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Predictive permeability model of faults in crystalline rocks; verification by grouting in Seyahoo dam

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Abstract

This paper deals with quantitative fault zone descriptions, qualitative fracture and fault rock properties, and engineering data in the study of the permeability structure of fault zones. Datasets include scan-lines, drill cores and cement grouting from Seyahoo dam in andesite and basalt rocks, from which systematic grouting volumes can be used to analyze the in-site relative permeability both in host rocks and fault zones. Dam-scale injection of cement reveals patterns that can be ascribed to the impact of faulting; there is an increase in cement injection in fault zones compared to areas with background fracturing away from faults. In detail, there is an innate division of the rock volume into sub-zones characterized by distinct structural style and permeability, with a background level and three fault related sub-zones (fault core, inner damage zone, and outer damage zone). Injection data shows that the background sub-zone commonly can be injected with less than 0.05 m^3 cement per meter dam (commonly not injected), whereas the fault core has permeability characteristics nearly as low as the outer damage zone, represented by 0.1 m^3 cement per meter dam, with occasional peaks towards 0.2 m^3. The maximum of cement injection lies in the inner damage zone, the marginal to the fault core, with 0.3-0.5 m^3 cement per meter dam, locally exceeding 0.7 m^3. This gives a relative relationship for cement injection of approximately 1:3:1 between fault core, inner damage zone, and outer damage zone of extensional fault zones in crystalline rocks.

Keywords: Permeability, Fault zones, Fracture distribution, Cement injection, Seyahoo dam.

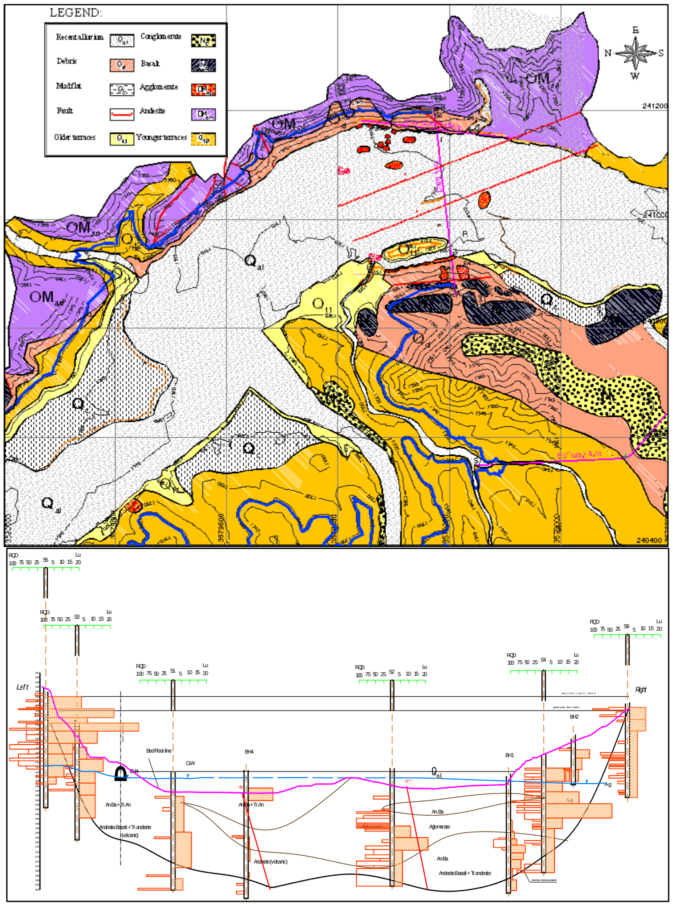
Introduction

Faults represent a challenge in all type of engineering projects, especially in tunnels and quarries, because of increased fracture density, weak rocks, poor rock stability, and enhanced fluid flow (Hoek & Bray, 1981; Hoek, 2000; Nilsen & Palmstrom, 2000; Blindheim & Ovstedal, 2002). These subjects have promoted significant attention around faults, spanning from fault arrays and displacement fields (Walsh *et al.*, 2003a, b), to intrinsic fault geometry and fault architecture (Chester *et al.*, 1993; Caine *et al.*, 1996; Braathen *et al.*, 2004; Collettini & Holdsworth, 2004), and into the realm of frictional behaviour, linked to mechanical and chemical processes (Sibson, 1986, 2000; Stewart *et al.*, 1999; Braathen *et al.*, 2004). Major faults truncate a significant part of the crust, and will reveal different fault products (mylonites, cataclasites, breccias) related to depth, temperature, strain rate, and internal processes, as the fault is unroofed (Sibson, 1986). Fluids play an important role in weakening and generating of faults in general (Chester *et al.*, 1993; Sibson, 1986, 2000; Seront *et al.*, 1998; Faulkner & Rutter, 2001; Faulkner *et al.,* 2003; Wibberley & Shimamoto, 2003; Collettini & Holdsworth, 2004).

