Verification of swelling and landslides of smectite-bearing ground due to hydrothermal alteration in non-volcanic region

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Abstract

Bedrock deterioration by hydrothermal alteration has been overlooked in previous geological investigations in non-volcanic regions, and has been interpreted as fault gouge or fault breccia instead. Firstly, this paper describes the swelling characteristic of smectite bearing ground generated by hydrothermal alteration. Next, it shows that there are discernible hydrothermal alteration zones along the Median Tectonic Line in central Shikoku. The hydrothermal alteration zones mainly consist of smectite bearing clay around the intrusive rhyolite body of the middle Miocene. Hydrothermal alteration generate degradation of the bedrock and the smectite bearing clay cause the unexpected landslide in a cut slope constructed several years ago. In addition, using the cation exchange capacity test it has been shown that the smectite produced from hydrothermal alteration in the Shikoku area is of the Ca-type.

Keywords: hydrothermal alteration, bedrock deterioration, smectite, swelling, Ca-type

1. Introduction

Ground heaving can cause the deformation of buildings set up directly on cut-ground, landslides due to the bedrock deterioration and larger displacements in tunnels. The heaving of a dam foundation composed of shale (Goodman, 1993), the heaving of ground in residential area composed of shale (Meehan, 1975） and the heaving of ground at a residential area due to the crystal pressure of gypsum (Oyama et al., 1998), etc. have been reported. In tunneling, heaving is referred to as squeezing ground, and has been extensively studied and investigated. In tunnel deformation, two effects, deformation due to swelling smectite and deformation due to insufficient strength of the rock can overlap. Discerning both effects is difficult. Although the cause of heaving is due to the swelling of smectite in many cases, there is almost no research about heaving of foundations due to swelling of smectite using in-site data.

In Shikoku, a hydrothermal alteration zone with expansive clay minerals including smectite was formed around the intrusive body or along the fault produced by hydrothermal alteration due to the igneous activity in the middle Miocene (Hasegawa, et al., 2001a). It is pointed out that this should be the cause for the troubles during construction works such as unexpected landslides on cut ground slope (Tamura et al., 2007b), large landslides in ancient era (Hasegawa, et al., 2001a), large displacements in the tunneling (Hasegawa, et al., 2006), and heaving of cut ground (Tamura et al., 2007a).

Smectite is generated not only by a hydrothermal alteration but also due to weathering. It is important to verify if the origin of smectite depended on hydrothermal alteration as this can give important knowledge of the distribution of smectite-bearing ground. Unfortunately, such verification is not carried out enough.

In this paper, we present the swelling characteristic of smectite-bearing ground, based on in-situ data. This case shows the occurrence of the heaving of a cut caused only by the change in thickness of the overburden load due to the construction the cut and thus, can be used to properly evaluate the swelling characteristic of smectite.

Next, we present the case of hydrothermal alteration around the intrusive rock consisting of rhyolite of the middle Miocene along the Median Tectonic Line (MTL) in Shikoku. It shows that the generation of expansive clay minerals such as smectite is closely related to the intrusive rock and the extension of hydrothermal alteration of the fault and its surrounding ground. Notably, it shows that the bedrock classification of the deep underground declines due to hydrothermal alteration, resulting in bedrock deterioration including progressed argillation.

Furthermore, the exchangeable cation of smectite generated by the hydrothermal alteration on Shikoku is the Ca^{2+}-based Ca type.

2. Geological setting and distribution of hydrothermal alteration

The geology in Shikoku is divided by the MTL into the northern Inner zone and the southern Outer zone, and the zonation of the following geological belts extends east and west (Fig. 1). The MTL is an active right-lateral fault.

The Inner zone is composed of the Ryoke-belt, and from north to south the Outer zone is composed of the Sanbagawa belt, the Chichibu belt, and the Shimanto belt. The Ryoke belt is composed of the Izumi group, in which Cretaceous granite is uncomformably overlain by Late Cretaceous sedimentary rocks. The Sanbagawa belt is composed of high-pressure intermediate-type metamorphic rock, and the Chichibu belt is a Jurassic accretionary complex, composed mainly of sandstone and mudstone. The Shimanto belt is mainly composed of a Cretaceous accretionary complex on the north side, and a Paleogene accretionary complex mainly on the south side.

