Rock mass characterization for tunnelling by the geological history of hydrothermal alteration and landsliding

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Abstract: This paper describes the rock mass characterization of the Izumi Group for tunnel construction of the expressway in the Shikoku region, Japan. The Izumi Group is mainly composed of interbedded sandstone and shale of Late Cretaceous age. The rock mass characteristics of the Izumi Group that are intersected by the tunnel are geologically classified into four types based on the damage history of rock mass sliding and hydrothermal alteration. This classification was confirmed by the rock mass grades and convergences during tunnelling. The first N-type ground is composed of sound rock mass and shows very small convergence during tunnelling. The second S-type ground is composed of cracked rock mass, but shows small convergence during tunnelling. The third H-type ground is composed of altered rock mass and shows very large convergence during tunnelling even if the rock mass at the face seems to be sound. The fourth HS-type ground is composed of altered and cracked rock mass and shows very large convergence during tunnelling. These four types of rock mass show distinct characteristics during tunnelling. In particular, it is clear that the large convergence tends to appear in H-type and HS-type tunnel ground. X-ray diffraction analysis suggests that smectite-bearing clay veins originated from hydrothermal alteration and are an important contributory factor to large convergence during tunnelling. Therefore, it is very important to confirm the presence of the swelling clay mineral (smectite etc.) before and during tunnel construction.

Résumé: Ceci l'article décrit la caractérisation de la masse de roche du groupe d'Izumi pour le tunnel construction de l'autoroute urbaine dans la région de Shikoku, Japon. Le groupe d'Izumi est principalement composé de grès et de schiste intercalés d'âge crétacé en retard. Le tunnel la terre du groupe d'Izumi sont géologiquement classifiées dans quatre types basés dessus l'histoire de dommages du glissement de masse de roche et du changement hydrothermique. Ceci la classification a été confirmée par les catégories et les convergences de la masse de roche pendant perçage d'un tunnel. Le premier N-type la terre se compose de masse saine de roche et montre convergence très petite pendant le perçage d'un tunnel. Le deuxième S-type la terre se compose de la masse criquée de roche, mais montre la petite convergence pendant le perçage d'un tunnel. Le troisième H-type la terre se compose de masse changée de roche et montre la convergence très grande pendant perçage d'un tunnel même si la masse de roche au visage semble être bruit. Le quatrième HS-type la terre se compose de masse changée et fendue de roche et montre très grand convergence pendant le perçage d'un tunnel. Ces quatre types de tunnel montrent distinct caractéristiques pendant le perçage d'un tunnel. En particulier, il est clair que la grande convergence tend à apparaître dans le H-type et le HS-type au sol de tunnel.

Keywords: classification, clay minerals, landslides, sandstone, shale, tunnels.

INTRODUCTION

Shikoku is the smallest island of four main Islands in Japan and has a population of 4,170,000. Shikoku is divided into Northern Shikoku and Southern Shikoku by the Shikoku Range, which reaches its maximum height of 1982m at Mt. Ishizuchi. Shikoku is a mountainous region and most of the people live on the narrow plains of North Shikoku. Shikoku is administratively divided into four Prefectures; Tokushima, Kagawa, Ehime and Kochi Prefectures. The three seats of prefectural governments are located in North Shikoku at Tokushima city (260,000 population) of Tokushima Prefecture, Takamatsu city (330,000 population) of Kagawa Prefecture and Matsuyama (480,000 population) city of Ehime Prefecture.

As national highways which connect Tokushima, Takamatsu and Matsuyama are usually crowded, new expressways have been constructed by Japan Highway Public Corporation since 1985. At present, four expressways connect Tokushima, Takamatsu, Matsuyama and Kochi cities. Three expressways have been constructed in North Shikoku. They are Tokushima, Takamatsu and Matsuyama expressways. As these three expressways run through narrow and highly populated plains, their routes have been shifted along the foot of mountains. As a result, many tunnels are constructed.

Most of these tunnels are constructed in the sedimentary rocks of the Cretaceous Izumi Group. Moreover, Tokushima and Matsuyama Expressways have been constructed along active faults of the Median Tectonic Line (MTL). These tunnel constructions have revealed the difficulty in predicting the ground condition before and during tunnelling, because the convergences during tunnelling do not correspond to lithology or face observation. We have re-examined the tunnelling data and have clarified the rock mass characteristics of the Izumi Group near the MTL. This paper proposes a rock mass characterization of the Izumi Group for tunnel construction on the basis of the damage history of both rock mass sliding and hydrothermal alteration.

GEOLOGICAL SETTING

Median Tectonic Line (MTL)

The Median Tectonic Line (MTL) is the main topographical boundary in north Shikoku, and it runs from Naruto city on the north of Tokushima city to Matsuyama city, trending N75°E. The MTL is marked by remarkable contrast in topography between the mountains and plains. The active faults of the MTL run along the foot of the Sanuki Range in eastern Shikoku and along the foot of Shikoku Range in central and western Shikoku. The fault scarps reach up to 1000 meters in height in central Shikoku.

