INTEGRATED GEOPHYSICAL SURVEY TO CHARACTERIZE THE GEOLOGICAL SETTING FOR THE ISE BAY MOUTH HIGHWAY PROJECT

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ABSTRACT

Geophysical investigations have been systematically carried out since 1992 in the terrain where the Ise Bay Mouth Highway was planned. The planned highway crosses 20-km wide mouth of Ise Bay, central Japan, along islets studding the terrain. Oversea long-spanned bridges and submarine tunnels are proposed as the main facilities, however, geological setting of the terrain and physical properties of the bearing rocks was uncertain due to the difficulties of geological surveying in offshore region. We therefore applied geophysical surveys involving marine reflection, underwater refraction, offshore magnetic, land seismic, and borehole logging at the early stage of the project. Over 300 km of single coverage and 40 km of multi-channel marine seismic data were obtained during 4 fiscal years. The data were utilized to map the thickness of bottom sediments and the area of bedrock outcrop, locate low velocity zones or fractured zones in the bedrock, and identify faults in the terrain. The offshore geophysical data, together with the land seismic and geological investigations, have clarified the complex geological setting featured as bundling of five major geologic terranes within a narrow zone about 10 km just at the mouth of Ise Bay. Based on the geological information, several crossing routes were proposed to weave through the suitable portion for bridge or tunnel construction. Comparative assessment is now undertaken for each route, taking account of construction cost and period, difficulty of seismic design, influence to the natural environment, and effect on the regional transportation network.

INTRODUCTION

The Ise Bay Mouth Highway is being planned as a new trunk road crossing over the entrance of Ise Bay through islets studding the region. The planned length is about 90km including a 20-km long offshore part. The project is purposed to form a new transportation axis called “the New Pacific Ocean Coastal National Axis” in conjunction with other highway projects planned at the Pacific coastal regions.

The Japan Islands comprises major four islands and form a long chain-like island arc at the northwestern margin of the Pacific Ocean. The area of the country is 372,000 km2, which is smaller than that of California State. Because of the mountainous topography, at most 20 % of the whole country are the habitable areas where 124 million populations crowd. Accordingly, the Japan has thirteen million cities, most of which are located at the Pacific coastal side. Dependently on this geographic feature, the transportation network system of Japan is also characterized as “uniaxial”.

Actually, both the domestic physical distribution and passenger transportation are concentrated into the Pacific coastal region mainly by making use of the ground traffic facilities. The uniaxial transportation system is, however, very weak to the disaster. For example, “Shinkansen”, which is the famous high-speed railway system in Japan, was damaged by the 1995 Great Hanshin earthquake, and four months were required to resume service. As for the Hanshin Expressway, it took a year and eight months for the repair of collapsed viaducts approximately 600 m long. The physical distribution, which had passed through these trunk transportation systems, was strongly affected during the period due to the lack of bypass.

