Advances in Geological Surveying for Railways in Japan

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Start of Geological Surveying in Japan

The opportunity provided by modern Western geological studies to Japan came in the form of surveying for mineral resources in the late 19th century from the end of the Edo period (1603–1867) to the early Meiji period (1868–1912). American geologists William Blake and Raphael Pumpelly were recruited together with Japanese counterparts by the shogunate in 1861 to survey the mineral and coal resources of southern Hokkaido.

The Satsuma clan on Kyushu island recruited French mining engineer Jean Francisque Coignet in 1867 to survey the region's mineral resources. With the Meiji Restoration in 1868, Coignet moved to the Ikuno silver mine in Hyogo Prefecture, providing instruction in mining techniques, and engaging in surveys of mines across Japan.

The Hokkaido Development Commissioner hired American Benjamin Smith Lyman in 1869 to instruct students at Kaitakushi Tentative School (what would later become Sapporo Agricultural College and then Hokkaido University). He also surveyed coal and other resources in the Ishikari and Sorachi areas. Lyman completed Japan's first broad geological map, called the 'Geological Sketch Map of the Island of Yesso, Japan' in May 1876.

German Heinrich Edmund Naumann came to Japan in 1875 where he started lectures in geology in the Faculty of Science at Tokyo University. Naumann was instrumental in forming the foundations for geological studies in Japan through efforts such as establishing a geological surveying organization and implementing systematic geological surveys through that organization. These efforts helped establish geological studies as an academic discipline in Japan. Naumann also greatly influenced later geological studies in Japan through works such as his 1885 thesis that presented the geological history of the Japanese archipelago in a systematic manner, taking into account the framework of Japan's geological structure.

Start of Geological Survey of Japan

A section in charge of lumber and ore was established in Japan's Ministry of Home Affairs in 1874, and collection of unusual rocks and minerals from across Japan was also initiated. In 1878, an imperial geological surveying agency was established by Naumann and Tokyo University Associate Professor Tsunashiro Wada. That agency developed into the ministry's Department of Geology.

Although the Department of Geology had been established, actual geological surveys did not progress at any speed, so Naumann wrote to Home Affairs Minister (later Prime Minister) Hirobumi Ito, stating that geological surveys would be beneficial to areas such as agriculture, mining, metallurgy, civil engineering, and construction. In the letter, he stressed the necessity to organize a geological surveying agency and to create geological maps.

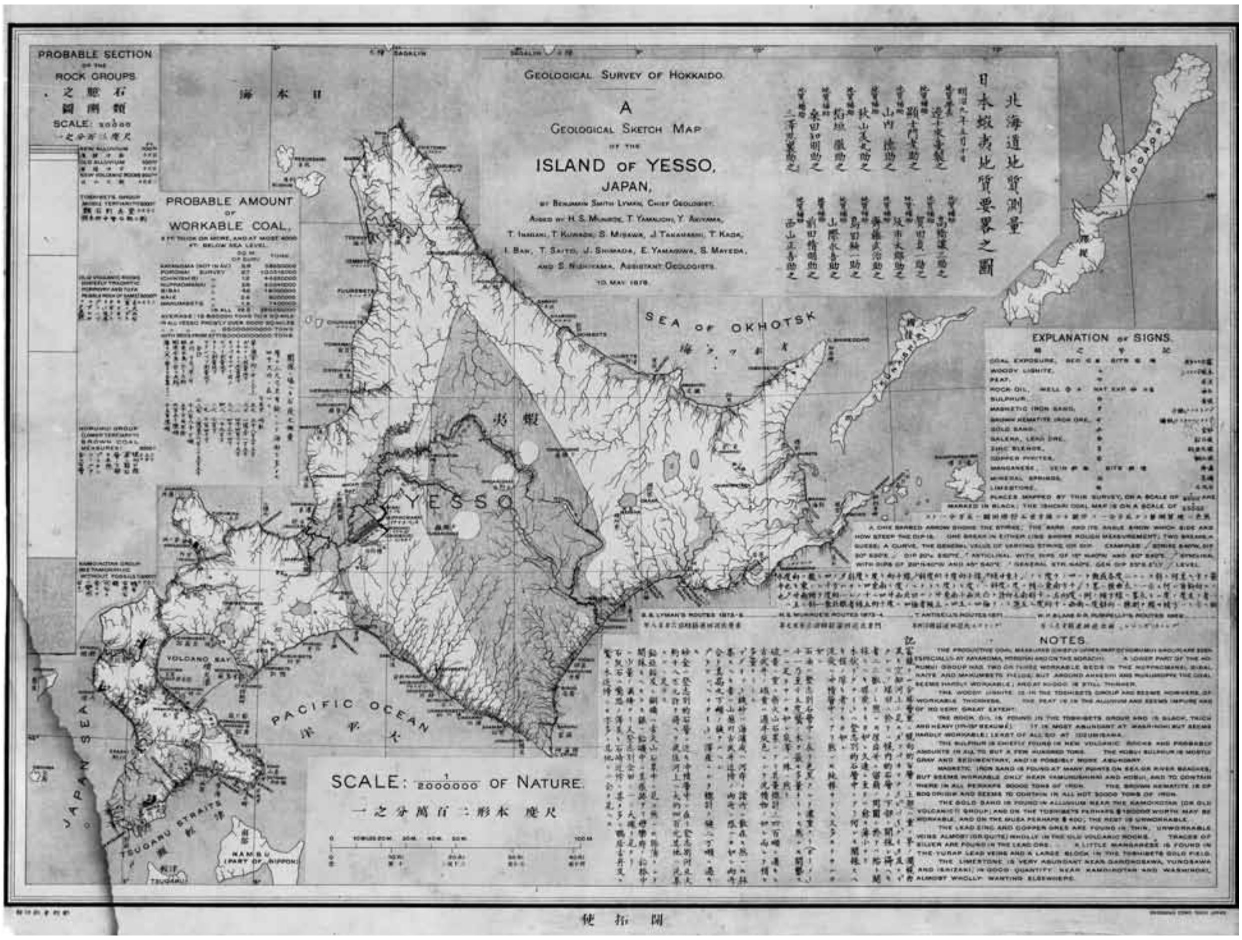
The Department of Geology came under the Ministry of Agriculture and Commerce and was renamed the Geological Survey of Japan in 1882. Full-scale surveys in geology, soils, terrain and the like started along with work in quality control and analysis of industrial products. Efforts were put into research in pedology (soil science) thanks to measures for promotion of agriculture, and the concept of agricultural geology was born. However, work in that area was transferred subsequently to agricultural research stations.