In this work, we combine fault rock descriptions related to polyphase activity during faulting and unroofing, with damage zone fracture properties, and with engineering data. The uniqueness in the work relates to the connection between structural observations that can be linked with pre-grouting cement volumes in Seyahoo dam. This opens for in situ considerations of the permeability structure of fault zones.

Investigation site

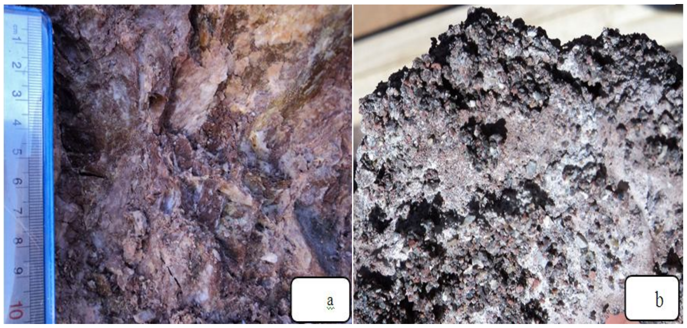
Fig. 1. Geological map of the foundation site of the Seyahoo dam.



The Seyahoo dam site is located on the Seyahoo River in South Khorasan province of east Iran approximately 67 km northeast of town of Sarbisheh. It is a zoned earthfill with a clay core dam which is 32 m high and 352 m long, with a crest elevation of 1342 m, the reservoir has a volume of 15 million m^3. The dam is flood control and capable to supply the needed water for the regions of downward lands and 700 hectares of Doroh lands.

A geological cross-section of the dam site was prepared using information from exploration holes (Fig. 1). The dam foundation is andesite, and generally associated with basalt. Discontinuity planes are constituted by joint sets, faults and irregular fractures. During the foundation excavations, it was observed that the size of fault zones ranges from a few cm to 3 m. Fault surfaces are smooth and slicken sided and are composed of fault gouge and breccias. Fracture opening are predominantly filled with clay and calcite. This chronology is confirmed in outcrops of faults on the Seyahoo and elsewhere in the region, which reveals several types of fault rocks, ranging from semi-ductile mylonites to cataclasites and non-cohesive breccias and gouge (Fig. 2).

Fig. 2. Examples of fault rocks foundation in the Seyahoo dam. where a range of fault rocks commonly occur in the fault cores. (a) An ultrabreccia and gouge (b) protobreccia



RQD values obtained from the measurements in explanatory boreholes and face reports, 0% and 75%. On the basis of geological strength index (GSI) classification, rock quality is 10% blocky, 25% very blocky, 25% blocky-disturbed, 20% disintegrated and 20% foliated/laminated/sheared.

Fault models and permeability

The established terminology on fault zone architecture in metamorphic and crystalline rocks (Caine *et al.*, 1996; Seront *et al.*, 1998) is the fault core, damage zone and protolith. Fault models outline a core that has seen the bulk of displacement, and is therefore hosting fault rocks. Outside this, deformation is accommodated mainly by fractures of the damage zone. The boundary between core and damage zone is typically sharp, and defined by slip surfaces (shear fractures), whereas the transition between damage zone and protolith is marked by a decrease in fracture intensity, to a regional background frequency level. These models predict a zoned permeability field in fault zones in crystalline rocks (Caine *et al.*, 1996; Evans *et al.*, 1997; Wibberley & Shimamoto, 2003), where typically a low permeability fault core is surrounded by a more permeable damage zone toward pristine, lower or impermeable host rocks. Protolith rocks have neglectable primary porosity and permeability unless damaged by brittle deformation (Norton & Knapp, 1977; Morrow & Byerlee, 1988, 1992; Morrow & Lockner, 1997).

In the damage zone, the fracture intensity shows a significant increase in frequency from the background level towards the fault core (Caine *et al.*, 1996; Braathen *et al.*, 1998). Not only the frequency but also the length of fractures is of interest, since a key conclusion from simulation of flow in fracture systems is that long fractures will conduct more water than short fractures, due to higher connectivity (Odling, 1997; Masumoto *et al.*, 2007). Detailed analyses of damage zones reveal sub-zones characterized by distinct fracture sets and populations, as outlined in Braathen *et al.* (1998). They describe a core of fault rocks surrounding lenses of host rock with a dense network (20-100 f/m) of short fractures. The damage zone has an inner part, 5-50 m wide, dominated by fault-parallel, moderate frequency long fractures, which are connected by shorter fractures. In total, this gives an overall good connectivity. The outer part of the damage zone shows decreasing frequency of fractures that varies in length and orientation, demarcating the transition from damage zone to background fracture level.

