Washout of clay-rich gouge in a pre-grouted fault zone and increase in groundwater inflow during tunnel excavation in Neogene siliceous mudstone (Horonobe, Japan)

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Abstract

This manuscript describes an unpredicted groundwater inflow that occurred during tunnel excavation through a permeable fault zone comprising clay-rich gouge, despite the fault zone being pre-grouted. Observations indicate that the gouge was increasingly washed out into the tunnel through the rockbolts penetrating the gouge and the boundary between the shotcrete and the gouge on the sidewall during excavation. The resultant piping/erosion of the gouge probably accelerated groundwater flow from the outer aquifer of the pre-grouted zone to the tunnel. After an excavation face exposing the fault zone was temporarily shotcreted, a major inflow occurred from the newly formed flow channel in the gouge, breaking the shotcrete. When a fault zone including such clay-rich gouge is pre-grouted, washout of the gouge during tunnel excavation should be fully prepared because the gouge itself is not cemented by pre-grouting due to its low porosity.

Keywords: clay-rich gouge; fault zone; grout; tunnel excavation

1. Introduction

Reducing groundwater inflow is an important issue during the construction and maintenance of underground facilities. At the Horonobe site in Japan (Fig. 1), an underground facility for research and development into high-level radioactive waste disposal has been constructed (Fig. 2). The amount of

Fig. 1 Map showing the location of Horonobe.

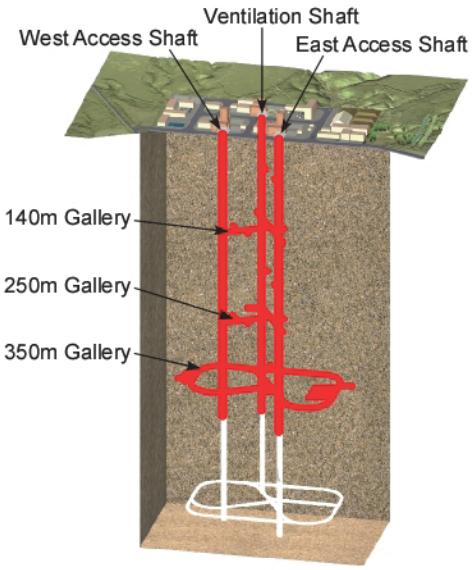

Fig. 2 Diagram of the Horonobe Underground Research Facility. Red-colored shafts and galleries have already been excavated as of April 2015. This layout may be changed depending on the results of future investigations.

drain water is limited to 750 m^3/day under an agreement with the local community. Neogene siliceous mudstone occurs around the facility and highly permeable fault zones, which typically comprise fault breccia, have been identified by borehole investigations in the siliceous mudstone (Ishii, 2012, 2015). The groundwater is saline and contains dissolved methane gas.

This paper reports an unpredicted groundwater inflow that occurred during tunnel excavation and discusses the cause and recommendations for future excavation.

2. Groundwater inflow

Tunnel excavation was carried out while pre-grouting the fault zones; however, when one of the fault zones (the S1 Fault) comprising clay-rich gouge (mainly smectite; Figs 3 and 4; Table 1) was pre-grouted at the 350 m East Loop Gallery (Fig. 5), unusual muddy material exhibiting the same results

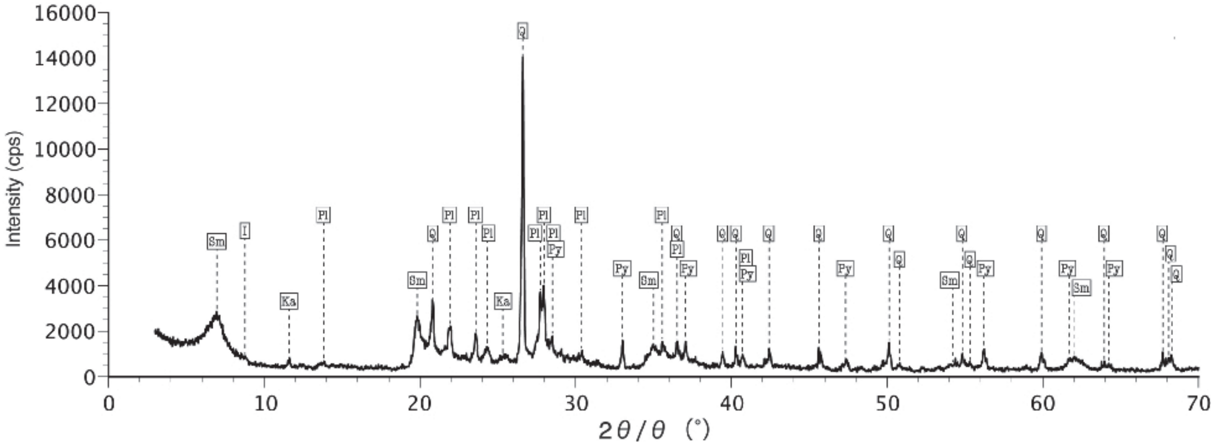

Fig. 3 Result of XRD analysis of gouge (whole-rock) of the S1 Fault.