The Geological Survey of Japan also conducted geological surveys when commissioned by outside bodies, conducting several civil engineering surveys. For example, geological opinions about building a railway line through the Jizo Pass of the Nakasendo presented in 1885, noted the importance of geological surveys in selecting railway routes. The report stressed that geological surveys could cut construction and repair costs, leading to greater profitability.

Nobi Earthquake and seismology

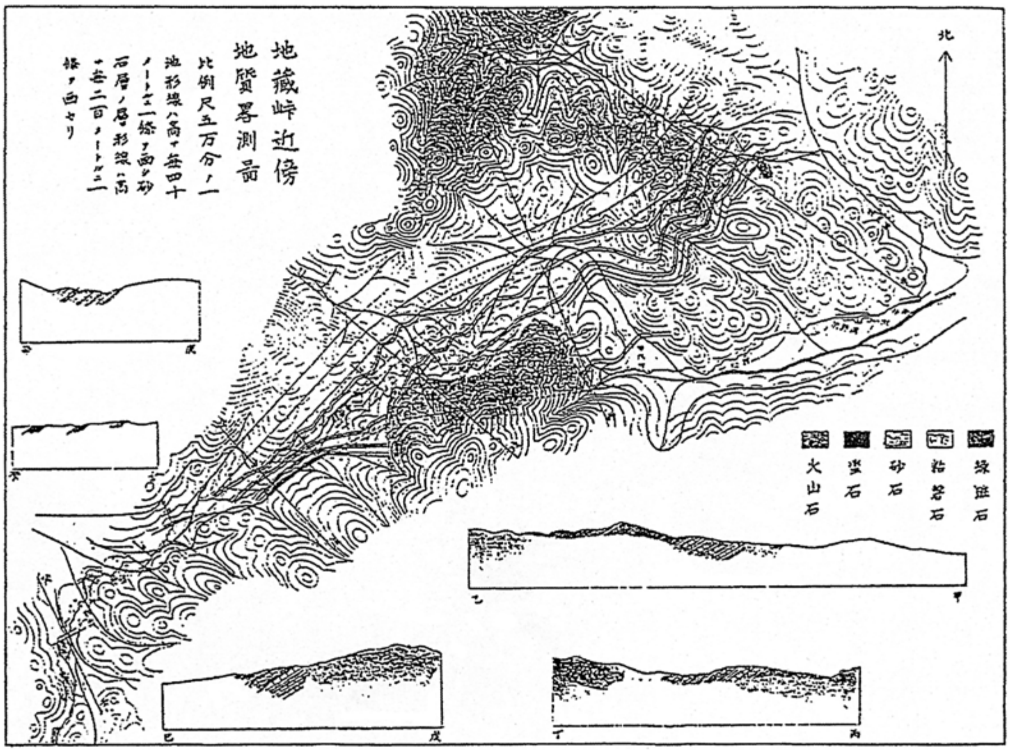
The magnitude (Mj) 5.8 Yokohama Earthquake of 1880 did not cause major damage, but caused great shock among residents of the foreign settlement in Yokohama. British Professor John Milne at the Imperial College of Engineering (a forerunner of the Tokyo University's Faculty of Engineering) founded the Seismological Society of Japan as the world's first academic group dedicated to the study of earthquakes and started full-scale research into them.

Figure 1 Geological Sketch of Yezo Island, Japan (1876)



(Geological Survey of Japan)

Figure 2 Geological Measurements near Jizo Pass (1885)



(“Kogaku-kaisi” (Engineering magazine), No.40 (1885))

Milne along with Tokyo University Professor James Alfred Ewing came up with various ideas for seismometers, and compiled a history of past earthquakes.

The magnitude (Mj) 8.4 Nobi Earthquake in October 1891 with its epicentre in Gifu Prefecture killed about 7000 people in areas including neighbouring Aichi, Fukui, Ishikawa, Mie, and Shiga prefectures. This earthquake exposed the Neodani Fault at the surface, and the relationship between faults and earthquakes was soon a focus of study. Due to the severe damage caused by the Nobi Earthquake, the government established the Imperial Earthquake Investigation Committee in 1892 to research earthquake disaster prevention and earthquake prediction in an organized manner. Researchers in areas such as geology, civil engineering, and architecture came together to start the research.