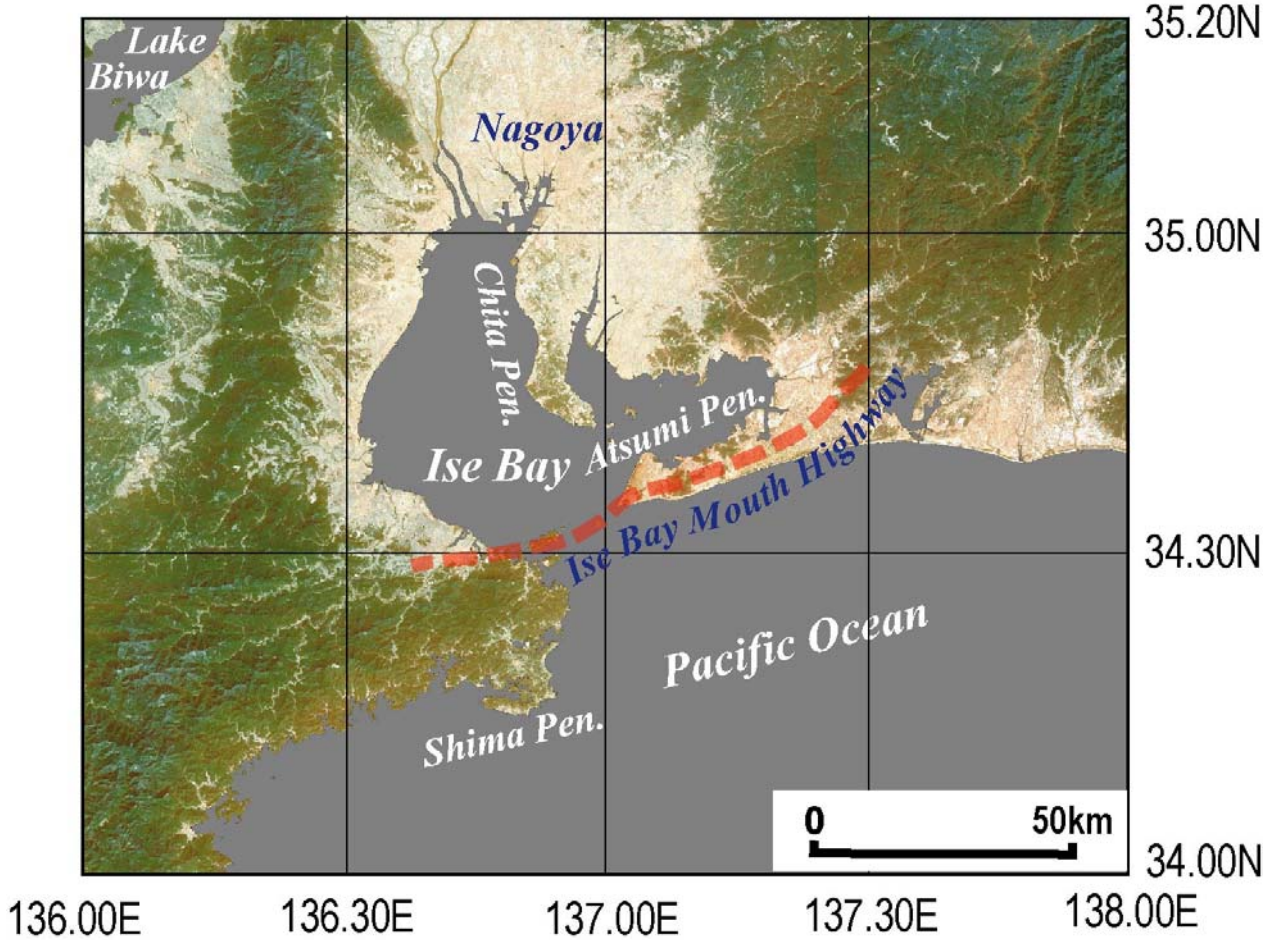

Fig. 1. A LANDSAT image of the Ise Bay and its surrounding area, central Japan.

Then, it was planned to form a new transportation axis at the Pacific Ocean side. The Ise Bay Mouth Highway will form a part of the axis. The planned route goes through Atsumi Peninsula, crosses over the entrance of Ise Bay, and extends to Shima Peninsula (Fig.1). Although the coastal route has high potential of large-scaled earthquake, the construction cost and the seismic safety of the route were estimated to be still advantageous compared with those of the mountain route.

In general, it takes two to three decades from the planning stage to the construction stage of a new roadway. Regretfully, comprehensive consultation by geologists throughout the duration was rare, especially in Japan. Resultantly, the simple borings at specific sites have been adopted as the major geological survey methods, and little of regional tectonic investigation. Such insufficiency in geological survey might cause the delay or disadvantage of a highway project.

As for the Ise Bay Mouth Highway, the master plan was made in 1985, and geological surveys started at 1990. To execute geological and geophysical surveying efficiently, we have been engaged in the survey planning, management of each survey, implementation of geophysical surveying by ourselves, processing of acquired dataset, and comprehensive interpretation of surveyed data, as the professional geologists and geophysicist since 1992. The representative results of the applied geophysical explorations and their engineering utilization are introduced in this paper.

GEOLOGICAL SETTING AND THE OBJECTIVES OF GEOPHYSICAL SURVEYS

The planned Ise Bay Mouth Highway crosses the 20 km wide narrowest part at the mouth of Ise Bay, along the small islands scattered in the region. Ultra-long spanned bridges or undersea tunnels are designed

as the main facilities at the oversea part.

It is essential to have the detailed geological and geotechnical information for locating the route and designing the main facilities. However, there had been no useful information on the geology of the terrain due to the difficulty of geological surveying at the offshore area. We therefore started to compile the geological setting and to make clear the survey problem.

