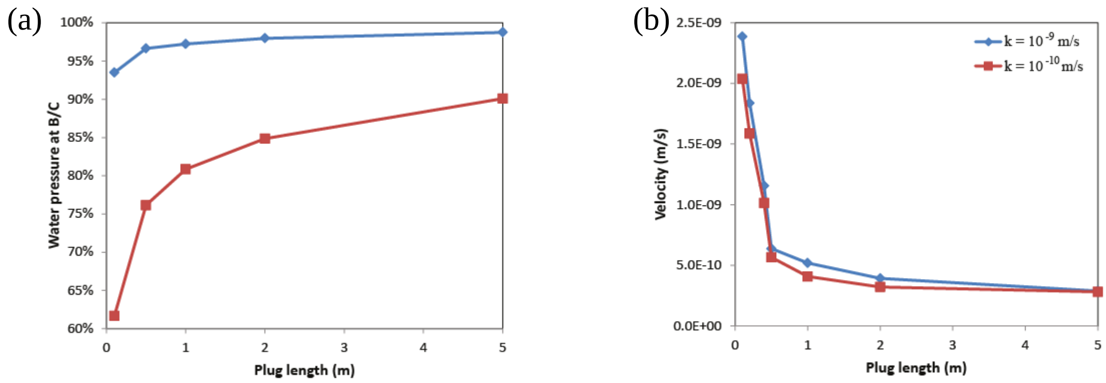

Figure 4. (a) Percentage of water head taken by the plug verses sealing length for different backfill hydraulic conductivity; (b) Maximum velocity in the domain versus sealing length for different backfill hydraulic conductivity

5 Conclusions

Two main requirements for the plug system for the Dutch geological repository have been distilled: i) a plug that keeps the backfill in place and ii) a seal that prevents axial water flow. The system shall prevent erosion of backfill so that the backfill maintains its function.

Two types of conceptual mechanical plug design have been studied. One where linings are locally removed and the second where they have not. The plug lengths in all cases considered are thought to be reasonable, being in the range of the radius. With the conceptual design A leading to a plug length of 2.85 – 4.80 m and conceptual design B leading to a plug length of 0.99 – 1.67 m. From the mechanical point of view, removing tunnel lining segments leads to significantly reduced plug length (conceptual design B), but this may lead to a more difficult construction process.

A bentonite seal has been chosen to hydraulically seal the plug system, when bentonite is hydrated, the swelling pressure exerted against the clay will locally lower the hydraulic conductivity of the clay and close any cracks present around the bentonite seal. An appropriate length was shown to be approximate between 0.5 and 1.0 m. Close contact with the rock is required to ensure a good seal, therefore the tunnel lining should be removed in this location. The bentonite seal could additionally be inset in a slot with a minimum depth larger than the depth of EDZ to ensure good sealing.

6 Acknowledgements

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