In Shikoku, not only the intrusive rocks of rhyolite of the middle Miocene distributed along the MTL, but granite and rhyolite are also scattered throughout the Inner zone or the Outer zone. These rocks indicate K-Ar age of about 13 to 15Ma, with many of them concentrated around 14Ma (Shinjoe and Sumii, 2000 etc.). The hydrothermal alteration zone, which shows the combination of mineral of the

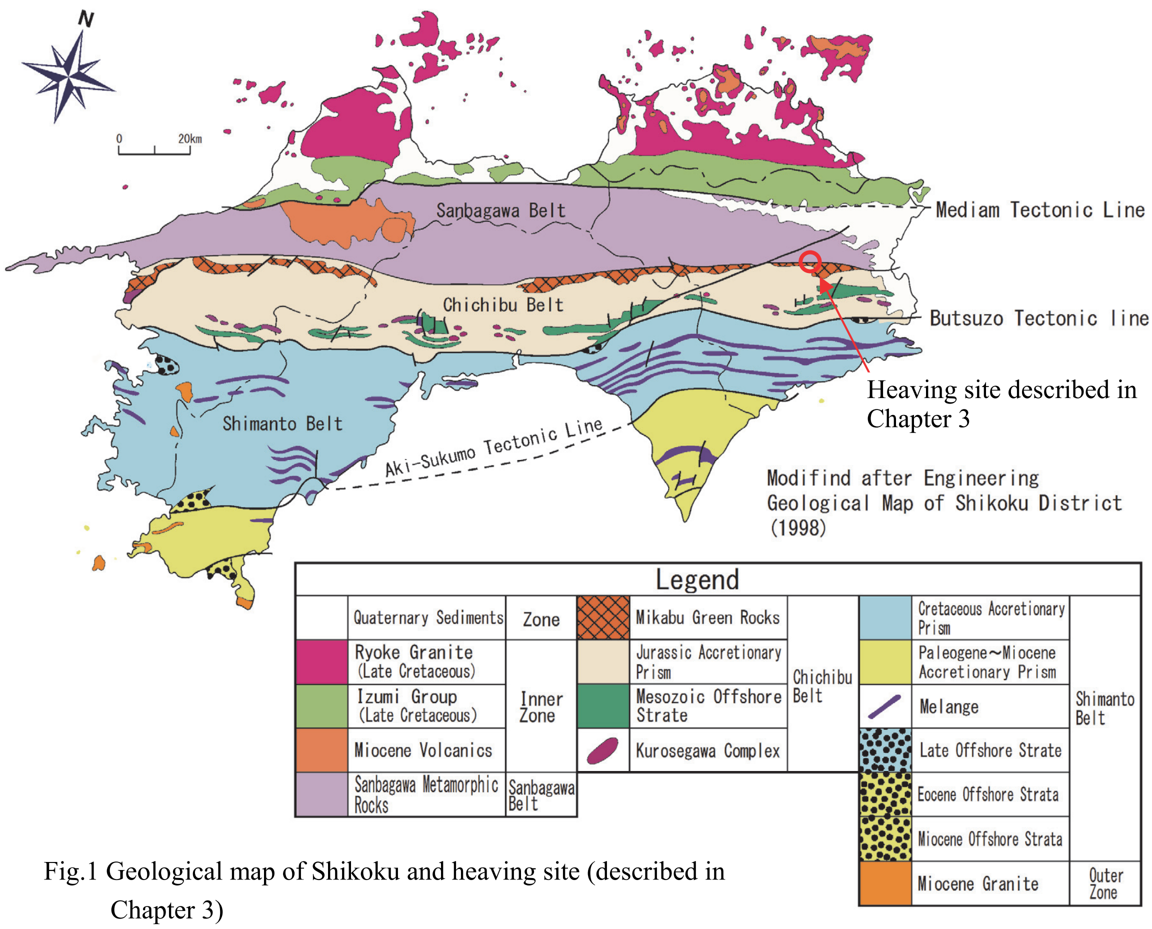

Fig.1 Geological map of Shikoku and heaving site (described in Chapter 3)

smectite zone, is distributed in the region without distribution of the intrusive rocks beyond the region along the MTL, as well as in the region near the intrusive rocks of rhyolite of the middle Miocene (Hasegawa et. al., 2001b).