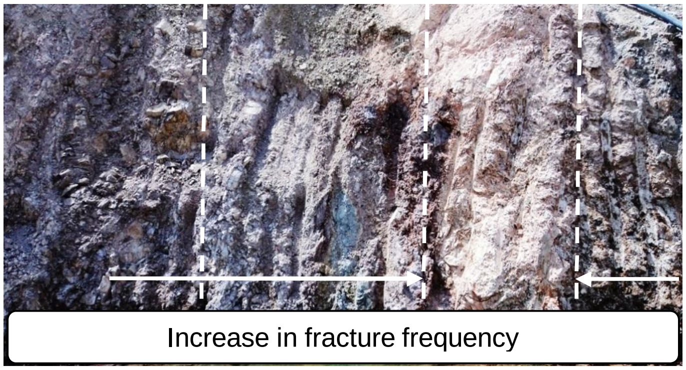
Permeability models of faults combine numerical simulations with laboratory permeability measurements (Morrow & Byerlee, 1988, 1992; Morrow & Lockner, 1997; Seront *et al.*, 1998; Faulkner & Rutter, 2001). The latter study confirms that the permeability of rocks and fractures is reduced with depth, i.e. with increasing effective pressure (Morrow & Byerlee, 1988, 1992; Morrow & Lockner, 1997). In accordance with the studies presented above, permeability studies aimed on faults at shallow depth show that the lowest permeability is found in the fault core, as addressed by for example Seront *et al.* (1998). Their field and laboratory results suggest that the damage zone conduct most fluid due to its higher values of permeability, which are several orders of magnitude higher than the protolith and the core. These results are undermined by Faulkner and Rutter (2001), who question the value of laboratory test results in which the natural fault rocks are without intact *in situ* fabrics. Anyhow, Evans *et al.* (1997) conclude that there is a permeability contrast between fault core and damage zone in the order of magnitude of $10\text{-}10^4$, with a maximum contrast of 10^6. Further, they argue that the permeability field is anisotropic, in an order of 10^4, with the highest permeability parallel to the fault.

Methods and datasets

Presented data sets include scan-lines, drill cores and pregrouting cement volumes. The main data set on structures is from drill cores, which implies that the fault zones and their subordinate parts are classified from this data set. Note that the fracture frequency in drill cores is regarded as higher than in situ fracture frequency due to the applied stress during drilling. In addition, where the rock has poor quality, as in fault cores, core loss is common.

Pre-grouting, i.e. injection of cement through drill holes ahead of the dam, was performed according to predefined pressure thresholds. Pumping/injection pressure was initially set to 3.5-12 bar. If the rock was still permeable at this pressure, the cement was changed to a more viscous cement type. Therefore, the recorded volumes of cement may be seen as minimum values. During the dam constructions, 3-4 types of cement ranging from fibrous to armoured are applied, with densities varying from 2800 to 3200 kg/m^3, with an average of 3000 kg/m^3, and with different viscosity properties. The heavier, armoured cement type is commonly reserved for heavily fractured and loose rock, commonly found around the fault core, and is used mainly for stability reasons.

Fig. 3. Cross-section showing fault (F1) and/or fracture zones (red) encountered in foundation in the Seyahoo dam



Discussion

Fault zone characteristics

All faults intersected by the tunnels show a fault zone of 60-80 m width, where the fracture frequency commonly increases towards the core of the fault (Fig. 3). Further, a polyphase history characterized the studied faults, with fault products including impermeable mylonites and cataclasites, which are reworked in porous breccias and gouge. In the Seyahoo dam the fault cores are in general narrow, seldom more than 3 m wide, and characterized by cataclasites superimposed by non-cohesive fault rocks. The detailed descriptions of major faults transected by the dam reveal common fault rocks surrounding intensively fractured rock lenses in the core. Encountered fracture frequencies in these lenses are commonly around 50 f/m, but can locally reach 100 f/m before the rock disintegrate to breccias. In the surrounding damage zones, networks of fracture sets can be divided into two parts, one that is made up of fairly high frequencies (20-30 f/m) and another with lower frequencies (< 20 f/m). The part with higher frequencies are mostly found as a narrow zone marginal to the core (inner damage zone), whereas the lower frequency part covers the stretch outwards to background fracture level (outer damage zone). Outcrop studies by Braathen *et al.* (1998) suggest that the high frequency sub-zone has longer, fault sub-parallel structures, whereas the latter sub-zone is characterized by more diverse fracture orientations and lengths. This difference has significant implications for the permeability field in the damage zone, since longer fractures will conduct more water than short fractures, due to higher connectivity (Odling, 1997). Hence, due to higher frequencies and longer fractures in the inner damage zone, this sub-zone of faults should show higher injection values compared to the outer damage zone.