Milne Seismometer (National Important Cultural Property) (1894)
(National Museum of Nature and Science)

When the Sanriku Earthquake and tsunami of June 1896 struck, it left about 20,000 dead from a 38-m high tsunami that wreaked havoc on the Sanriku coast. Theories on the cause of the tsunami were discussed, including volcanic eruption, faults, and undersea landslide, but terrain and sea depth were discovered from later research to be dominant factors.

Start of hazard geology

In Japan, where weather-related disasters such as typhoons occur regularly along with earthquakes, the relationship between weather and geological phenomena was the early focus of study. Surveys on these phenomena were promoted by the Imperial Earthquake Investigation Committee and others.

In 1901, Tokyo Imperial University Professor Kotora Jinbo, who had surveyed denuded land in Yamanashi, Ishikawa, and Shizuoka prefectures under contract to the Imperial Earthquake Investigation Committee, published a report in *The Journal of the Geological Society of Japan*, advocating the necessity for geological surveys. Jinbo further stressed that geologists would need to cooperate more closely with civil engineers, stating that knowledge in areas such as ground collapse and weathering of rock is imperative for civil engineers, and that geologists should bear this in mind.

The magnitude (Mj) 7.9 Great Kanto Earthquake that struck the southern Kanto region on 1 September 1923 was the worst natural disaster Japan ever faced, with close to 100,000 people dead and 44,000 missing. The government immediately established the Imperial Capital Reconstruction Agency and started reconstruction, including about 800 bore surveys to identify the ground structure under the capital region. The survey results were released in 1929 as a report on geological surveys of Tokyo and Yokohama, which was subsequently used in civil engineering and architectural construction, disaster prevention planning, etc.

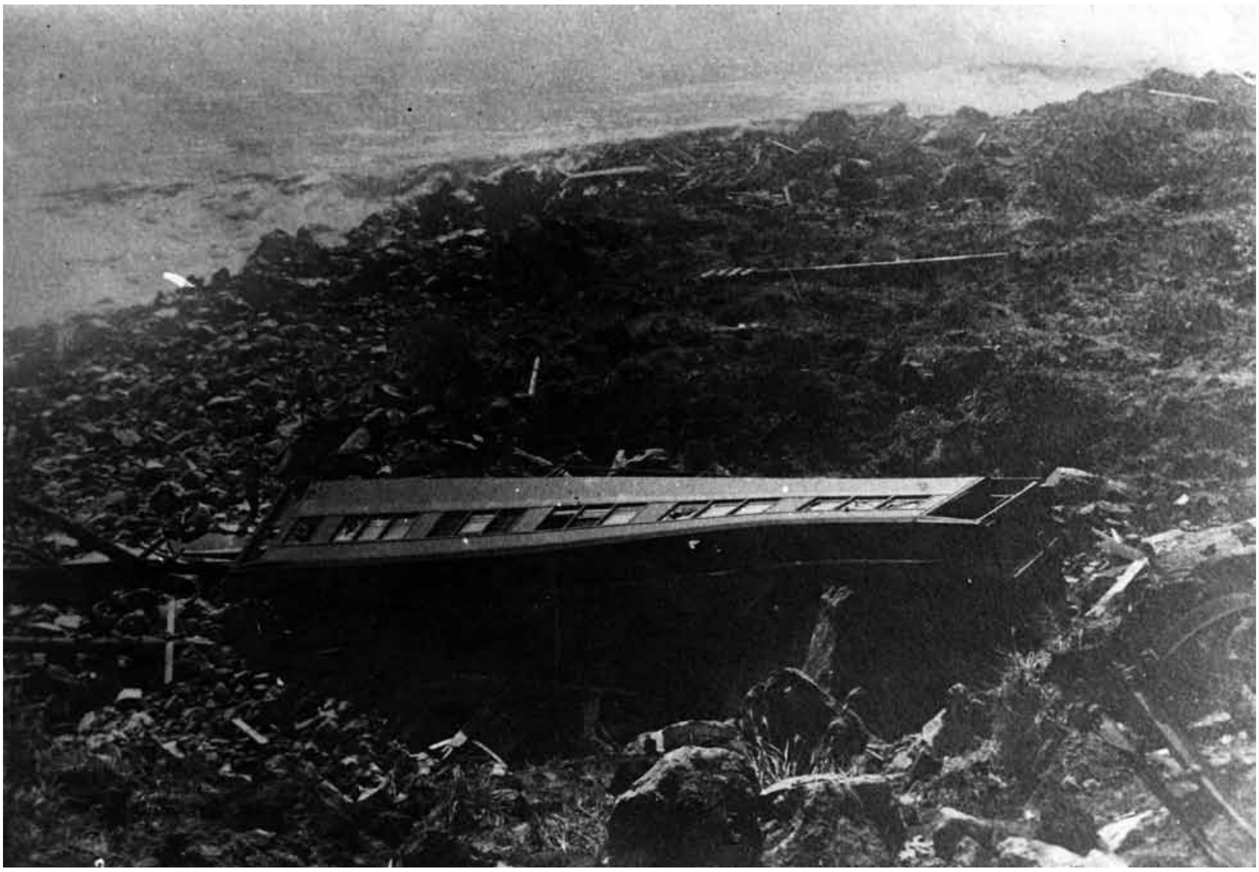
Aerial photography, which had advanced along with aircraft development, was put to use in tasks such as identifying disaster areas in the Great Kanto Earthquake, but this kind of technology was still used mostly for military purposes. The Ministry of Railways first tried using aerial photography to survey lines in 1932 with the cooperation of the army. In 1937, it used six aircraft with photographic equipment and pilots to start independent line surveys using aerial photography. Approximately 5000 km of rail lines had been surveyed using aerial photography by the end of WWII, but aerial photography was suspended in 1943 due to the war. All documents were destroyed at the end of the war, so none passed down to history, but this did provide an opportunity for aerial photography to be used in surveys for civil engineering construction works.