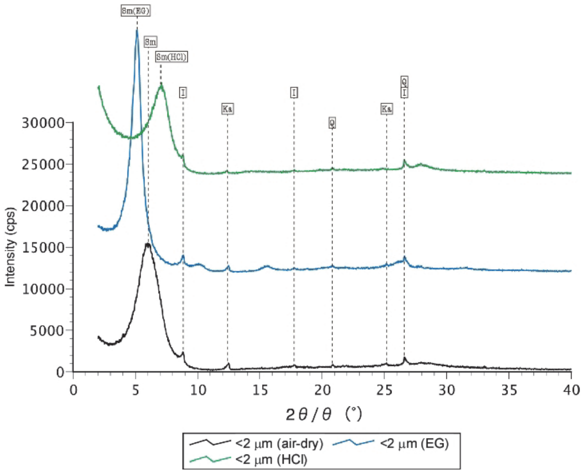

Fig. 4 Results of XRD analysis of gouge (<2 µm fraction) of the S1 Fault.

Table 1 Minerals detected by XRD analysis of the gouge.

	Qz	Pl	Sm	I	Ka	Py
Whole rock	◎	○	△	△	△	△
<2 µm fraction	△		◎	△	△	
Quartz index	1	0.28	0.14	0.01	0.03	0.09

Qz: quartz	I: illite	◎ High abundance
Pl: plagioclase	Ka: kaolinite	△ traces
Sm: smectite	Py: pyrite	○ Low abundance

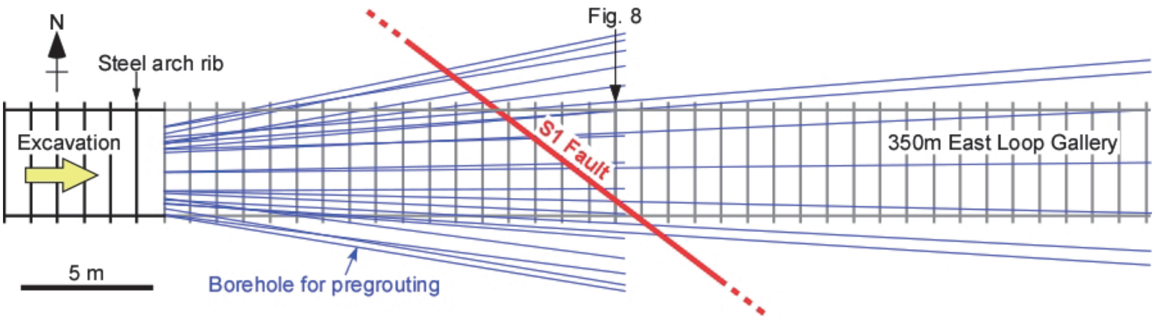

Fig. 5 Layout of boreholes drilled for pre-grouting at the 350 m East Loop Gallery (horizontal map).

of XRD analysis as the gouge of the S1 Fault was ejected from boreholes during drilling (Fig. 6). Excavation of the S1 Fault revealed clay-rich gouge (~10 cm thick) and a surrounding damage zone (a few meters thick). However, the gouge itself was not cemented by grout material (Fig. 7) whereas the gouge-bounding fractures and damage zone fractures were cemented. Intensive spalling occurred at the S1 Fault. During excavation of the fault, the clay materials were increasingly washed out into the tunnel through the rockbolts penetrating the fault and along the boundary between the shotcrete and the gouge on the excavation sidewall (corresponding to the spalling zone and possibly not fully shotcreted) at a flow rate of <1 m^3/hr (Fig. 8a and 8b). After an excavation face exposing the S1 Fault was temporarily shotcreted, a major groundwater inflow suddenly occurred, breaking the shotcrete corresponding to the gouge (Fig. 8c). As a result, the inflow rate temporarily increased to five tens of cubic meters per hour. Observations of the broken shotcrete and at the excavation sidewall revealed that the gouge was largely eroded away from the S1 fault (no photos due to the regulation of the scene). This sudden inflow required post-grouting for more than 1 month.