3. Swelling characteristic and upheaval mechanism of smectite-bearing crush zone

3.1 Case of heaving of a cut in smectite-bearing fracture zone

This chapter explains the swelling characteristic and upheaval mechanism of a smectite-bearing fracture zone for a case in which a concrete foundation built in a cut in the Sanbagawa belt in Shikoku that heaved 66mm in the seven years after the foundation was constructed (Tamura et al., 2007a, Fig. 1). The fracture zone is 20 m in width, and it is inclined 50 degrees from the level. The heaving of the cut in this case was caused only by the conditions of the cut.

The investigation site is located in the pelitic schist area at the southern edge of the Sanbagawa belt of the Shikoku region. The heaving ground is the cut has a thickness of 25 m and is composed mainly of pelitic schist and partially of basic schist fracture zones. The site is within a fresh bedrock area whose overlying bedrock with a thickness of 25 m was removed and is close to the large fault in the Sanbagawa southern edge. Therefore, smectite at the site is assumed to be generated by hydrothermal alteration.

3.2 Geotechnical behavior of a smectite-bearing fracture zone

The heaved pelitic schist fracture zone is composed of sandy clay or clayey sand having a density of soil particles of 2.701 to 2.770g/cm^3, a unit weight of 22.9 to 23.3kN/m^3, a natural water content of 5.3 to 7.6%, and a clay content of 7 to 42%. The fine fraction of this crush zone is mainly composed of muscovite and chlorite, and contains a large amount of smectite which is expansive clay mineral. Smectite content is between 10 to 15% in the pelitic schist fracture zone and approximately 27% in the basic schist fracture zone.

The swelling pressure of the fracture zone was 30 to 60kN/m^2 in the pelitic schist crush zone and 90 to 130kN/m^2 in basic schist fracture zone. For both samples, the swelling reaction during the laboratory test occurred immediately after the inundation and finished within approximately 30 minutes, which shows the swelling reaction occurred immediately under a forced wet-state (Left figure in Fig. 2).

In the swelling test, the swelling pressure was measured at four-level loading pressures. The swelling pressure of the pelitic schist fracture zone is 0 to 11% under the loading pressure of 0 to 98 kN/m^2. A negative correlation was found between the loading and the swelling pressures as shown in the right figure in Fig. 2. The maximum swelling pressure in the right figure in Fig.2 is 160kN/m^2, which is equivalent to the overburden thickness of 7.5 m.