Tanna Tunnel and geological surveying

Construction of the Tanna Tunnel on the Tokaido main line started in 1918 and was one of the world's most difficult projects in the history of tunnel construction. With works often disrupted by cave-ins and floodings due to distensible geology and large volumes of groundwater, the tunnel was not completed until 1934.

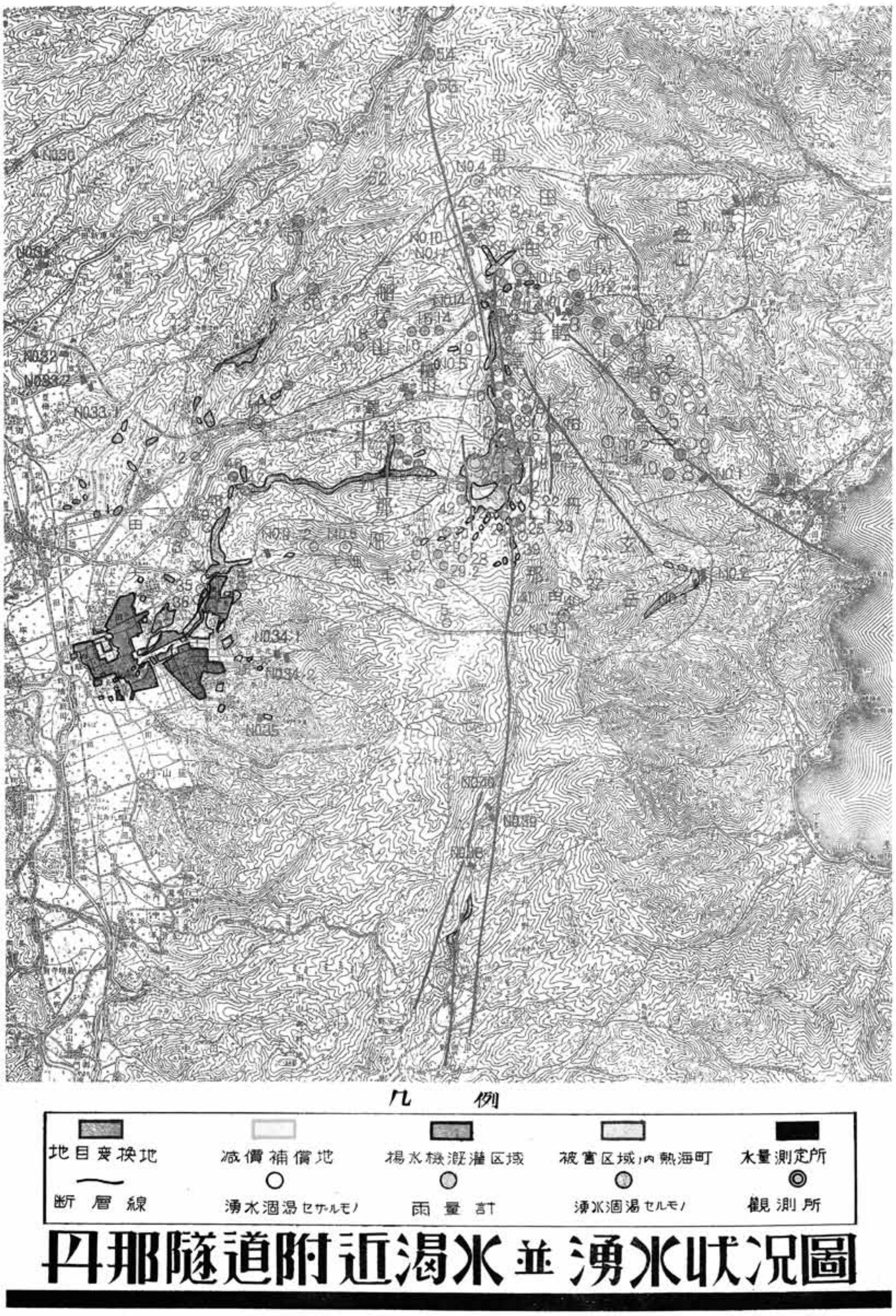
Tokyo Imperial University was commissioned to perform a survey for construction of the Tanna Tunnel, and predicted large volumes of spring water. However, construction went forward without gaining a clear conclusion from the geological factors. The tunnel was in danger of non-completion and was criticized by overseas tunnel engineers as a reckless endeavour. As a result, the Ministry of

Railway Damage due to Nobi Earthquake (Nagaragawa Bridge) (1891) (Dr. Hiki's collection of Kyoto University)



