Investigation of sediment environments in closed water body using RI-density Log

Investigation environnementale des sédiments dans une nappe d'eau fermée au moyen du log de densité à RI

T. Umezaki, T. Kawamura

Department of Civil Engineering, Shinshu University, Nagano, Japan

M. Yoshimura

Soil and Rock Engineering Co., Ltd., Osaka, Japan

ABSTRACT

A new technique using a radioisotope (RI) density log with gamma rays is proposed for investigation of sediment environments. A series of field investigations was carried out by penetrating an RI cone probe by its own weight from a small boat. Main conclusions are obtained as follows: The wet density of sediments comprising suspension, fluid mud, and bed mud can be measured with sufficient accuracy using an RI-density log. The lower limit of water, which is the sediment surface, is definable based on a pore water pressure distribution obtained from a cone penetration test.

RÉSUMÉ

Une nouvelle technologie du log de densité à radio-isotope (RI) type pénétration sous l'effet de son propre poids mettant en usage les rayons gamma se propose pour l'investigation environnementale des sédiments dans une nappe d'eau fermée. Une série d'investigations ont donné les résultats suivants: les densités humides de sédiments comprenant la suspension, des boues fluides et des boues de fond, sont mesurées avec précision au moyen du log de densité à RI proposé. La limite inférieure d'eau qui est la surface des sédiments peut être définie sur la base de la distribution des pressions d'eau obtenue par les essais de pénétration de cône.

Keywords: site investigation, radioisotope, density log, sediment environment, echo sounder

1 INTRODUCTION

Suspended fine silt and clay particles settle on the bottoms of seas, lakes, and other bodies of water. Fluid mud and bed mud subsequently form deposits, which often include hazardous materials such as organic matter and heavy metals that engender serious environmental damage. The thickness of deposits differs among points. Therefore, it is difficult to estimate their volume theoretically. In order to consider influence of the materials on ecosystem or water quality purification, it is effective to evaluate sediment environments such as the amount or speed of deposition and seasonal change of sediments. Since sediments are usually dredged and discarded to disposal pond, investigation of sediment environments is effective also in dredging efficiently.

As described in this paper, a new investigation technique on sediment environments using a radioisotope (RI) density log with gamma rays is proposed as presented in Fig. 1. Using this technique that an RI cone probe is penetrated by its own weight, in-situ investigations can be conducted easily for wide areas. A series of field investigations was carried out in an inland lake, Lake Suwa, and a bay, the Ariake Sea (Fig. 2). The method's applicability and effectiveness were examined.

2 INVESTIGATION OF SEDIMENT ENVIRONMENTS

2.1 *New technique using RI-density log by self-weight penetration*

Shibata et al. have developed RI-cone penetrometers of two kinds: a nuclear density cone and a neutron moisture cone (Shibata et al., 1994). The level of sealed radiation sources in these cones is less than levels subjected to legal regulation in Japan. The authors carried out transmitted type RI density log with gamma rays during a series of sedimentation tests in the laboratory. The results show that the value of the wet density (ρ_t) with a wide range of 1.0–1.3 g/cm^3 can be measured with high accuracy during condition changing from suspension to sedimentation (Umezaki et al., 2006). Since sediments are very soft, investigation could be carried out by penetrating an RI cone probe with a sinker by its own weight. Especially this technique is very useful for fluid mud which cannot be sampled easily. Figure 1 shows an outline of the proposed investigation of sediment environments using an RI-density log (RI-DL). An RI cone probe (Fig. 1) is hung by a wire from a small boat. It descends through the water at a specified rate and then penetrates into the sediment by its own weight. The RI cone