Figure 2 shows the tectonic outline of Ise Bay area. The basement rocks of the Japan Islands are mainly composed of accretional complexes, metamorphic rock of accretional complex origin, and the granitic rocks. In particular, successive accretion of trench sediments and oceanic plate materials in the geologic age formed the characteristic zonal alignment of geotectonic units, which are traced over 1,000 km along the Japan Islands. Four major units of such accretional complexes expose in the area, Ryoke metamorphic belt, Sanbagawa metamorphic belt, Chichibu belt, and Shimanto belt from north to south. The boundaries

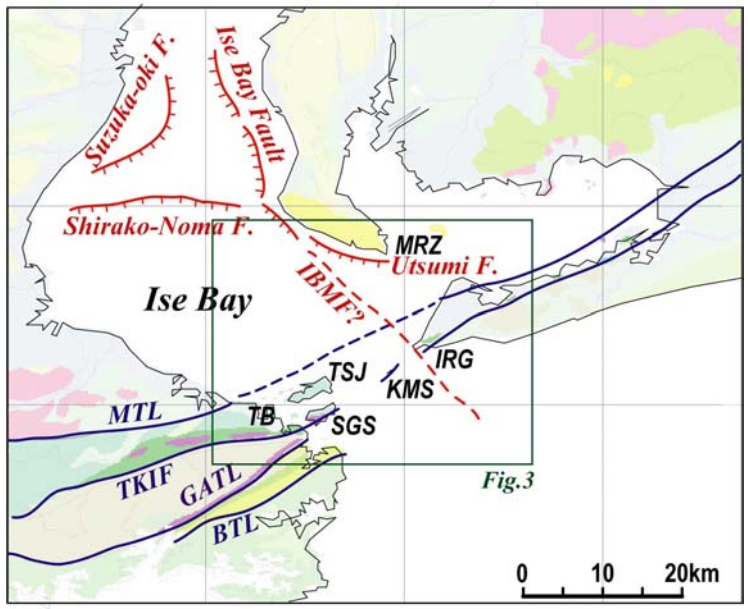

Fig. 2. Tectonic map of the Ise Bay Mouth area. Active faults are distributed inside the Ise Bay and a fault IBMF (Ise Bay Mouth Fault) had been speculated to extend towards the open sea. The major four tectonic faults limiting different accretionary complexes run within a narrow zone at the mouth of Ise Bay; MTL: Median Tectonic Line, TKIF: Toba-Kami-shima-Irago Fault, GATL: Gokasyo-Arashima Tectonic Line, and BTL: Butsuzo Tectonic Line. Other abbreviations used in the figure are as follows; IRG: Irago Cape, KMS: Kami-shima Islet, TSJ: Toshi-jima Island, SGS: Suga-shima Island, TB: Toba, MRZ: Morozaki Cape.

Table 1. A diagram showing the applied geophysical surveys and geological problems at each subdivision of the Ise Bay Mouth Area.

Subdivision	Land/Island	TB		TSJ/SGS		KMS		IRG
	Offshore		Small Channel		Reef		Main Strait	
Geophysical Survey	Reflection				■		■	■
	Refraction	■	■	■	■	■	■	■
	Magnetic	■	■	■	■	■	■	
	VSP						■	■
	Logging			■	■	■	■	■
Geological Problem	Tectonics				TKIF GATL	TKIF	MTL TKIF GATL	MTL TKIF
	Engineering Properties	Ultramafic Rocks	Faulted Zone	Ultramafic Rocks Weathered Rocks	Ultramafic Rocks Serpentinite	Faulted Zone	Faulted Zone	Ultramafic Rocks Faulted Zone

between these belts are featured as tectonic lines or large scaled faults, which are also traced over 1,000 km, with broad fractured zones. The Median Tectonic Line (MTL) between Ryoke and Sanbagawa belt is the most prominent tectonic lines which divides the Japan Islands into the Inner Zone and Outer Zone tectonically. Several segments of it are still active and regarded as the seismogenic active faults. Accordingly, it was requested to locate the MTL in the offshore area, certify whether the MTL deforms the recent sediments, and scale and physical properties of the associated fractured zone.

The TKIF (Toba-Kami-shima-Irago Fault) and GATL (Gokasyo-Arashima Tectonic Line), which seem to be constricted at the offshore, are characterized to bring the ultramafic rocks and serpentinite. It is well known that the serpentinite is soap-like, easily deformed rock extremely unsuitable for the bridge foundation or tunnel support. Thus it was essential to clarify whether unexplored block of serpentinite was present or not in the offshore region.