Railway Damage due to Great Kanto Earthquake (1923) (Author's Collection)

Figure 3 Tanna Basin Fault and Groundwater Survey Chart (1934)

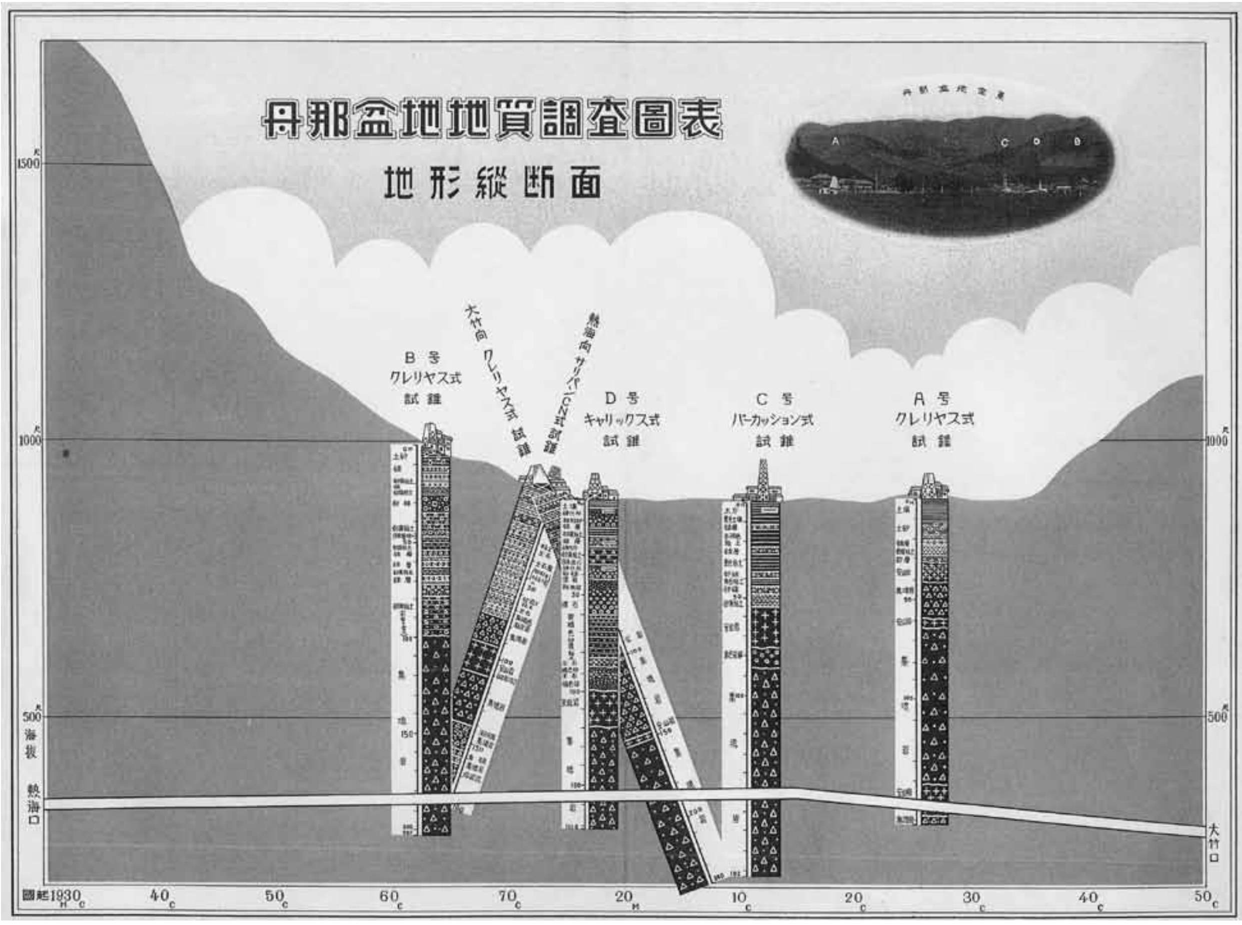


("Construction record of Tanna Tunnel" (JGR/1936))

Railways hired geological experts in 1923 to its conduct own geological surveys.