The MTL forms a boundary between the Upper Cretaceous Izumi Group on the north and the Sambagawa metamorphic rocks on the south (Fig. 1). The distinct fracture zone of the MTL reaches 80 meters into the bedrock, and hydrothermal alteration zones are widely distributed in the bedrock (Hasegawa et al., 2001).

Bedrocks

The Sanuki Range in eastern Shikoku and hills to the north of the MTL in central and eastern Shikoku are underlain by the Upper Cretaceous Izumi Group (Fig. 2.). The Izumi Group consists mostly of interbedded sandstone and shale, with subordinate felsic tuffs and conglomerates. The Sambagawa metamorphic rocks are widely distributed in the southern Shikoku Range and are mainly composed of pelitic schists and greenschists.

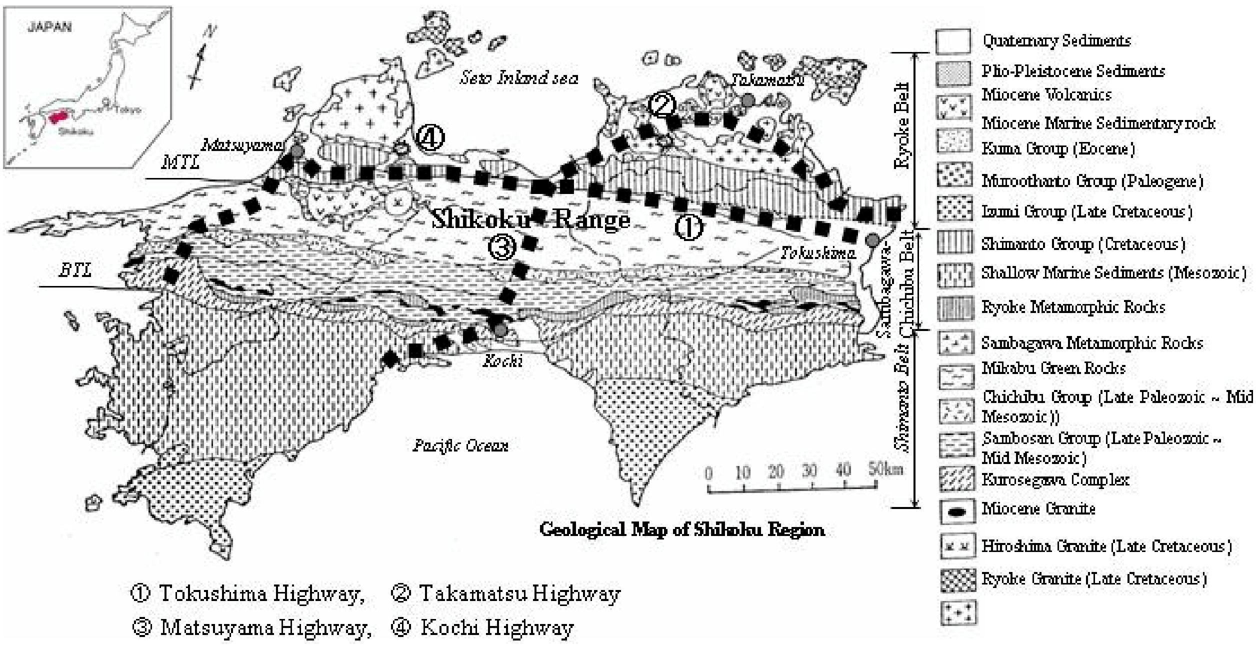

Figure 1. Geological map and expressway of Shikoku region (modified after Hasegawa and Saito, 1991)

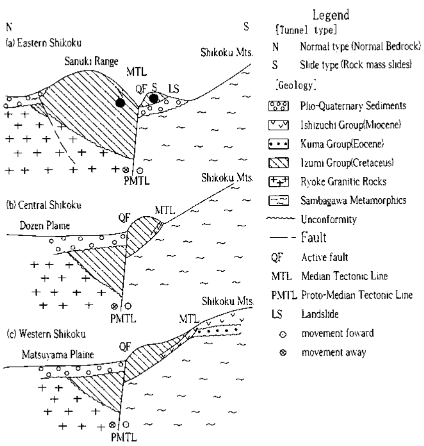

Figure 2. Geological profile along the Median Tectonic Line in Shikoku (Hasegawa et al., 2002)

Rock mass slide

Large-scale rock mass slides composed of the Izumi group are distributed along the foot of the Sanuki Range. They were formed between the early Pleistocene to Holocene (Hasegawa, 1992; Hasegawa and Sawada, 2001). They are estimated to have slid rapidly due to large earthquakes and have been stable since their sliding. These rock mass slides formed hills whose landslide topography has been completely dissected by erosion, so that recognition by topography is difficult.

Lithologic characteristics of the rock mass slide of the Izumi Group are as follows:

- Original stratifications are roughly preserved, but sandstone beds are disrupted by fracturing to form polygonal-shaped fragments and shale beds are sheared parallel to the bedding.
- Sandstone beds have many open fractures, some of which are filled with soils from the ground and unconsolidated pebble bearing muddy materials, derived from the sediments of footwalls.