3.3 Mechanism of heaving of a smectite-bearing fracture zone in the cut

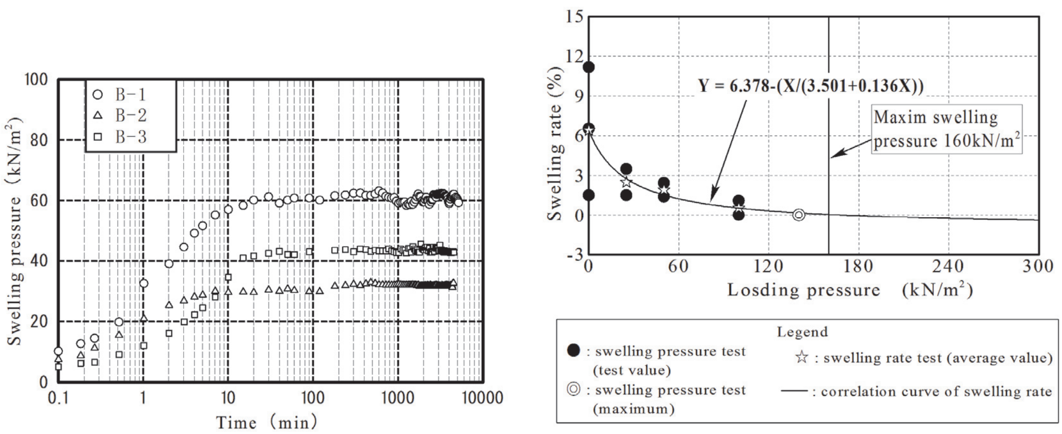

Fig. 2 Example of swelling pressure test of pelitic schist crush zone (left figure) and correlation between loading pressure and swelling rate in crush zone (right figure)

The mechanism of heaving of smectite-bearing fracture zone in the cut ground can be summarized as follows.

In the smectite-bearing fracture zone, overburden pressure of about 600kN/m^2, which is equivalent to the ground overburden thickness of about 25 m, was released through excavation. Swelling occurred in the smectite-bearing fracture zone. This resulted in upheaval of the concrete foundation on the fracture zone. It is assumed that the swelling reaction continues to the depth at which the overburden and the swelling pressures are balanced is reached, after the swelling of smectite finishes. Measuring of underground displacement by borehole inclinometer using a CCD camera revealed that the underground swelling reached a depth of approximately 7.5 m (Tamura et al., 2007a). Because this is consistent with swelling of the fracture zone when a loading pressure of not more than 160kN/m^2, which is equivalent to the overburden of 7.5 m, is applied, therefore swelling can be determined to not progress deeper than 8 m. Namely, it can be considered that this fracture zone has a swelled to an amount corresponding to the overburden.

As shown above, it is assumed that removal of overburden by a large excavation causes a swelling reaction based on the swelling of smectite near the ground's surface in the fracture zone having the expansive capacity. The swelling reaction extends downwards over several years and finally finishes at the depth in which the overburden and the swelling pressures are balanced.

4. Hydrothermal alteration and landslide along the MTL

4.1 Hydrothermal alteration and fault gouge along the MTL

Along the MTL in Shikoku, from Kawanoe, Shikoku-chuou-city, Ehime prefecture, which is the center of Shikoku (Fig. 3), westward, the rhyolite and andesite belonging to the Ishizuchi group of Miocene intrude into the fracture zone of the MTL and its surrounding area, as a result, hydrothermal alteration occurred.

Hasegawa et al. (2001a, 2001b) and Tamura et al. (2001) reported that the fault gouge along the intrusive rock of the MTL contains tridymite, dolomite and magnesite, as well as smectite and illite-smectite mixed-layer mineral and reported that those mineral composition had been produced by hydrothermal alteration.

In this chapter, the state of bedrock deterioration by hydrothermal alteration on the cut ground slope along the MTL is described as previously by Tamura et al. (2007b). In addition, the case of the low-angle landslide predisposed by the hydrothermal alteration originated smectite-bearing clay is presented. An landslide occurred five years after the construction of the cut, and was preceded by heavy rain.