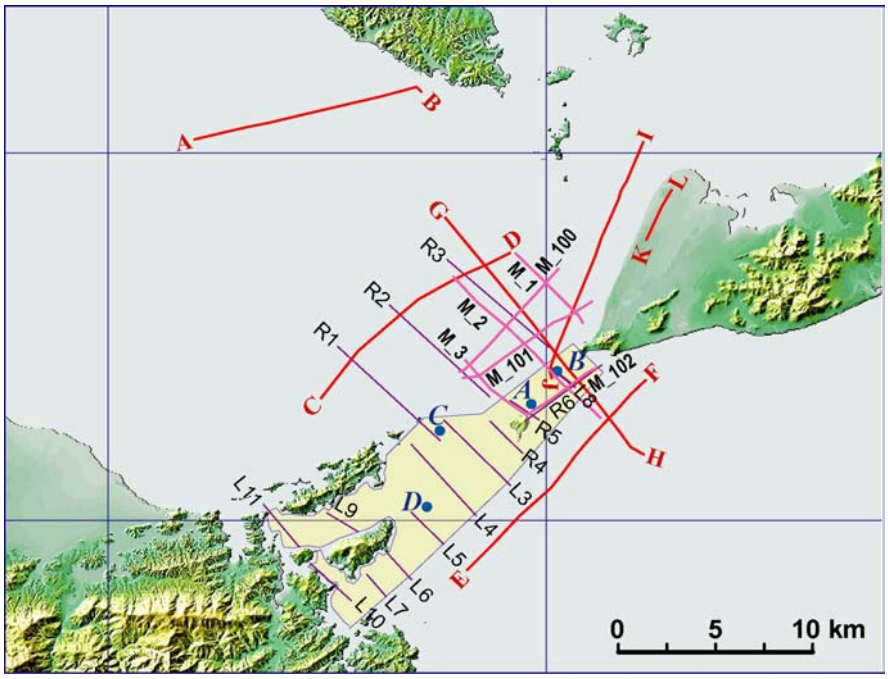

Fig. 3. Map showing geophysical survey lines and a field set at the Ise Bay Mouth area. Circles indicate offshore boreholes in which integrated logging was carried out. Heavy lines marked A-B to I-J and six solid lines marked as M_1 represent marine reflection survey lines. Fifteen short lines (R1-R6 and L3-L11) indicate offshore refraction survey lines. Shaded part delineates the field where shipborne magnetic survey was conducted. Over 300 km of single coverage reflection survey was also carried out at the area. The line marked K-L represents a profile of 3.2 km long land seismic reflection survey.

Several active faults were discovered inside the Ise Bay by means of multi-channel and single channel reflection survey as shown in Fig. 2. Another fault named Ise Bay Mouth Fault (IBMF) was not based on the site evidence but supposed at the drawn position in Fig. 2 to make it consistent the complicated tectonic setting observed at only land area. The IBMF had been considered to displace the MTL left-laterally by 5 km (Kanaori, 2000). Then it was one of the important issues of the survey to confirm whether the IBMF existed actually at the inferred position.

It was also required to map the depths to bedrock surface and to estimate the geotechnical properties of the bearing rocks. Because the in-situ tests but also sampling of test specimens are very hard at offshore region, underwater refraction survey lines were densely set to have the profiles of Vp, which has close relation to the strength of rocks.

GEOPHYSICAL SURVEYS

To cope with the survey tasks above mentioned, we carried out the following geophysical explorations systematically, that is, multi-channel and single channel reflection, underwater refraction, sea-surface magnetic, land seismic, and borehole logging. Table 1 sorts the applied geophysical methods and the geological problems or survey tasks for each subdivision of the surveyed area. Survey lines, an area in which dense magnetic survey was conducted, and the points of borehole logging are illustrated in Fig.3.

Reflection Survey

The purposes of the marine seismic reflection survey were to confirm whether the IBMF existed actually at the inferred position, to locate the MTL, and to certify whether the MTL deformed recent sediments. To fulfill these tasks, we set the Line A-B, C-D, and E-F to intersect the inferred extension part of the supposed IBMF, the Line G-H, I-J, and several short lines across the MTL. A 3 km long land seismic reflection survey was conducted at the tip of Atsumi Peninsula where the MTL was presumed to be covered with thick sand bank deposits (Line K-L in Fig. 3).

Figure 4 shows a time section (a) and a interpreted depth profile (b) of the Line A-B placed to traverse the confirmed fault named Utsumi Fault and speculated IBMF close to Chita Peninsula (see Fig.3 also Fig.1). The faulting structure of Utsumi Fault is clearly reconstructed at the eastern end of the profile and the layered