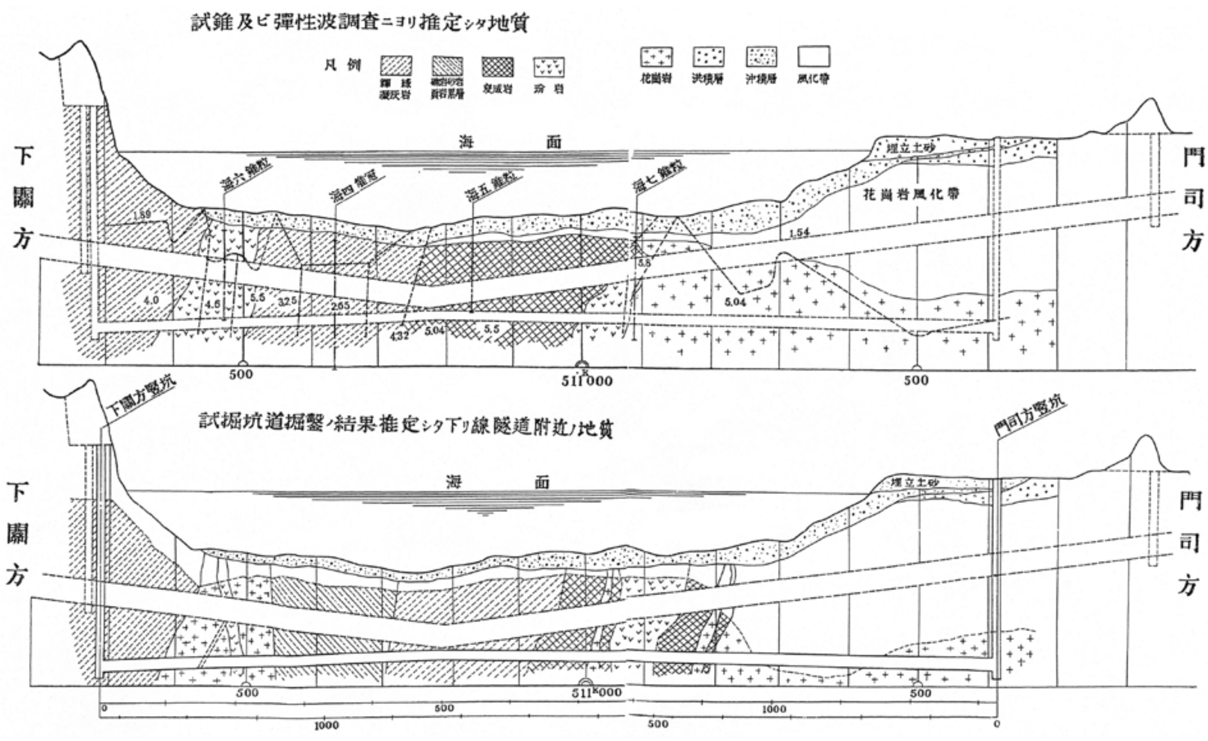
When surveying for a railway across the Kanmon Straits, bridge and tunnel proposals were compared, with geological surveys involving boring being conducted in 1919. Such geological surveys by boring were already common in mining, but at last came into popular use in civil engineering with geological surveys for the Tanna Tunnel and the Tokyo Subway (part of the Tokyo Metro Ginza Line today), which started operation in 1927.

Figure 4 Tanna Tunnel Boring Geological Survey (1934)

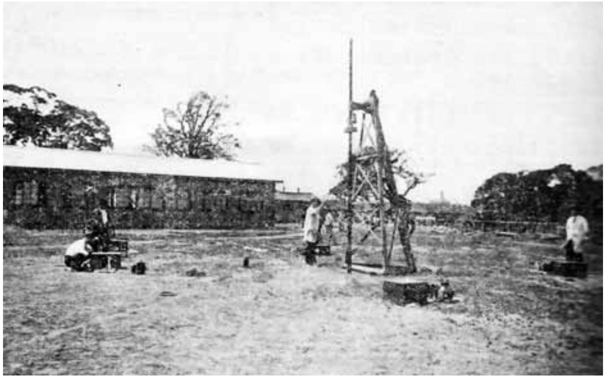


(Construction record of Tanna Tunnel" (JGR/1936))

Figure 5 Kanmon Undersea Tunnel Geological Map (1939)



("Construction record of Kanmon Tunnel" (JNR/1949))



Preliminary geophysical prospecting Test by Ministry of Railways' Geotechnical Committee (1933) (RTRI's Collection)

Formation of Ministry of Railways Geotechnical Committee

The Ministry of Railways recognized the importance of geological surveys in reflections on the difficulties with the Tanna Tunnel construction, setting up its Geotechnical Committee in 1930. At the time, new concepts in new soil mechanics were being established in Europe by the likes of Karl von Terzaghi, Wolmar Fellenius, and Albert Atterberg. Swedish State Railways, in particular, organized its Geotechnical Commission and achieved great results in areas such as disaster geology.

Such knowledge from abroad was introduced to Japan through various means such as activities of the Ministry's Geotechnical Committee, greatly influencing the country. The Committee, along with outside people such as researchers from Tokyo Imperial University, started studies to apply geological knowledge to engineering. The purpose of the Committee was stated as being to 'survey and research the characteristics of soil in a scientific and engineering-based manner for conducting construction, maintenance, improvement and other work for national railways lines, and to execute construction appropriate for the condition of the particular location, and contribute to construction cost reduction and safety for lines.' The Committee established study groups on design and building methods for structures, etc., based on geological surveys, and it tirelessly conducted activities such as bibliographic surveys, holding of study groups, testing commissioned by outside entities, and consulting, until 1938.

The Committee put much effort into practical use of elastic prospecting, electrical prospecting and other geophysical prospecting methods and into development of testing methods to identify the physical properties of soils and rock, thereby establishing the foundations of today's engineering geology. Geophysical prospecting technologies, such as elastic prospecting, had already been used in mining by the 1920s, but the first attempts to use these technologies for railways were electrical prospecting in surveying the foundations for the Chuo main line Tamagawa River Bridge in 1930 and elastic prospecting for the Tanna Tunnel in the same year.

Such results were applied later to construction of the Kanmon Undersea Tunnel, but the Ministry of Railways' engineers were sent overseas or transferred to tasks such as construction of underground bunkers and other defensive facilities as the war intensified. This situation continued until the end of the war.