Fig. 4. Inner damage zone: This zone had the highest Water leakage (Q=1lit/s, p=0.8 bar).

Fault zone permeability

The overall differences in structural characteristics between faults in the Seyahoo dam may affect porosity and permeability properties. If this is so, the faults with narrow cores and less abundant porous fault rock and also lower fracture frequency in damage zones, should in general see less injection of cement. Contrary, faults of the have wide cores of both porous breccia and impermeable gouge, and also higher fracture frequency in the damage zones. Despite the presented contrary examples presented above, the general results from this study agree well with results presented by for example Evans *et al.* (1997), which show that the damage zone has the highest permeability (Fig. 4). When comparing results of the two faults in Seyahoo dam, as present in Fig. 5, the datasets from the damage zones contradicts the assumption presented above. There is slightly higher cement injection values for damage zones of the F1, with 0.7-1.1 m^3 per meter compared to 0.5-0.7 m^3/m for F2. Fault core injection volumes are also fairly similar, in the range of 0.1-0.15 m^3 per meter. In other words, the resolution of the datasets (see next paragraph) is not sufficient for detailed comparison of the permeability characteristics of individual faults (Table 1).

Table 1. Amount of injected cement and their characteristics in the different sub zones: The fault core (c), the inner damage zone (ID) and the outer damage zone (OD) of totally two faults in the Seyahoo dam

Faults	Fault core (c)				Inner damage zone (ID)				Outer damage zone (OD)				Ratio	Ratio	Ratio
	Cement (Kg/m)	Volume (m^3/m)	FF (max/m)	Width (m)	Cement (Kg/m)	Volume (m^3/m)	FF (max/m)	Width (m)	Cement (Kg/m)	Volume (m^3/m)	FF (max/m)	Width (m)	ID/C	OD/C	ID/OD
F1	250	0.08	60-70	3	1000-1500	0.33-0.5	25-45	12-20	300	0.1	5-15	15	4	0.8	3
F2	550	0.18	70	2	1400-1800	0.5	30-35	18-25	530	0.17	10-20	20	2.9	1.1	3
Average		0.1-0.15				0.3-0.5				0.1-0.2	5-15		3	1	3

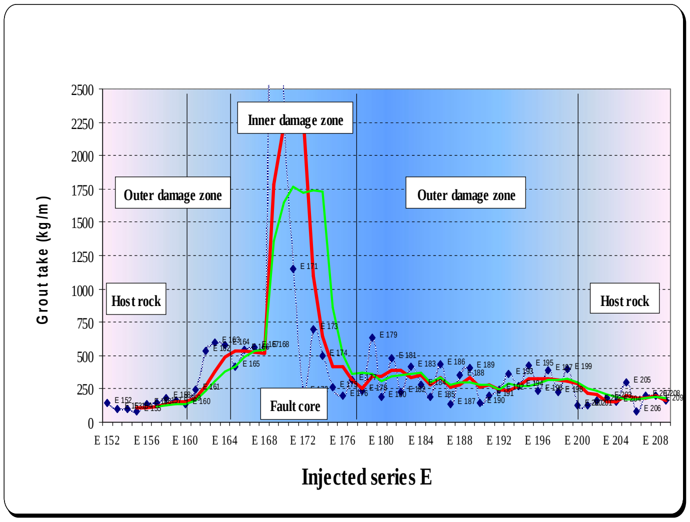
In this dataset, the outer damage zone has average cement injection volumes of 300 kg/m (0.1 m^3/m), and fracture frequency in the range of 5-15 f/m. For the inner damage zone, the cement volumes are in the range of 1000-1500 kg/m (0.33-0.5 m^3/m); with a width of the sub-zone from 12 to 30 m that has a fracture frequency in the range of 25-45 f/m. The average thickness of the fault core is about 2 m, with a peak fracture frequency in rock lenses hosted by fault rocks of 60-70 f/m, and an average cement volume of 250 kg/m (0.08m^3/m). This gives an injection average ratio of inner damage zone and fault core of approximately 4:1, core and outer damage zone ratio of 0.8:1, and inner and outer damage zone ratio of 3:1.