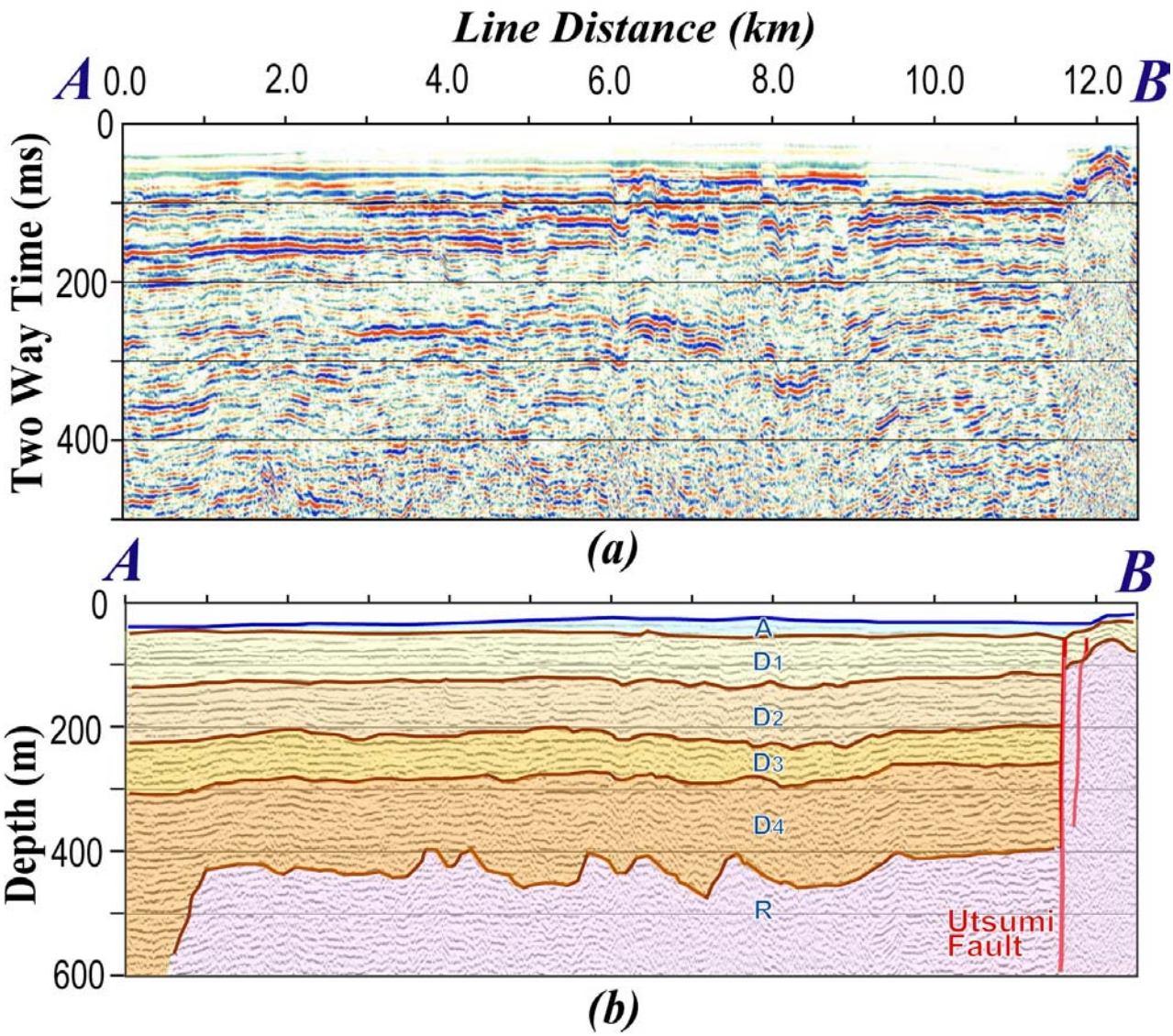

Fig. 4. Time section (a) and interpreted depth profile (b) along the multi-channel reflection Line A-B which intersects the confirmed fault named Utsumi Fault near the eastern end of the line and also the supposed Ise Bay Mouth Fault (IBMF) somewhere along the line. Faulting structure of Utsumi Fault is obvious, while no evidences of IBMF were recognized in the profile.

structure, slightly dipping westward, is dominant in the most part without any faulting that deforms the layered sediments. No evidences of such faulting were recognized in the Line C-D or E-F, which strongly indicates the supposed IBMF is not present at the Ise Bay Mouth.

Refraction Survey

Underwater seismic refraction survey was purposed to delineate the faulted zones of the MTL, evaluate the physical properties of the bedrock along the proposed routes. Small land refraction surveys were also performed to map the weathering layer and to detect faulted zone.

The velocity profiles of 3 refraction survey lines are compared in Fig. 5. These 3 profiles were located across the extension of the MTL (Fig.3). The P-wave velocities (Vp) of the bedrock are about 4.0 km/s to 5.0 km/s. Characteristic pairs of low velocity zones (Vp:2.7-3.3 km/s) in the bedrock are traced at the marked positions by arrows. The distances between these two zones are about the same as 1 km, in addition, these pairs occur distinctively at the northern shoulder of the bedrock rise. We interpreted the pair and the inner zone between the pair as the fractured zones of the MTL.