Postwar Reconstruction and Geological Surveying

Start of Railway Technical Research Institute's Geological Research Laboratory

Advancement in geological surveying for railways was halted for a time due to WWII but the need for geological surveying grew rapidly with the postwar recovery. Railways and roads, and water resource facilities such as dams and large irrigation canals were being built at a rapid pace.

Demand increased for construction of railways along with postwar reconstruction, so Japanese National Railways (JNR) launched the Geological Research Laboratory at its Railway Technical Research Institute (RTRI) in April 1955. The geological consulting industry had not sufficiently developed at the time, so the Laboratory primarily conducted its own surveys. The first job was a geological survey for the Hokuriku Tunnel then in planning. It conducted bore surveys, electrical prospecting, elastic prospecting, and hydrogeological surveys, establishing the foundations for later tunnel geological surveys.

Railway disasters and geological surveying

JNR set up a landslide experimental station at Nou on the Hokuriku main line in 1948 and started activities such as general monitoring using measuring devices and model experiments. A committee on countermeasures against disasters on the Dosan Line was later established by JNR in response to the 1962 slope disaster on the line between Tosa-Iwahara and Toyonaga, with experts from inside and outside the company coming together to perform analyses. The committee identified levels of disaster risk from the cause and effect relationship between geological structure and slope disasters. It also accomplished results such as extraction of broken terrain by deciphering aerial photos.

Aerial photographs were put to full-scale use for slope disasters from 1970 with creation of a grading chart to evaluate degree of soundness. Multispectral photographs were used from 1972 in an attempt to more accurately extract the terrain of slope disasters. These results were published in 1978 as a study group report on methods of deciphering aerial photographs, and manuals were created for methods of deciphering disaster terrain and interpreting the results of deciphering.

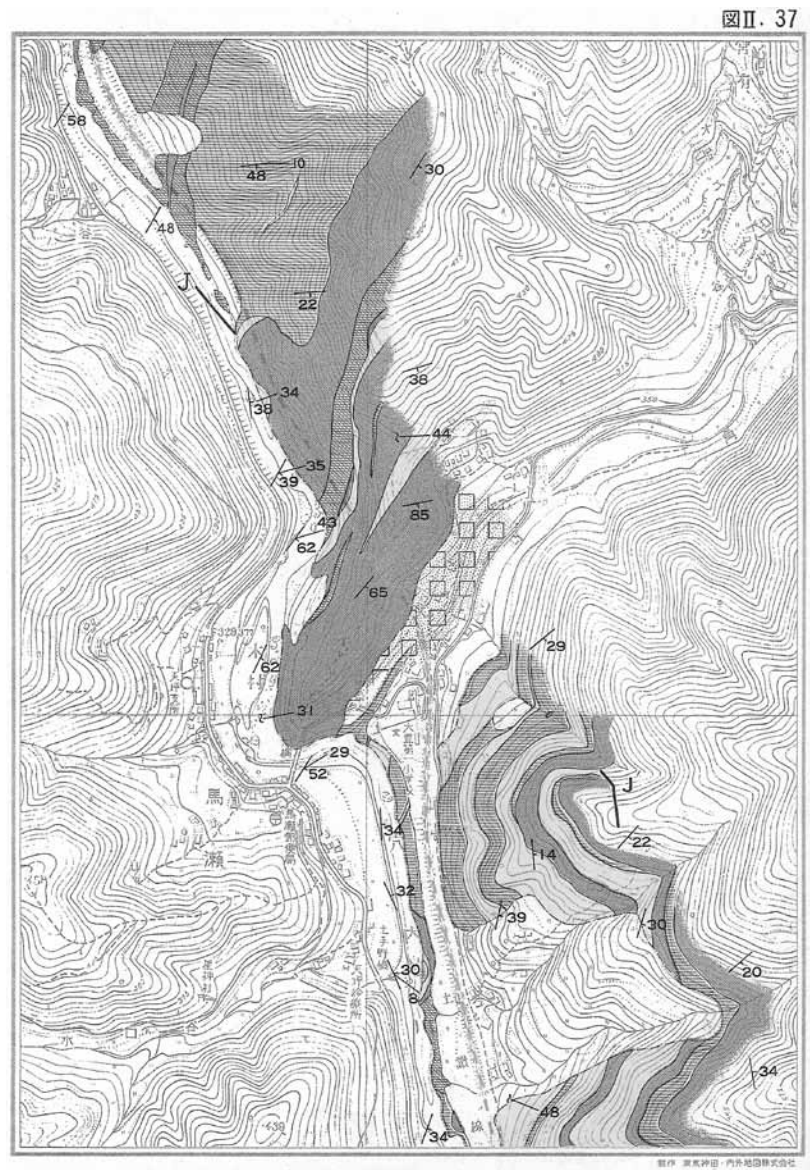
Railway construction and geological surveying

Seabed geological surveying was conducted in 1960 using deep-submersibles for the Seikan Tunnel, which had been under survey from the 1950s. Other methods included bore surveys, elastic prospecting, electrical prospecting, and physical and chemical tests. Thanks to these, the seabed geology of the Tsugaru Strait was almost completely known by about 1962.

Railway construction and improvement works expanded in the 1960s with Japan's rapidly growing economy, and geological survey work also eventually broadened with shinkansen construction projects. Standard specifications for geological surveying were thus established by JNR in 1969, and a framework for conducting geological surveys was put in place ahead of civil engineering construction.