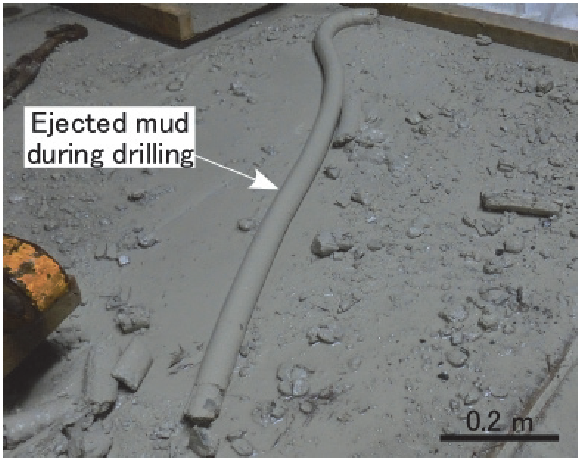

Fig. 6 Muddy material ejected from a borehole during drilling.

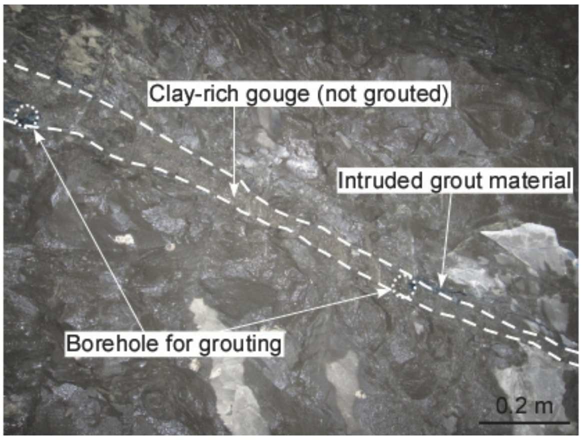

Fig. 7 Occurrence of clay-rich gouge pre-grouted on an excavation face.

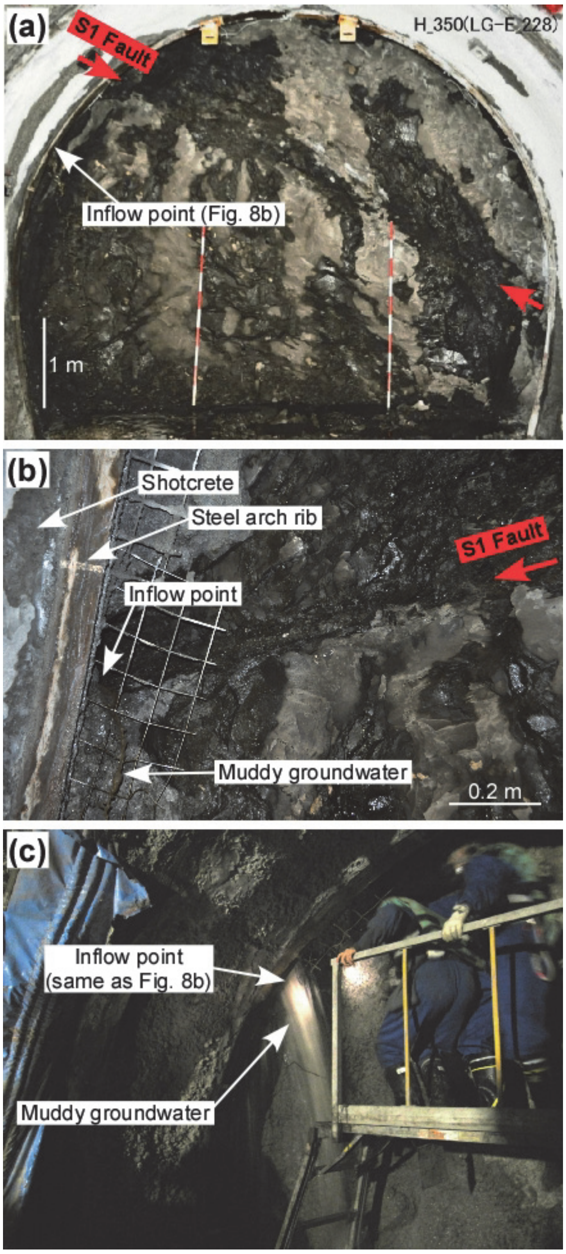

Fig. 8 (a) Excavation face exposing the S1 Fault in the tunnel. (b) Inflow of muddy groundwater from the boundary between the shotcrete and the gouge of the S1 Fault on the excavation sidewall. (c) Major inflow from broken shotcrete corresponding to the gouge of the S1 Fault.

3. Discussion

The above observations indicate that piping/erosion in the clay-rich gouge of the S1 Fault occurred by washout of the clay materials into the tunnel through rockbolts penetrating the S1 Fault and along the boundary between the shotcrete and the gouge on the sidewall during excavation (Fig. 9). Clay is commonly resistant to liquefaction; however, in this case the groundwater flow into the tunnel and the gas/fluid pressure build-up due to shotcreting probably accelerated liquefaction or fluidization and thereby caused washout of the gouge. When a fault zone including such clay-rich gouge is pre-grouted, washout of the gouge during excavation should be fully prepared because the gouge itself is not cemented by pre-grouting due to its low porosity, meaning that flow channels may form by piping/erosion. For example, expanding the grouting area and/or reducing the number of rockbolts might be effective in preventing the washout of clay-rich gouge.