Geotechnical characteristics of the rock mass slides of the Izumi Group are as follows:

- The rock mass slides of the Izumi Group are extremely loose and have no cohesion. They have preserved the original stratifications, but some of them resemble debris.
- Fractured portions of the rock mass slides are looser than rock masses of the tectonic fault fracture zone. The rock mass slides are more permeable than the bedrocks and fine Quaternary sediments.

Hydrothermal alteration

The Middle Miocene hydrothermal alteration has produced smectite and smectite-bearing mixed-layer minerals in bedrocks as fault gouges or clay veins and these are an important causative geological factor for landsliding (Hasegawa et al., 2001).The hydrothermal alteration along the MTL is as follows:

- Smectite or smectite-bearing mixed-layer minerals are the main constituent clay minerals in fault gouges of the MTL. The fault gouges also contain dolomite and magnesite, which indicate hydrothermal alteration.
- Dacite and rhyolite of the Ishizuchi Group have intruded into the fracture zones of the faults. Thus smectite, smectite bearing mixed-layer minerals, dolomite and magnesite are inferred to have been formed by the hydrothermal alteration during or after the intrusion of dacite and rhyolite of the Ishizuchi Group. K-Ar ages of dacite and rhyolite are about 14 Ma (million years ago).

METHODOLOGY

We have collected data for rock mass grades and convergences of 21 tunnels in the Izumi Group from Tokushima, Takamatsu and Matsuyama expressways (Table 1). The rock mass grade of each face of tunnelling was based on Japan Hghway Public Corporation (1992). Japan Highway Public Corporation (1992) has classified tunnel ground into the following seven rock mass grades from sound rock mass to faulted rock mass: A, B, C1, C2, D1, D2, E. The rock mass grade is chiefly described on the basis of P-wave velocity, boring cores, and measured GN ($GN = qu/\gamma h$, where qu = uniaxial compressive strength of ground, gamma =: unit weight of ground, h = thickness of overburden). All the convergence measurements were based on the standard of the Japan Highway Public Corporation. The rock mass grades and convergences near to tunnel entrances are excluded, because the aim of this research is to characterise the main parts of tunnel routes.

Expressway	Tunnel	C-grade Number of face	C-grade Length (m)	D-grade Number of face	D-grade Length (m)
Takamatsu	Minamitonaedani	4	74	76	510
	Kitatonaedani	34	340	27	270
	Ohsaka	102	1,700	8	100
Tokushima	Uranoike	——	——	12	120
	Mizuta-daiichi	——	——	24	480
	Mizuta-daini	——	——	8	140
	Akizuki	——	——	12	145
	Kirihata	2	55	28	475
	Kanakiyo	5	175	16	290
	Tachino	8	140	95	1,220
	Shinyama	——	——	38	740
	Hakuchi	98	2,430	14	280
	Shin-sakaime	94	2,640	4	80
	Shimokawa	22	430	2	30
Matsuyama	Hayakawa	5	92	7	110
	Iioka	——	——	74	1,240
	Hachidozan	20	710	14	170
	Maruyama	15	400	4	50
	Myoukou	——	——	30	550
	Ohto	——	——	53	770
	Norinouchi	10	250	2	20
Total		419	9,436	548	7,790

Table 1. Collected tunnel data from Takamatsu, Tokushima and Matsuyama expressway

EFFECT OF LITHOGY

We have first examined the effect of lithology on rock mass grades and convergences. As the Izumi Group mainly consists of interbedded sandstone and shale, we have divided interbedded sandstone and shale into five lithologies: sandstone, sandstone predominant interbedded sandstone and shale, interbedded sandstone and shale, shale predominant interbedded sandstone and shale, and shale (Table 2).

Figure 3 shows the rock mass grades and convergences of each lithology. Although shale or mudstone of the Izumi Group have lower unconfined compressive strength than sandstone and the shale is easy to slake, Figure 3 does not indicate that shale-rich zones are relatively lower rock mass grade and larger convergence than sandstone predominant zones. This suggests that lithology is not a useful criterion for estimating rock mass grades and convergences.

Lithology \ Rock mass grade	content of shale(%)	C-grade Length(km)	C-grade Number of measurement	D-grade Length(km)	D-grade Number of measurement	Total
Sandstone(Ss)	0-10	3.3	163	1.5	165	328
Ss predominant interbeddely Ss & Sh	10-40	2.4	61	2.5	144	205
Interbedded Ss & Sh	40-60	0.8	51	1.1	90	141
Sh predominant interbedded Ss & Sh	60-90	1.1	46	0.4	41	87
Shale(Sh)	90-100	3.7	113	0.9	35	148
Other lithology (Tuff etc.)	-	1.7	—	1.2	—	—
Total	-	13.0	434	7.6	475	909