4.2 The bedrock deterioration due to hydrothermal alteration observed on the cut slope

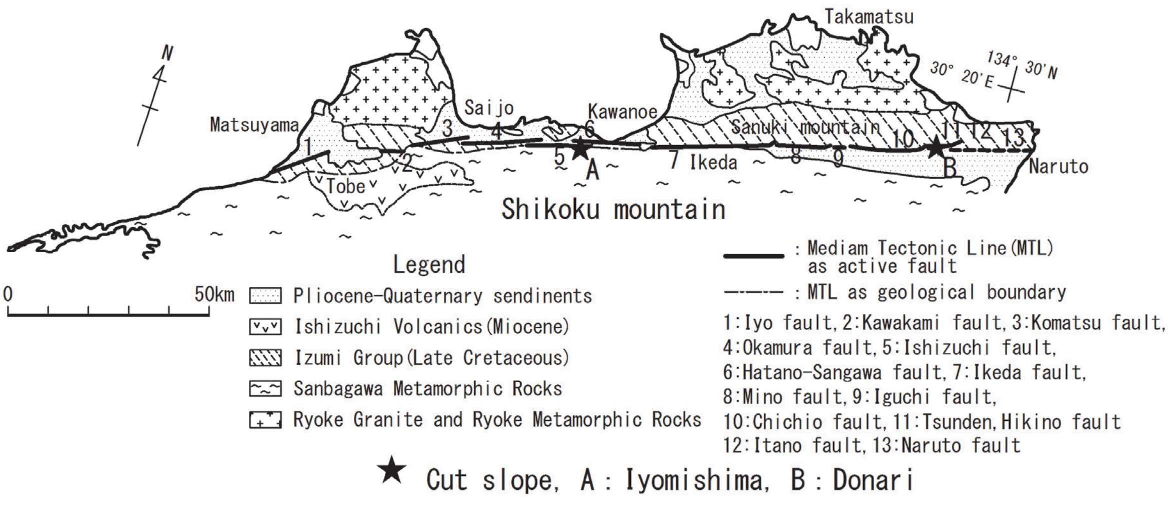

Fig.3 Locations of alteration zone(A) and landslide(B) along the MTL in Shikoku

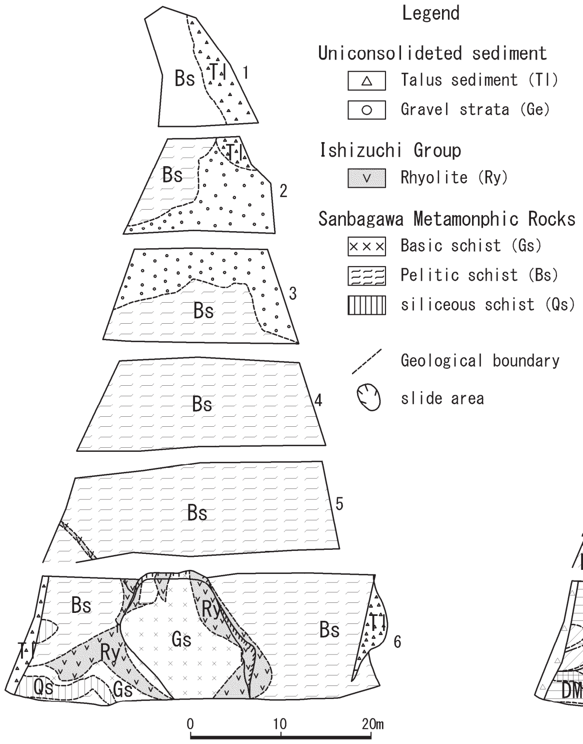

Fig.4 Geology of cut slope in Iyomishima region, Ehime prefecture (modified after Tamura et al., 2007a)

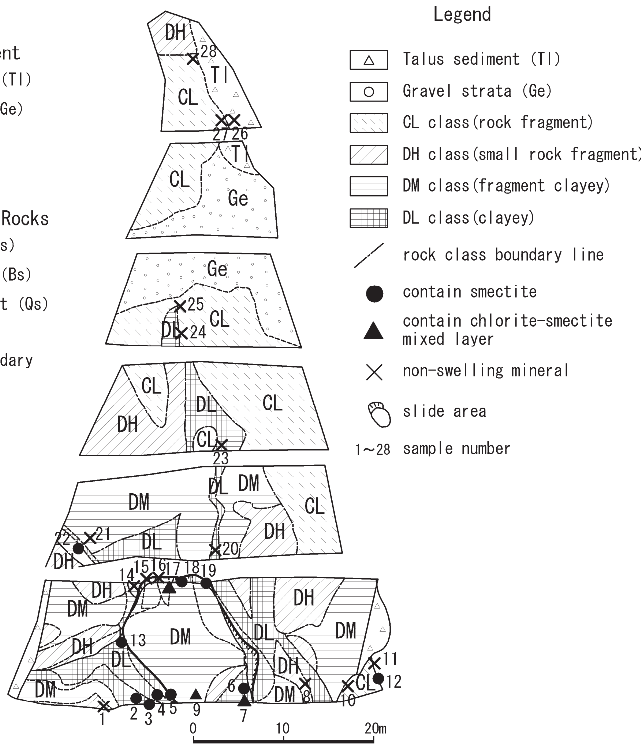

Fig.5 Rock mass classification and distribution clay minerals of cut slope (modified after Tamura et al., 2007a)