Magnetic Survey

Sea-surface magnetic prospecting was aimed to map the ultramafic rocks and related serpentinite blocks along the TKIF and GATL. Shipborne method was used to have high-resolution total intensity geomagnetic field data. The interval of survey ship tracks was about 50 m. As shown in Fig. 6, a 10 km long elongated magnetic anomaly was delineated between Suga-shima (SGS) and Kami-shima (KMS) with a trend in the

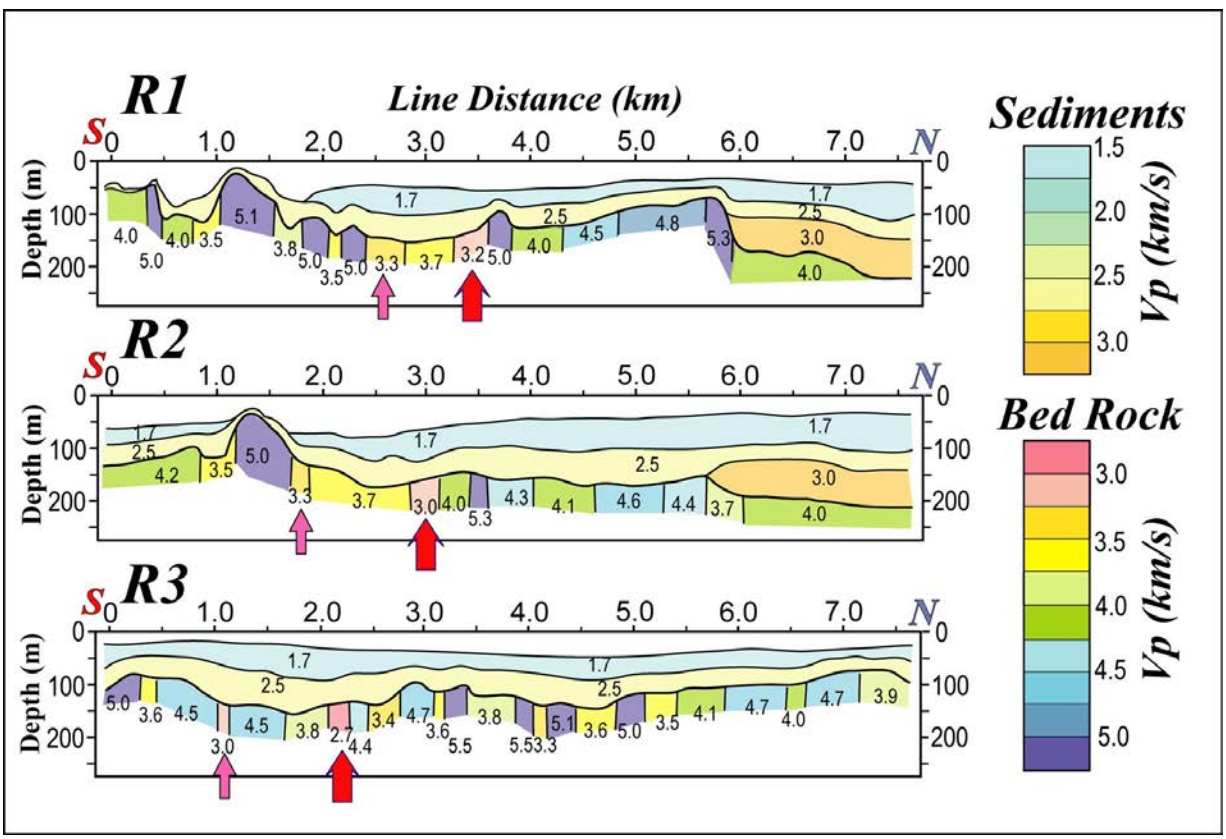

Fig. 5. Velocity structures along the offshore refraction survey line; R1, R2, and R3. Distinctive pairs of low velocity zones (marked with arrows) in the bedrock are interpreted at the northern shoulder of the bedrock rise as the fractured zones associated with MTL.