Table 2. Lithology and rock mass grade of expressway tunnels in the Izumi Group

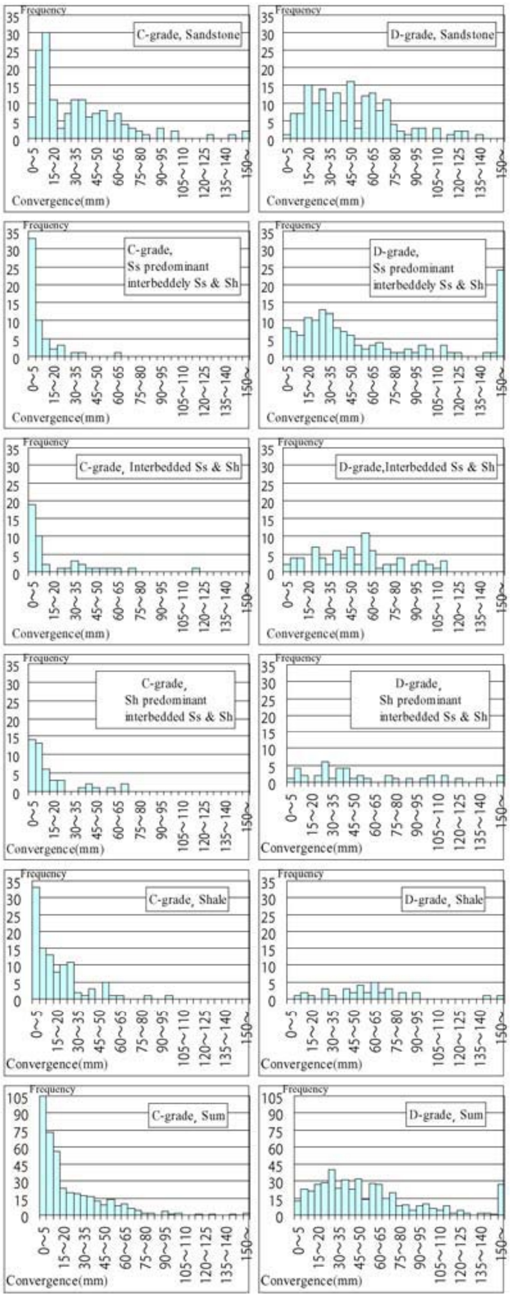

Figure 3. Rock mass grades and convergences of different rock type of the Izumi Group

EFFECT OF ROCK MASS SLIDE

The ground conditions of the Izumi Group are geologically divided into the following two ground types: N (normal)-type ground is undisturbed interbedded sandstones and shales, and S (slide)-type ground is the rock mass slide. The seismic tomographic surveys clearly distinguish the two ground types (Hasegawa et al., 2002).

Tokushima and Takamatsu expressways

N-type grounds of Tokushima and Takamatsu expressways are Shinsakaime, Shimokawa, Hakuchi, Tachino and Osaka tunnels. Hakuchi and Tachino tunnels are located near the MTL. S- type grounds are Ikeda-daiichi tunnel, Uranoike, Mizuta-daiichi, Mizuta-daini, Akizuki, Kirihata, Kanakiyo and Minamitonae-dani tunnels.

Figure 4 shows the length of rock mass grades in N-type and S-type ground of the Izumi Group. The majority of rock mass grades of N-type ground are C-grade, and the majority of rock mass grades of S-type ground are D-grade. This result supports the estimation from ground characteristics.

Figure 5 shows the convergence of C-grade rock mass. The convergences of C-grade rock mass in N-type ground varies between 0mm and 180mm, but they are usually less than 25mm. The convergences of C-grade rock mass in S-type ground are between 25mm and 50 mm. This result supports the estimation from ground characteristics.

Figure 5 shows the convergence of D-grade rock mass. The convergences of D-grade rock mass in N-type ground vary between 0mm and 140mm and medium convergence is about 60mm. The convergences of D-grade rock mass in

S-type ground vary between 0mm and 170mm and medium convergence is about 30mm, which is smaller than for N-type.

This result indicates that D-grade rock mass in S-type ground is a better rock mass for tunnelling than D-grade rock mass in N-type, because most of fractures have been formed by shearing during sliding and have preserved the strength of constituent rocks. This rock mass characteristic is supported by observation of faces and point load tests of rocks from faces. In contrast, D-grade rock mass in N-type ground is truly fractured and altered rock mass.

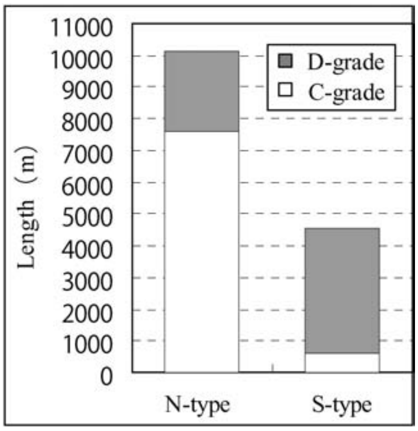

Figure 4. Length of rock mass grades in N-type and S-type ground in tunnels of Tokushima and Takamatsu expressway