Similar patterns of injection can be found for the two studied faults in the Seyahoo dam (Fig. 1), with an injection average ratio of outer damage zone and fault core of approximately 1:1, core and inner damage zone ratio of 1:3, and inner and outer damage zone ration of 3:1. However, there are exceptions, gives the largest water leakage. This fault has a wide damage zone of densely fractured rock and a narrow (0.5-1 m) fault core. With such a narrow core, the expected low ratio in cement volume of the fault core may be overshadowed by the damage zone, and therefore not show up, as discussed in next section.

Resolution in datasets and permeability considerations

A major challenge in in-situ analysis of faults is the different resolutions of available datasets. That is, drill cores reveal results on millimeter (mm) to meter scale, whereas dam data commonly covers intervals on meter-scale. The engineering data such as the injected cement is related to excavation campaigns, commonly of 5 m length, setting off a new swarm of drill-holes ahead of the tunnel face. These drill holes are 41-60 m long (T-MAECO, 2012). The permeability fields along these holes are unknown but assumed to be more permeable near the tip, in the previously un-injected 5 m section at the base of the hole. Therefore, standard engineering results on pre-grouting can at best be considered viable on 5 m scale, and can only be regarded exact on 35-40 m scale. This lends support to the discussion above, in that structural zoning of faults below a minimum 5-m threshold may not be revealed in injection data, as suggest for some faults.

Fig. 5. Conceptual model of faults in crystalline rocks, divided into sub-zones.The curves describe anticipated fracture frequency of the damage zone and volumes of injected cement (pre-grouting) into the fault zone



Despite such limitations in injection data, one can crudely calculate effective porosity of the rocks. However, even with these uncertainties, it is likely that large-scale *in situ* injection data is better representing fault porosity and permeability fields than the up-scaled result of laboratory measurements of selected structures within major fault zones (Morrow & Byerlee, 1988, 1992; Evans *et al.,* 1997; Seront *et al.,* 1998; Wibberley & Shimamoto, 2003), where the flow characteristics of faults are established through numerical models.

Permeability models of faults in crystalline rocks

As outlined, most detailed outcrop studies of fault zones show an increase in fracture frequency towards the fault core (Fig. 5), in some cases even supporting a difference in the fracture distribution between a wider hanging-wall and a narrower footwall (*e.g.,* Caine *et al.*, 1996; Braathen *et al.*, 1998; Gudmundsson *et al.*, 2001; Micarelli *et al.*, 2003; Berg & Skar, 2005). The pattern of significantly increased injection volumes in the inner damage zone is well documented above, and can be explained by such an empiric model through fracture frequency alone. Alternatively, the explanation may be a general pattern of higher fracture frequencies and longer fractures in the inner damage zone, or a combination of the two models.

Despite the presented contrary examples presented above, the general results from this study agree well with results presented by for example Evans *et al.* (1997), which show that the damage zone has the highest permeability. However, the proposed fault zone contrast, with permeability 10-1000 times lower in the fault core and the protolith compared to the damage zone, seems very high compared to our results on in-site fault permeability. At the best, such contrasts may be valid in comparisons between the inner damage zone and an un-fractured protolith domain. Our combined study of quantitative fault zone descriptions, qualitative fracture and fault rock property assessments, and engineering pre-grouting data sustains the conclusion that there is much more cement injected into the inner damage zone than in the fault core and the outer damage zone.

Conclusions

This study of extensional fault zones in andesite combine datasets from Seyahoo dam, including scan-lines, drill cores, and pre-grouting cement volumes. Fault zones show an increase in fracture frequency from the background fracture level in protolith towards the fault core. Fault zones can be divided into a core, inner damage zone, and outer damage zone with basis in structural characteristics. There is a substantial increase in injected cement volumes in fault zones compared to areas with background fracturing. Fault cores shows clear reduction in injected cement compared to the inner damage zone, likely caused by abundant impermeable fault rocks in the core. High injection values in the inner damage zone likely relates to a high frequency of long, fault-parallel fractures with good connectivity, whereas lower injection volumes in the outer damage zone is controlled by lower fracture frequencies and more variable fracture orientations and lengths. Average injection volumes of cement per meter dam for the fault core is 0.1 m^3, for the inner damage zone is 0.33 m^3, and for the outer damage zone is 0.1 m^3. Injection volume of cement has a relative relationship of 1:3:1 between fault core, inner damage zone and outer damage zone.

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