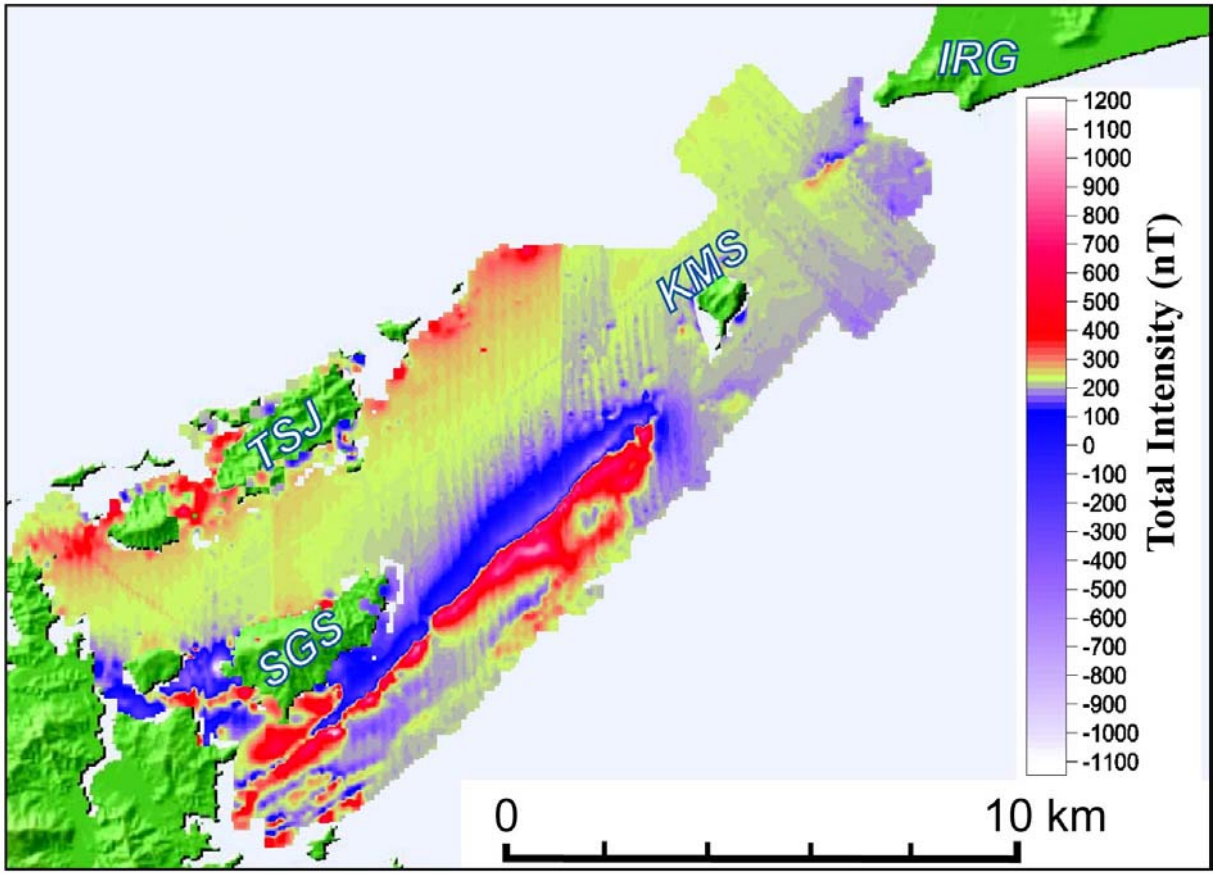

Fig. 6. Total intensity magnetic anomaly map of the Ise Bay Mouth Area. A linear magnetic anomaly occurs between KMS (Kami-shima Islet) and SGS (Suga-shima Island) in parallel with the island chain. The large magnetic anomaly suggests that serpentinite is present along a tectonic boundary.

NE-SW direction, which is concordant with the strikes of the TKIF and GATL. This linear shaped strong magnetic anomaly indicates that high magnetic rocks are present along the TKIF or GATL. Just on the magnetic anomaly, serpentinite was dredged. The bulk chemical analysis revealed that the dredged serpentinite belongs to the GATL.

Logging in Boreholes

Integrated logging was carried out in the offshore boreholes but also in the ground boreholes. The suspension P-S logging and sonic log were applied to obtain P and S-wave velocities, which are useful to evaluate physical properties of the bedrock. Density and electrical logging were also performed for fracture characterization.

Figure 7 exemplifies composite logs in Borehole A (see Fig.3). The log profiles of the hole indicate that the uppermost part about 13 meters from the sea bed is strongly fractured. Anomalies are present at 52 m and 86 m where the significant change in log curves is identified, especially in the caliper and density curve. Both P- and S-wave velocities decrease at these portions, whereas the anomaly in velocity profiles at 27 m is inconsistent with other log data, which suggests mis-picking of the first breaks.