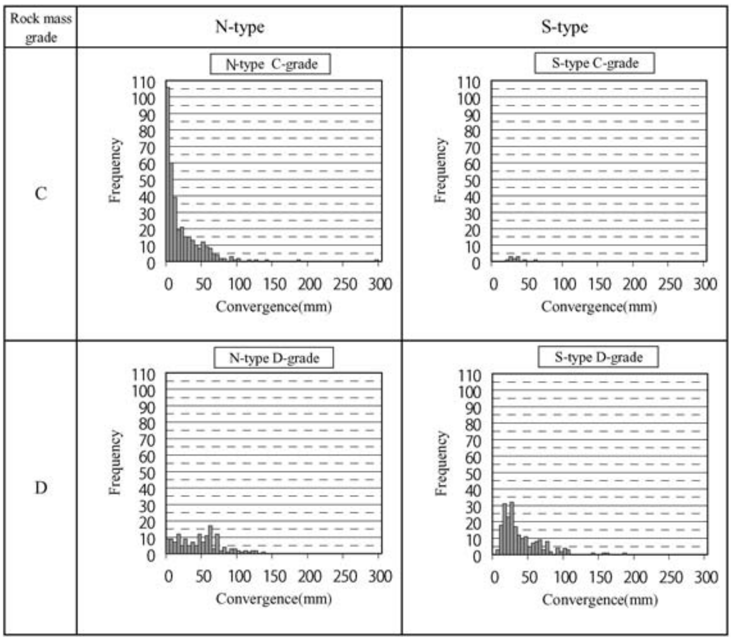

Figure 5. Convergence of C-grade and D-grade rock mass in N-type and S-type in tunnels ground of Tokushima and Takamatsu expressway

Matsuyama expressway

S-type ground of the Matsuyama expressway only occurs in the Haikawa tunnel and other tunnels are judged to be N-type grounds from topography and surface geology.

Figure 6 shows the length of rock mass grades in N-type and S-type ground of the Izumi Group. Most of the rock mass grades of N-type ground are D-grade.

Figure 7 shows the convergence of C-grade rock mass. The convergences of C-grade rock mass in N-type ground are less than 25mm. The convergences of C-grade rock mass in S-type ground are less than 30 mm. Figure 7 shows the convergence of D-grade rock mass. The convergences of D-grade rock mass in N-type ground vary between 0mm and 380mm and medium convergence is about 30mm. The convergences of D-grade rock mass in S-type ground vary from 0mm to 45mm and medium convergence is about 30mm.

This result is quite different from the result of Tokushima and Takamatsu expressways. Therefore other criteria are necessary for better characterization of tunnel ground.

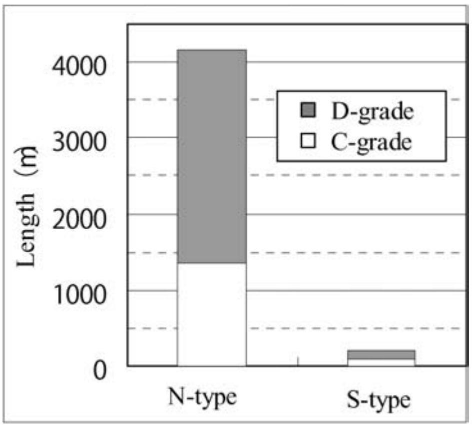

Figure 6. Length of rock mass grades in N-type and S-type ground in tunnels of Matsuyama expressway

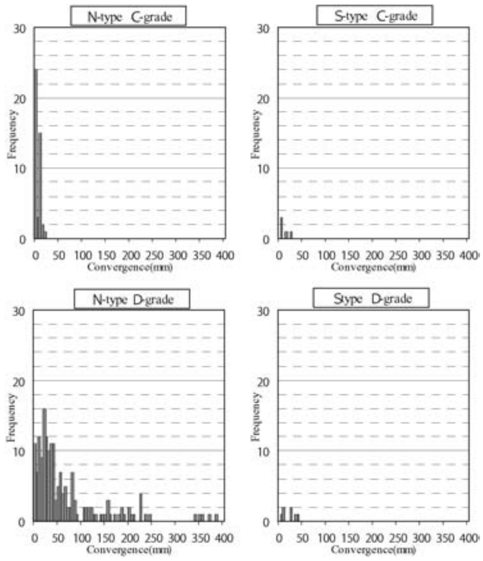

Figure 7. Convergence of C-grade and D-grade rock mass in N-type and S-type ground in tunnels of Matsuyama expressway

EVIDENCE OF HYDROTHERMAL ALTERATION

The MTL in central and western Shikoku commonly accompany rhyolite or dacite dykes in crush zones and their vicinities. Rhyolite or dacite dykes are locally altered into smectite-bearing clay rocks and soft rocks (Hasegawa et al., 2001). These tunnels in the Izumi Group are located near the MTL. Therefore, effects of hydrothermal alteration are examined by identifying clay minerals from X-ray diffraction analysis.

Figure 8 shows geology, rock mass grades and convergences of the Ohto tunnel of the Matsuyama Expressway which recorded maximum convergences during tunnelling. The route of the Ohto tunnel consists of sandstone predominant interbedded sandstones and shales, with ryholite at the eastern entrance. Rock mass grades of the tunnel are all D-grade and maximum convergence attains 400 mm.