The location of the bedrock deterioration in the Iyomishima region is close to the Ishizuchi fault of the Median Tectonic Line active faults system. The cut slope has a height of about 40 m. The geology of the cut ground slope is composed mainly of pelitic schist of the Sanbagawa belt. Rhyolite with a width of about 2 m, belonging to the Ishizuchi group of the middle Miocene intrudes into the lowest part of cut slope (Fig. 4)..

The geology from the top to fourth cut slope in the cut slope is composed of weathered rocks and classified as CL-class ground according to the rock mass classification by CRIEPI (Japan Society of Engineering Geology, 1992). The fifth and sixth cut slopes are composed of D-class ground (Fig. 5). The D-class ground is subdivided into DH class mainly in clast form, DM class mainly in small fragment form and with argillation and DL class in clay form.

On this cut slope, its deep underground, which is less weathered, shows argillation that has progressed further than its weathered ground surface. The rhyolite body in the 6th cut slope shows strong argillation itself, as well as causing argillation to its surrounding schist. Furthermore, an altered clay zone is observed from the rhyolite with argillation on the 6th cut slope toward the 5th to 3th cut slopes crossing the schistosity.

The clay zone of rhyolite and basic schist at the 6th layer matches the sliding surface of small landslide caused by the cut.

X-ray diffraction reveals that the part with argillation, when comparing with the mineral composition of the fragment of a basic schist or rhyolite, is characterized by containing more expansive clay mineral of smectite and a chlorite-smectite mixed-layer mineral. In particular, smectite and chlorite-smectite mixed-layer mineral are located mainly near the rhyolite observed on the bottom of the cut slope that is less affected by weathering, as shown in Fig. 5.

4.3 Unexpected low-angle landslide caused on a cut slope constructed five years earlier

In the east region of Shikoku, intrusive rhyolite is not observed along the MTL, however, hydrothermal alteration occur similarly as observed in the west and central regions of Shikoku. Shown below are the cases in which altered sandstone generated by hydrothermal alteration have developed sliding surface and caused unexpected landslides on a cut slope 5 years earlier.

The landslide site in the Donari region, Awa-city, Tokushima prefecture, is a cut slope which is composed of the Izumi group along the Hikino fault of the MTL active faults system (Fig. 3). It is an express highway cut slope that was cut 5 years earlier. After continuous rain with precipitation of 83.5 mm for 2 consecutive days, a landslide of weathered rock, 70 m in width, 80 m in length and 10 m in slide-depth, having a volume of 26,000 m^3 occurred (Tamura et al., 2007b). The landslide created a head cliff 10 m in height at the top after about 1 hour. The soil mass had slide downwards by about 8 m.

The cut slope where the landslide occurred was composed of 7 benches, each 7 m in height, and the cut gradient was 1:1.5. The sum total of slope height was 50 m (Fig. 6). The landslide occurred from the 2^{th} to 7^{th} cut bench. The sliding materials consisted of weathered altered sandstones of the Izumi group.

As shown in Fig. 7, the geology of the landslide is composed of weathered sandstone towards the top and mudstone below. The sandstone layer is brownish and is about 10 m thick. The boundary of both layers is composed of the white-cloudy altered sandstone with a system of fissure dipping towards the face of slope with a low angle, creating the sliding surface. The altered sandstone is 1 to 2 m in thickness and includes many white-gray clay veins. The thickness of the landslide is about 10m. The black mudstone layer has a fault fracture zone at the end point of the cut slope. This geological condition results in a structure that is difficult to drain the ground water.

The gray-white clay (A in Fig. 7) on the top of the sliding surface originates from sandstone and is composed mainly of quartz and chlorite. Smectite, an expansive clay mineral, is observed in the gray-white clay. The black clay (B in Fig. 7) on the fault crush zone originates from mudstone at the end point is composed of illite-smectite mixed-layer mineral.