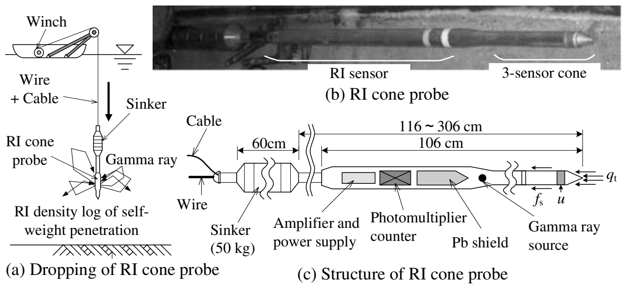

Figure 1. New technique of sediment environments using RI-density log

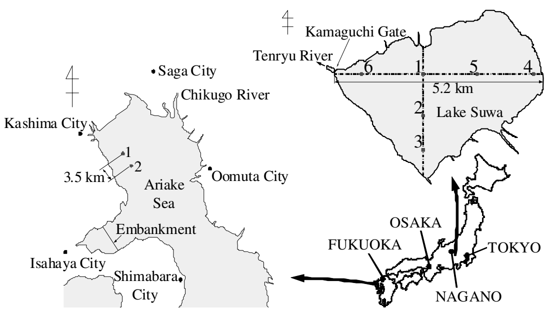

Figure 2. Locations of investigation sites

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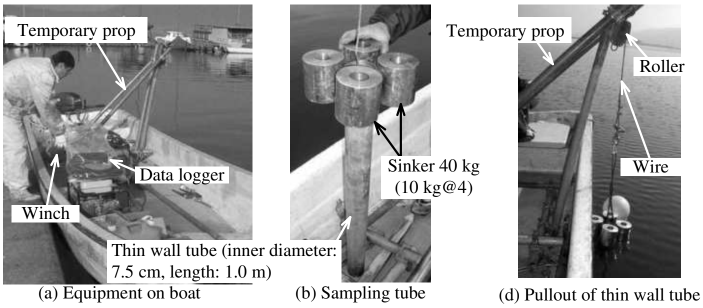


Figure 3. Investigation of sediment environments in Lake Suwa

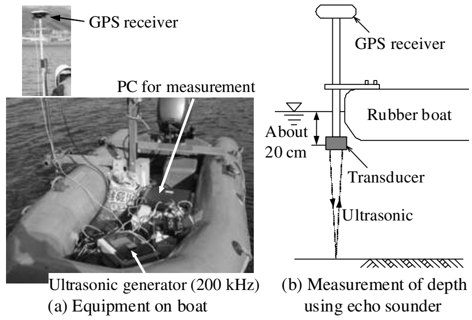


Figure 4. Bathymetry in Lake Suwa

probe comprises a three-sensor cone penetrometer and a scattering type RI sensor (Fig. 1(b)). In-depth profiles of ρ_t and natural gamma ray dosage (BG) are obtainable using RI-DL. In-depth profiles of cone resistance (q_t), skin friction (f_s), and pore water pressure (u) are obtainable simultaneously.

2.2 *Investigation in Lake Suwa*

Although Lake Suwa (Fig. 2) has 31 inflow rivers, it has only 1 outflowing river and it is a typical closed water body. This investigation was conducted at six points in Lake Suwa on 28 November 2005 (Fig. 2). The RI cone probe was dropped at a speed of about 10 cm/s from a small board on which was constructed a temporary prop (Figs. 1 and 3). It then penetrated into the lake bottom. The cone penetration test (CPT) and RI-DL were then carried out. Soil sampling was performed by self-weight penetration of a thin wall tube with a sinker. The water depth was measured using a portable echo sounder with 200 kHz frequency. In the laboratory after the field investigation, the water content w and ρ_t were measured at a fixed depth by pushing a sample from the tube.

Figure 4 shows that bathymetry using echo sounder for 19 survey lines was done on 30 November – 11 December 2005 (Nagano Prefecture 2006). It was performed using a rubber boat moving at about 10 km/h. A 200 kHz ultrasonic wave was sent to the lake bottom with a transducer installed at about 20 cm under the water surface, and then the reflective wave was received as shown in Fig. 4(b). The position data were recorded simultaneously using differential global positioning system (D-GPS).

2.3 *Investigation in the Ariake Sea*

The Ariake Sea (Fig. 2) is long in the north–south direction and it is an inner bay of 1700 km^2 area. Investigation of sediment environments using CPT, RI-DL, and ultrasonic exploration (USE) was done from a small boat on 23 November 2005. A diver performed sampling by pushing a thin walled tube into the seabed. Two investigation points are presented in Fig. 2. Only CPT and RI-DL were done at No. 2. Then CPT and RI-DL were performed using simple equipment with a winch, called a net roller, installed on the small boat (Fig. 5). The RI cone probe, hung from the wire, was dropped at the rate of 2 cm/s and it penetrated into the seabed. In USE, an ultrasonic wave generated on the boat was transmitted towards the seabed through a transmission/reception device installed underwater. A reflective wave was received. Two devices for 200 kHz and 24 kHz were used. The ultrasonic frequency was reflected by the apparent density 1.14 of and 1.27 g/cm^3, respectively, which are nominal values (Marui Co., Ltd. & Kaijo Corp.). Depths of the peak values of the obtained reflective strength were determined as depths corresponding to those densities according to the instruction manual. Position data of the investigation point were obtained from the GPS receiver.