Unfortunately the drill cores taken during construction have been discarded, but we examined the ryholite outcrops near the eastern entrance. Ryholite is partially altered and is composed of unaltered black hard rock and altered yellowish brown soft rock. Point load testing of each rock fragment indicates that calculated average uniaxial compressive strength of unaltered black hard ryholites is 232 MPa and that of altered yellowish brown soft ryholites is 1.5 MPa. This suggests that altered rock masses have lost strength compared with overburden

Figure 9 shows the X-ray diffraction chart of altered rhyolite. The altered rhyolite contains a fair amount of smectite and chamosite, which are evidence of hydrothermal alteration. Abundant smectite in altered rock mass is another factor of large convergences.

Rhyolite or andesite dykes do not occur in association with the MTL in eastern Shikoku, but the Izumi Group along the MTL is locally affected by hydrothermal alteration and smectite-bearing clay veins are often observed (Hasegawa et al., 2001). According to the above observation and identification of hydrothermally altered minerals, tunnel grounds that are affected by hydrothermal alteration are selected (table 3, 4).

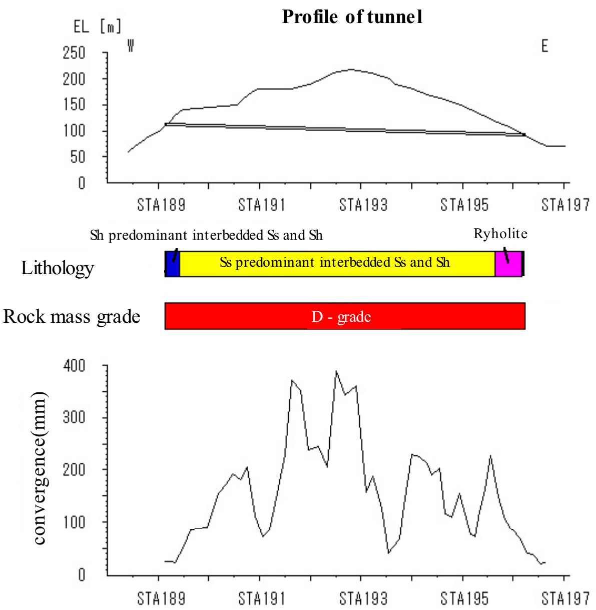

Figure 8. Geology, rock mass grades and convergences of Ohto tunnel of Matsuyama expressway

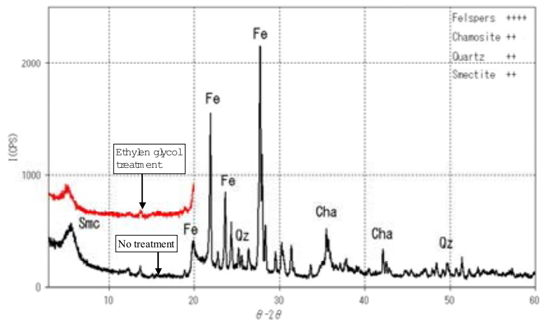

Figure 9 X-ray diffraction chart of altered rhyolite near Ohto tunnel of Matsuyama expressway

ROCK MASS CHARACTERIZATION OF TUNNEL GROUND

Tunnels in the Izumi Group are divided into the following four rock mass types as follows based on the history of damage (Table 3):

- N-type ground is undisturbed interbedded sandstones and shales.
- S-type ground is mainly affected by the rock mass slide.
- H-type ground is affected mainly by hydrothermal alteration.
- HS-type ground is affected by both hydrothermal alteration and rock mass slide.

According to these criteria, tunnel routes of Tokushima, Takamatsu and Matsyama expressways are divided into four types (Table 4)

Length of rock mass grade

Figure 10 shows the length of rock mass grades in each ground types of the Izumi Group. It has confirmed following facts:

- Majority of rock mass grades of N-type ground are C-grade.
- Most of rock mass grades of S-type ground are D-grade.
- More than half of rock mass grades of N-type ground are D-grade.
- Most of rock mass grades of HS-type ground are D-grade.

Table 3. Classification of tunnel ground in the Izumi Group from rock mass slide and hydrothermal alteration

		Hydrothermal alteration	
		×	○
Landslide	×	N-type	H-type
	○	S-type	HS-type

○: affected, ×: unaffected

Table 4. Ground types in tunnels of Tokushima, Takamatsu and Matsuyama expressways

Ground Type	Tunnel
N-type	Shimokawa, Shin-sakaime, Ohsaka, Kitatonaedani, Hachidozan, Norinouchi
S-type	Shinyama, Uranoike, Kanakiyo, Hayakawa
H-type	Tachino, Hakuchi, Iioka, Myokou, Ohto
HS-type	Minamitonaedani, Kirihata, Akizuki, Mizuta-daiichi, Mizuta-daini