References

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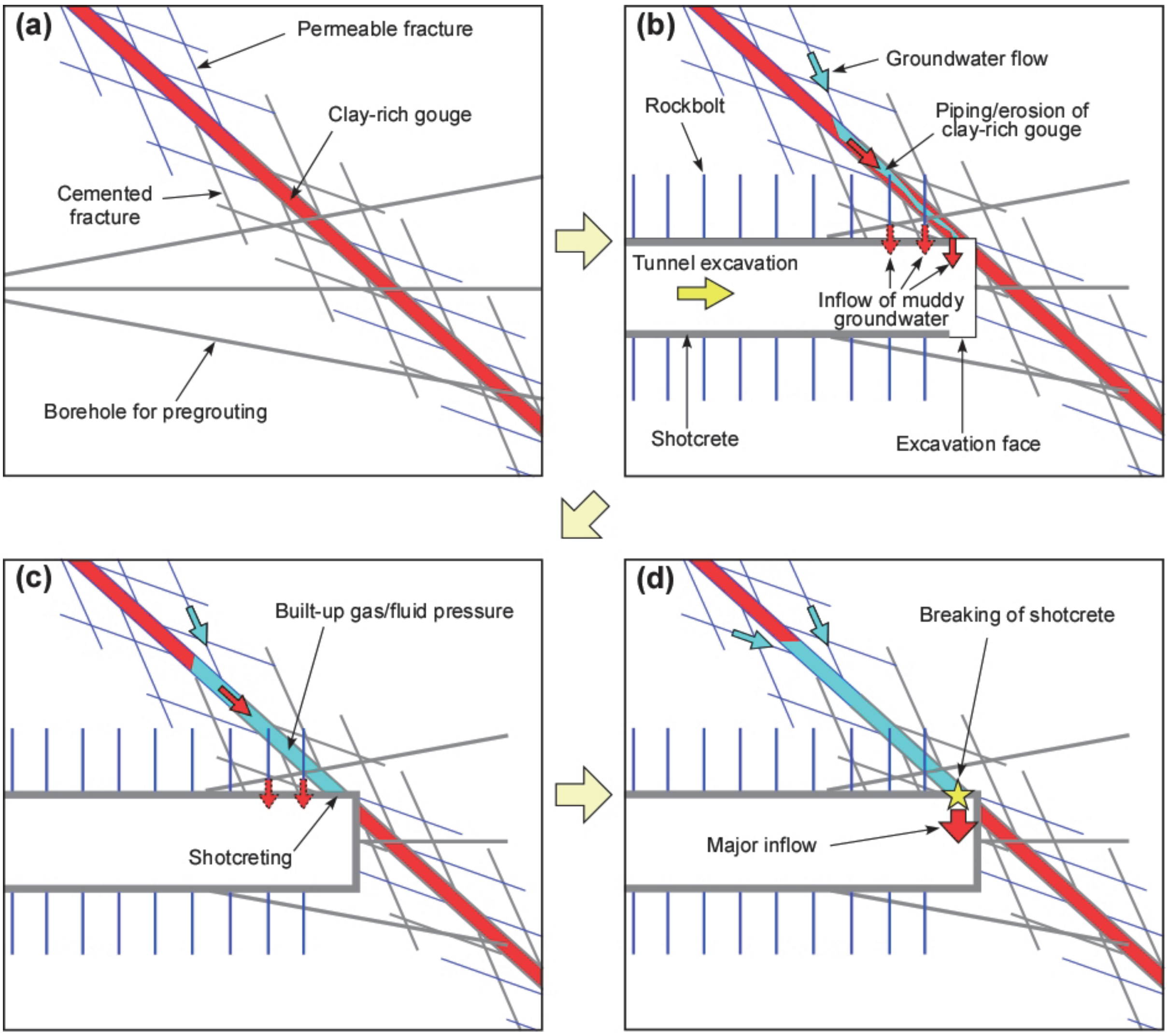

Fig. 9 Sketches showing the processes assumed to have caused the major inflow during tunnel excavation (horizontal sections). (a) The gouge-bounding fractures and damage zone fractures of the S1 Fault intersecting the boreholes were cemented by pre-grouting. (b) During excavation, the gouge was washed out into the tunnel through the rockbolts penetrating the gouge and along the boundary between the shotcrete and the gouge on the excavation sidewall. The resulting piping/erosion of the gouge induced groundwater flow from the outer aquifer of the pre-grouted zone. (c) After an excavation face exposing the S1 Fault was temporarily shotcreted, gas/fluid pressure in the S1 Fault zone built up. (d) A major inflow occurred, breaking the shotcrete.