The features of the landslide at this site are as follows: it has a high sliding speed and a large sliding amount similar to a collapse, however, the sliding gradient is as low as 22 degrees, and deformation of the rock slide is more like a landslide than a collapse. Also, the landslide occurred suddenly several years after cut ground. The occurrence of such an unexpected landslide is considered to be caused by the smectite-bearing altered sandstone, which is an expansive clay mineral with weak strength due to hydrothermal alteration, and the presence of fissure dipping towards the face of the slope (Tamura et al., 2007b).

5. Cation exchange composition of smectite due to hydrothermal alteration in Shikoku area

Smectite is classified by exchange cation into the Na-type, whose swelling characteristic is extremely strong, and the Ca-type, whose swelling characteristic is relatively weak.

We studied the cation exchange composition of smectite-bearing clay which is considered to originate

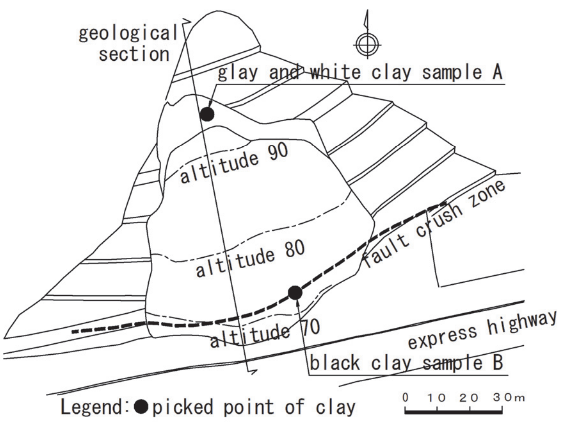

Fig.6 Plan view of the landslide in the Donari region, Tokushima pref. (modified after Tamura et al., 2007b)

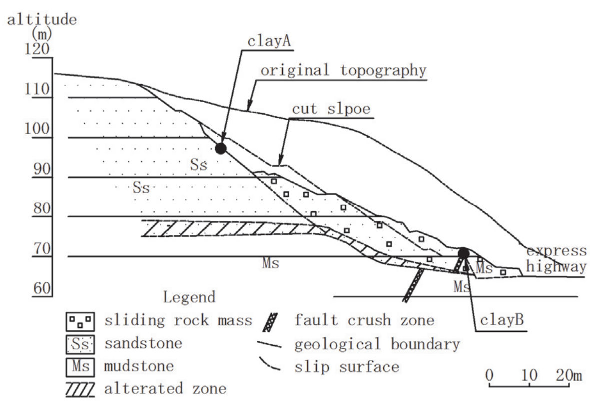

Fig.7 Profile of the landslide in Donari region, Tokushima pref. (modified after Tamura et al., 2007b)

from hydrothermal alteration in the Shikoku area, using a cation exchange capacity (CEC) test and X-ray diffraction data to examine the exchange cation of smectite.

CEC test samples consist of clay from the fracture zone which was determined to have originated from hydrothermal alteration. Origin of these samples are composed of granite from the Ryoke belt, andesite from the Sanuki group, mudstone and sandstone from the Izumi group along the MTL, basic schist from the southern margin of the Sanbagawa belt, and sandstone from the Shimanto belt. These samples do not include zeolite and vermiculite, which have significant influence on the CEC value. As shown in the test results in Table 1, in every sample, the exchange cation is mostly Ca ions and is assessed as Ca-type smectite.

In Neogene stratum of the Tohoku area where Na-type smectite with a strong swelling characteristic is distributed, the sliding surface average gradient is as small as 19 degrees (Table 2). The shear strength of smectite is small compared with other minerals. Na-type smectite swells strongly and degrades it's strength, so that low-angle slides will occur easily. On the other hand, in the Shikoku area, where landslides called Shear zone type landslides occur locally, Ca-type smectite in which the swelling potential is slightly smaller, sliding angles are between 22 to 27 degrees (average 24.5 degrees).