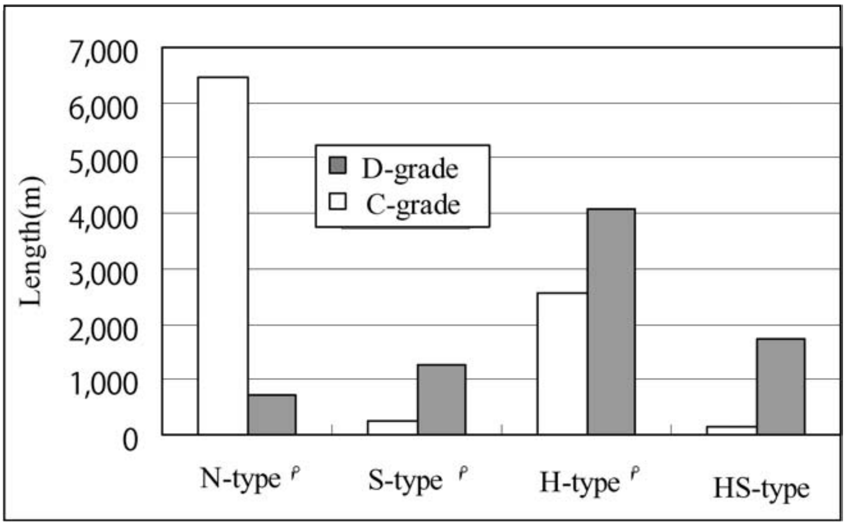

Figure 10. Length of rock mass grades in each ground types in tunnels of Tokushima, Takamatsu and Matsuyama expressways

Convergence of four types of tunnel ground

Figure 11 shows the convergence of four types of tunnel ground in the Izumi Group. Figure 11 indicates the following characteristics:

- Convergences of N-type ground are very small, usually less than 25mm in both C-grade and D-grade rock masses.
- Convergences of S-type ground are small, usually between 5 and 40mm in both C-grade and D-grade rock masses.

- Convergences of H-type ground are large, usually between 10 and 70mm in C-grade and usually between 10 and 120mm D-grade rock masses.
- Convergences of HS-type ground are large, usually between 10-110mm D-grade rock masses.

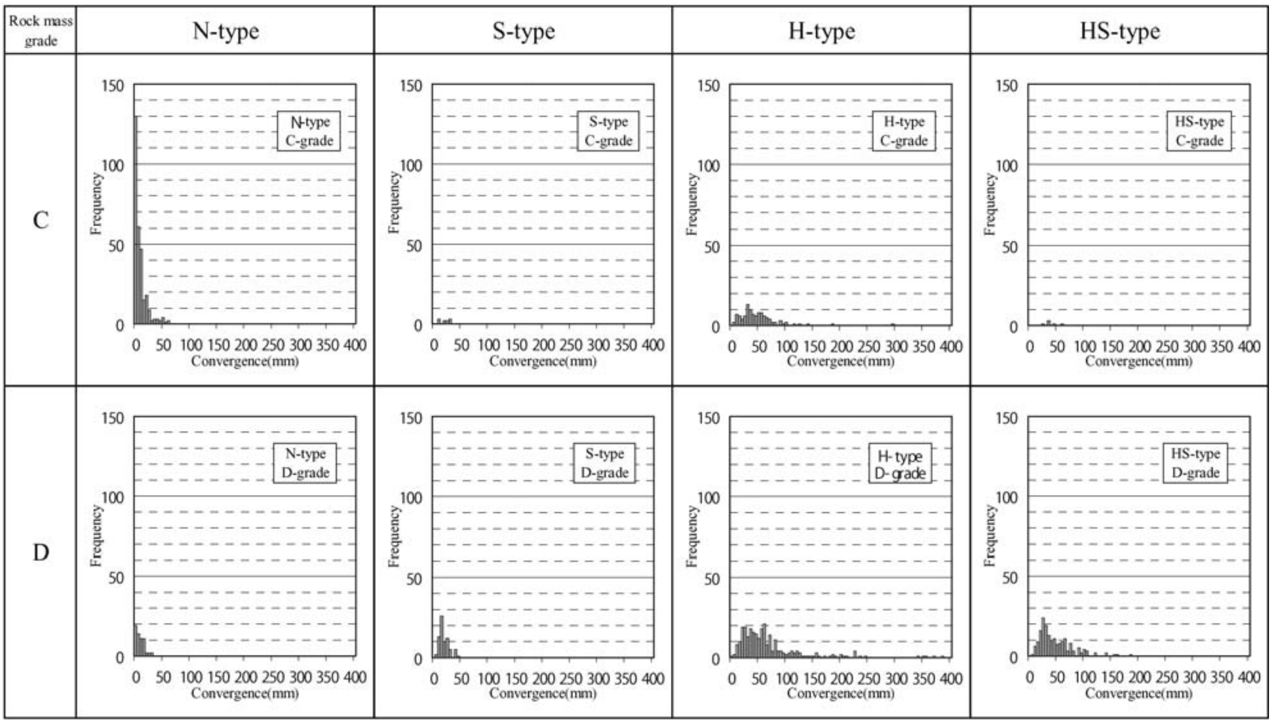

Figure 11. Convergence of four types of tunnel ground in tunnels of Tokushima, Takamatsu and Matsuyama expressways

Convergence of four types of tunnel ground

Figure 12 shows the convergence of four types of tunnel ground to thickness of overburden. Figure 12 indicates the following characteristics:

- Convergences of N-type ground are small, irrespective of the thickness of overburden.
- Convergences of S-type ground are small, where the thickness of overburden is less than 100m.
- Convergences of H-type ground gradually increase with respect to thickness of overburden and sometimes they attain 400mm without regard to thickness of overburden.
- Convergences of HS-type ground are large, irrespective to the thickness of overburden.