SUMMARY

To fulfill geological and geophysical surveying efficiently for the Ise Bay Mouth Highway Project, we have

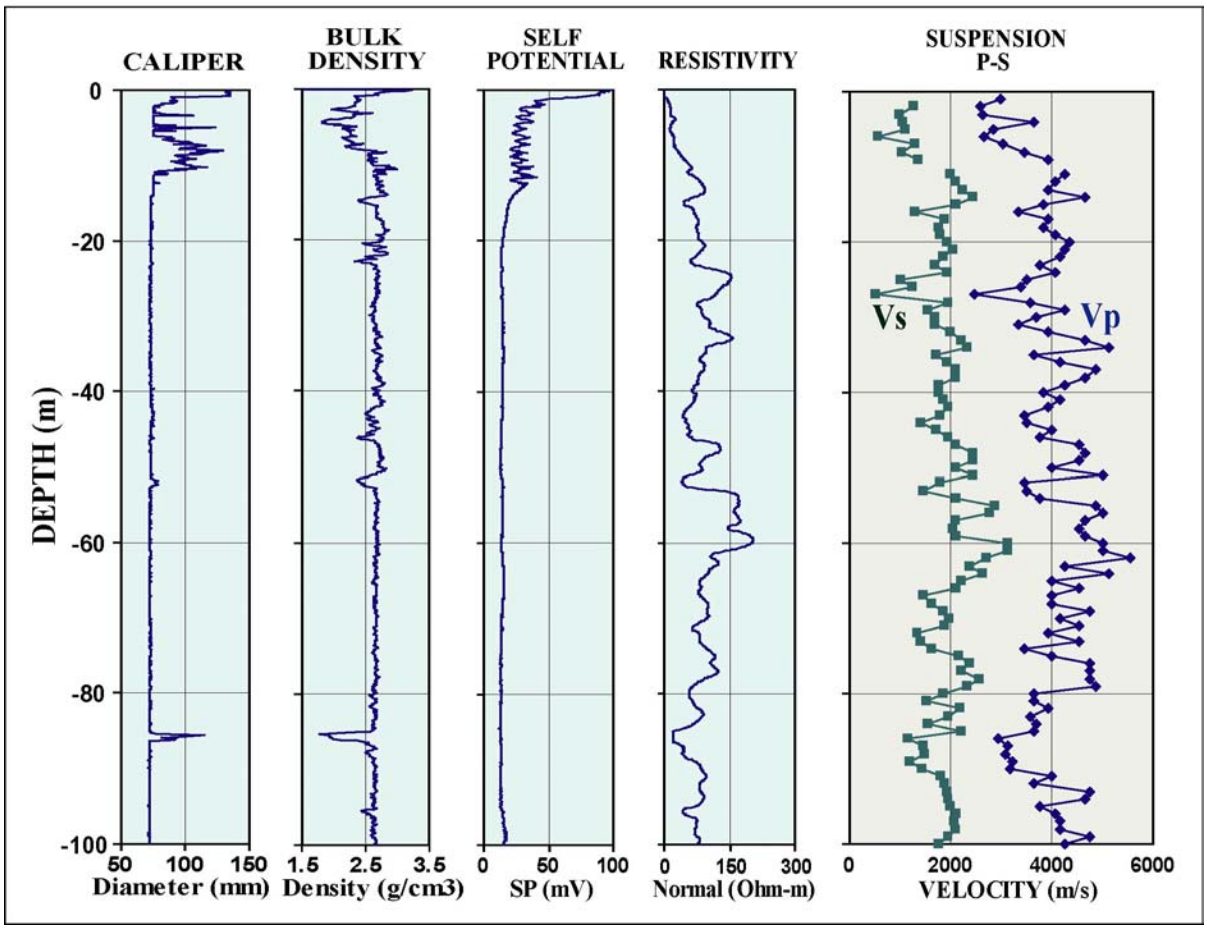

Fig. 7. Composite log profiles of the offshore borehole A. The log curves show the upper part about 13 meters is strongly fractured, which indicates the portion is inadequate as the foundation rock.

not only designed and managed the surveys but also conducted surveying by ourselves as the professional geologists and geophysicist. The survey results were comprehensively interpreted and used for the geological and geotechnical site characterization. The representative contributions of the geophysical surveys are as follows.

First, the reflection survey strongly indicated the supposed IBMF is not present in the mouth

Fig. 8. A view image of an ultra-long spanned bridge planned to cross over the main straight of the Ise Bay.

of Ise Bay. As a result, seismic risk of the supposed IBMF is evaluated as negligibly low. Second, the reflection and refraction surveys revealed the location and structure of the MTL. The information was utilized to locate offshore route and to design the main facilities. Third, the shipborne magnetic survey delineated a linear shaped unexplored serpentinite block. The survey result helped to interpret the tectonic setting of the surveyed area but also provided important geological information for the constraint of foundation design and offshore route.

Consequently, cooperative investigation of geology and geophysics, well designed surveying, and comprehensive management of geophysical survey from planning to the interpretation are essential for the large scaled highway project that takes two or three decades for the construction.

Figure 8 is a view image of an ultra-long spanned bridge planned as the main facilities to cross the main strait between IRG and KMS. A cable-stayed bridge over 4,000 m in total length with a center span of 2,240 m will be the longest bridge of its type in the world when completed.

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