The swelling characteristic of Ca-type smectite is smaller than that of Na-type smectite. Nevertheless, even for Ca-type smectite, deformation such as ground heaving and unexpected landslides due to degradation of ground strength at the smectite-

Table 1 Samples on cation exchange capacity test of smectite clay due to hydrothermal alteration in Shikoku (modified after Tamura and Hasegawa (2008))

unit：cmol(＋)/kg

Geology	Mother's rock	Number of the sample	Property of sample	Cation exchange capacity	Exchange-able cation	Exchange-able Na	Exchange-able K	Exchange-able Ca	Exchange-able Mg	Amount of smectite 1)
Ryouke granite	granite	B-Gr-W2	clay	7.4	6.2	0.8	0.2	4.2	1.0	＋＋
		C-Gr-W1	clay	14.9	12.5	0.8	0.2	8.3	3.2	＋＋＋
		D-Gr-W1	clay	10.0	8.2	0.9	0.2	5.4	1.7	＋
Sanuki group	andesite	F-An-f2	alterated rock fragment	11.4	13.7	0.8	0.3	9.5	3.1	＋＋
		F-An-W2	clay	33.9	37.6	0.7	0.4	25.0	11.5	＋＋＋＋
Izumi group along MTL	mudostone	Donari 0725D-1	rock fragment with clay	12.3	11.3	0.3	1.3	7.9	1.8	＋＋＋
	sandstone	Itano 0725I-1	rock fragment with clay	14.1	14.6	0.4	1.5	8.3	4.4	＋＋
margin of Sanbagawa belt	basic schist	K-№1	clay	13.1	113	0.6	1.1	101	10.5	＋＋＋
Shimanto belt	mudstone	K-№2	clay	16.1	22.6	0.5	1.4	12.2	8.5	＋＋＋＋

Note1) abundance of contents by XRD : ++++ very abundance, +++ abundance, ++ poor, + very poor

Table 2 Regional characteristic of smectite and ground disaster related to smectite in Japan (modified after Tamura and Hasegawa(2008))

Area	Smectite			Landslide		Degree of swelling of cut ground
	Distribution	Type of exchangeable cation	Capacity of swelling	Division by geology	Average angle of the slip surface	
Tohoku (green tuff area)	wide area	Na-type and Ca-type	strong ～ weak	Neogene type landslide	19°	strong
Shikoku (along large fault)	local area	Ca-type	weak	Shear zone type landslide	22～27°	weak

bearing ground occur. Therefore research to determine the presence or absence of smectite is important.

6. Conclusions

In this paper, the swelling characteristic of smectite was verified, based on the cases of ground heaving in smectite-bearing ground formed by hydrothermal alteration. Ground heaving depended only due to the conditions of the cut. In addition, the hydrothermal alteration around intrusive rhyolite along the MTL and the generation of smectite clay and deterioration of bedrock were described. Furthermore, it was shown that in smectite-bearing ground, due to much degradation of strength, there are cases of unexpected landslides, including low-angle landslides, and sudden landslides occurring several years after the construction of cuts.

This paper is summarized as follows:

1) In smectite-bearing ground, there is a negative correlation between the loading pressure and the swelling rate after water absorption, and swelling progresses to the depth where the stress release of the loading pressure caused by the cut and the smectite's swelling pressure balance.

2) Along the Median Tectonic Line (MTL) in Shikoku, due to hydrothermal alteration of the middle Miocene, smectite and its interstratified minerals were generated and a hydrothermal alteration zone composed of a smectite-zone is formed.

3) Hydrothermal alteration causes deterioration and argillation of the bedrock, which favors the occurrence of landslides.

4) Clay containing smectite produced by hydrothermal alteration or smectite mix-layered minerals, has small shear strength, can causes unexpected low-angle slides, and deformation can be observed as late as several years after the construction of the cut.

5) Although smectite in the Shikoku area is composed of Ca-type smectite which has a swelling potential slightly smaller than that of the Na-type, caution is required.

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