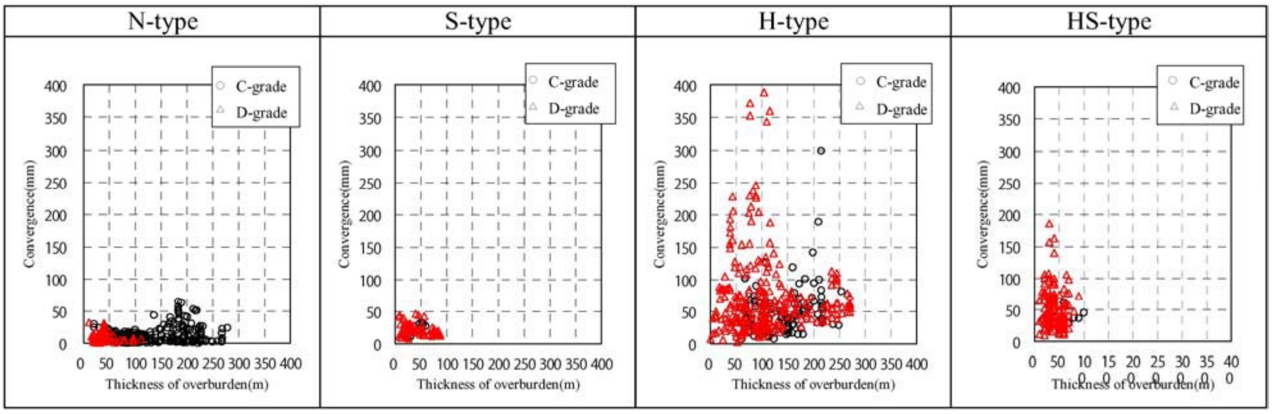

Figure 12 Convergences of four types of tunnel ground to thickness of overburden in tunnels of Tokushima, Takamatsu and Matsuyama expressways

Rock mass characterization by damage history of rock mass damage

Figures 10, 11 and 12 clearly indicate the characteristics of tunnel ground of the Izumi Group. The characteristics of tunnel grounds of the Izumi Group are summarised as follows (Table 5):

- N-type ground is composed of sound rock mass that shows very small convergence during tunnelling.
- S-type ground is composed of cracked rock mass, but it shows small convergence during tunnelling.
- H-type ground is composed of altered rock mass and it shows very large convergence during tunnelling even if the rock mass at face seems to be sound.
- HS-type ground is composed of altered and cracked rock mass that shows very large convergence during tunnelling.

	N-type	S-type	H-type	HS-type
Rock mass characteristics	Sound rock mass	Rock mass slide	Hydrothermal alteration	Hydrothermal alteration and rock mass slide
P-wave velocity	4km/s～	～3km/s	3～4km/s	～3km/s
Ground classification grade by JH	C-grade≫D-grade	C-grade≪D-grade	C-grade＜D-grade	C-grade≪D-grade
Convergence	C-grade:～25mm	C-grade:～50mm	C-grade:25～50mm	C-grade:25～50mm
	D-grade: ～25mm	D-grade:～50mm	D-grade:50mm～	D-grade:25mm～

Table 5. The rock mass characterization of tunnel ground of the Tokushima, Takamatsu and Matsuyama expressways

CONCLUSIONS

This paper describes the rock mass characterization of the Izumi Group for tunnel construction of the expressway in the Shikoku region. The Izumi Group is mainly composed of interbedded sandstone and shale of Late Cretaceous age. The rocks through which the tunnel passes in the Izumi Group are geologically classified into four types based on the damage history of rock mass sliding and hydrothermal alteration. This classification was confirmed by the rock mass grades and convergences during tunnelling.

Tunnels in the Izumi Group are divided into the following four ground types from history of damage:

- N-type ground is undisturbed interbedded sandstones and shales.
- S-type ground is mainly affected by the rock mass slide.
- H-type ground is affected mainly by hydrothermal alteration.
- HS-type ground is affected by both hydrothermal alteration and rock mass slide.

The characteristics of tunnel ground of the Izumi Group are summarised as follows:

- N-type ground is composed of sound rock mass and shows very small convergence during tunnelling.
- S-type ground is composed of cracked rock mass, but shows small convergence during tunnelling.
- H-type ground is composed of altered rock mass and shows very large convergence during tunnelling even if the rock mass at the face seems to be sound.
- HS-type ground is composed of altered and cracked rock mass and shows very large convergence during tunnelling.

X-ray diffraction analysis suggests that smectite-bearing hydrothermal alteration has caused large convergence during tunnelling. Therefore, it is very important to confirm the presence of the swelling clay mineral (smectite etc.) before and during tunnel construction.

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