For railway tunnel construction in particular, the New Austrian Tunnelling Method (NATM) was introduced in the late 1970s as a replacement for the conventional sheet piling method. NATM rapidly became commonplace as a flexible construction method that is well-matched to Japan's complex and varied geological conditions. Moreover, quantitative assessment of ground based on rock engineering became possible due to factors such as identification of ground deformation behaviour, use of mine workface observation records, and application of numerical analysis technologies, such as FEM. NATM gained prominent status in the railways field as the standard method of tunnelling in mountains with the 1983 establishment

Figure 6 Geological Survey Chart on Dosan Line (1964)



(JNR Report (1964))

Seikan Undersea Tunnel Construction (1983) (Japan Railway Construction Corporation)

Table 1 Classification of Rock Quality for Railway Tunnel Construction (1970)

Classification of quality of rocks

Quality of rocks	Rocks
A	(a) Paleozoic / Mesozoic rocks (clayslate, sandstone, conglomerate, chert, greywache, schalstein, limestone, etc.) (b) Plutonic rocks (granite, granodiorite, diorite, gabbro, peridotite, etc.) (c) Hypabyssal rocks (Granite porphyry, quartz porphyry, porphyrite, diabase) (d) Volcanic rocks (some part) (basalt, andesite and rhyolite of mesozoic era, etc.) (e) Metamorphic rocks (gneiss, hornfels, schist, phyllite, quartzite, etc.)
B	(a) Metamorphic rocks having conspicuous schistosity (b) Paleozoic and Mesozoic rocks having fine bedding plane
C	(a) Mesozoic rocks (some part) (shale, sandstone, tuff breccia, etc.) (b) Volcanic rocks (greater part) (rhyolite, andesite, etc.) (c) Palaeogene rocks (some part) (silicified shale and sandstone, volcanic tuff)
D	Neogene / Palaeogene rocks (mudstone, schale, sandstone, conglomerate, tuff, lapilli tuff, tuff breccia, welded tuff, etc.)
E	Pleistocene / Neogene rocks (mudstone, siltstone, sandstone, sand and gravel rock, tuff, talus, volcanic ejecta, etc.)
F	Alluvium / Diluvium rocks (clay, silt, sand, sand and gravel, loam, fan, talus, terrace, volcanic ejecta, etc.)

Classification of rocks conditions for tunnelling

Classification rock condition	Quality of rocks (km/sec)						
	A	B	C	D	E	F	
1	> 5.0		> 4.8	> 4.2			
2	5.0~4.4		4.8~4.2	4.2~3.6			Good
3	4.6~4.0	4.8~4.2	4.4~3.8	3.8~3.2	> 2.6		
4	4.2~3.6	4.4~3.8	4.0~3.4	3.4~2.8	2.6~2.0		Medium
5	3.8~3.2	4.0~3.4	3.6~3.0	3.0~2.4	2.2~1.6	1.8~1.2	
6	< 3.4	< 3.6	< 3.2	< 2.6	< 1.8	1.4~0.8	Bad
7					< 1.4	< 1.0	

Remarks

1) Reduce to a lower class, when groundwater inflows always into tunnel.
2) The rocks having expansibility have no relation to this classification.
3) Raise 1~2 ranks of classification, when the Poisson's ratio of the weathered rock is smaller than 0.3.

Notes

1) Numbers 1~7 are the ranks of the magnitude of intensity.
2) The numbers show the velocity of elastic wave in the rock.
3) A~F of quality of rocks are indicated by top table.
4) Numbers in the table show velocity of elastic wave propagation km/s.

(JNR Report 1970)

of the NATM design construction guidelines by JNR.

Interest in deep underground spaces increased from 1987 with the skyrocketing cost of land in urban areas, promoting technical development for deep underground railway tunnels.

Rock mass classification for railways had started around 1942 with the creation of simple rock classification charts for slopes, but more quantitative assessment methods were needed with the spread of geological surveying methods. A classification of rock conditions for tunneling was created in 1966 based on previous tunnel surveys and accumulation of knowledge from construction, with rock mass strength broken down into seven levels, based on rock type and elastic wave velocity (Table 1).

This classification is the basis of the later rock mass classification, and with the establishment of the 1983

Railway Damage due to Great East Japan Earthquake (2011) (JR East)

NATM design construction guidelines, a six-level rock mass strength classification was made based on rock type and elastic wave velocity and ground strength comparisons. Standard support patterns according to individual rock mass classifications were presented, and tunnel design and construction was conducted in a more streamlined manner thanks to these guidelines.

Conclusion

There was little interest in geological surveying during early railway construction in Japan, and almost no detailed surveys based on scientific knowledge were performed. However, the importance of geological surveying, was eventually recognized through construction of railway tunnels, bridges, etc. This led to the establishment of the Ministry of Railways' Geotechnical Committee and attempts ahead of other fields to reflect the results of geological surveys in civil engineering.

With the expansion of railway construction after WWII, it was recognized that careful preparatory geological surveys would lead to smoother construction, allowing for more streamlined and economical civil engineering. It was also recognized that identifying terrain and geological conditions in advance could help reduce damage from typhoons, earthquakes, and other disasters.

Recent efforts are being made to build railways that are resistant to natural disasters in light of lessons learned from the 1995 Great Hanshin Earthquake and the 2011 Great East Japan Earthquake. ■

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