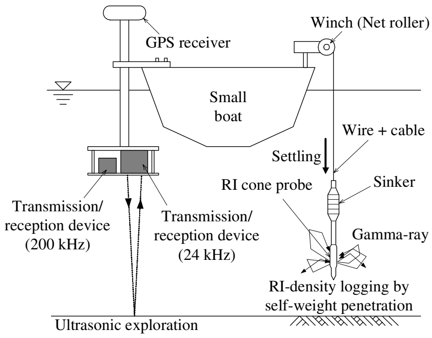
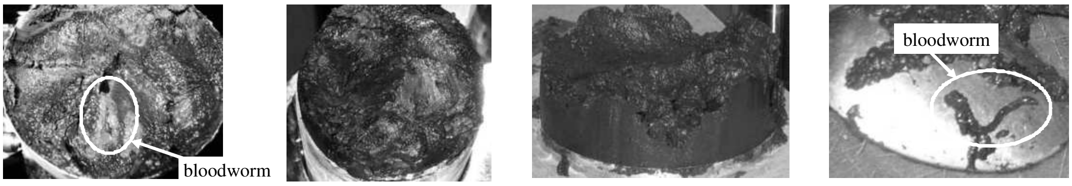


Figure 5. Investigation of sediment environments in the Ariake Sea

3 RESULTS AND DISCUSSION

Photo 1 shows the sample condition at depth z at Lake Suwa site No. 1. Presuming the upper end of the sample as the lake bottom, a sample with depth of z= 53.5 cm was obtained. The sample color changes with depth. Near the lake bottom surface, sediments are brown. Shallower than z=18.5 cm, black and ocher sediments were mixed (Photos 1(a) and 1(b)). Bloodworms were considered to live in holes there (Photos 1(a) and 1(d)). Those holes supply oxygen to the sediment, oxidizing it. Therefore, the sediment color differs. In parts deeper than z=18.5 cm, sediments were uniformly black (Photo 1(c)).

Figures 6 and 7 show summary results of CPT and RI-DL, respectively, in Lake Suwa No. 1 and the Ariake Sea No. 1. Where σ_{v0} is the total vertical stress, u_0 is the hydrostatic pressure, ρ_d is dry density, ρ_m is the unit water weight, and w_n is the natural water content. The fluctuation of q_t, f_s, and u distributions in Ariake Sea No. 1 is attributable to rocking of the boat during investigation. The depth at which u changes from the u_0 distribution is defined as the lower limit of water, which is the sediment surface, and the depth to the surface is the water depth (h_w). However, Fig. 6(c) shows the cause of negative excess pore water pressure at u distributions deeper than the sediment surface in Lake Suwa No. 1, since the penetration was too quick. At Ariake Sea No. 1 shown in Fig. 7(c), positive excess pore water pressure occurred with penetration at 2 cm/s. The depth distribution of ρ_t increases from about 10–30 cm higher than the depth of the sediment surface, this section is considered to be in a condition of suspension and fluid mud. Although the classification of fluid mud and bed mud is not defined exactly, when the sediment surface judged by u distribution is defined as the boundary surface, the wet density on this surface is ρ_t=1.14 g/cm^3 at Lake Suwa No. 1 and ρ_t=1.06 g/cm^3 at Ariake Sea No. 1. Figure 6(f) shows that, assuming a degree of saturation Sr=100%, the values of w_n calculated based on the result of RI-DL change greatly by ρ_s. Actually, the bed mud might contain organic matter. Consequently, the value of the sediment particle density (ρ_s) might differ greatly within approximately ρ_s=1.7–2.7 g/cm^3. For that reason, the determination of ρ_s at each depth is important.



(a)z=9.5 cm (b)z=18.5 cm (c)z=25.5 cm (d) bloodworm (z=25.5 cm)

Photo 1 Soil sample condition (Lake Suwa No. 1)

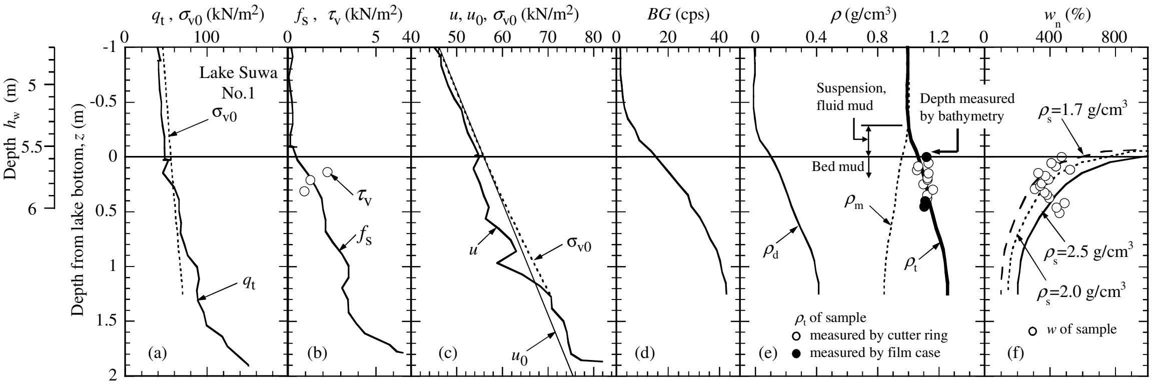


Figure 6. Results of RI-DL, CPT, (Lake Suwa No. 1)

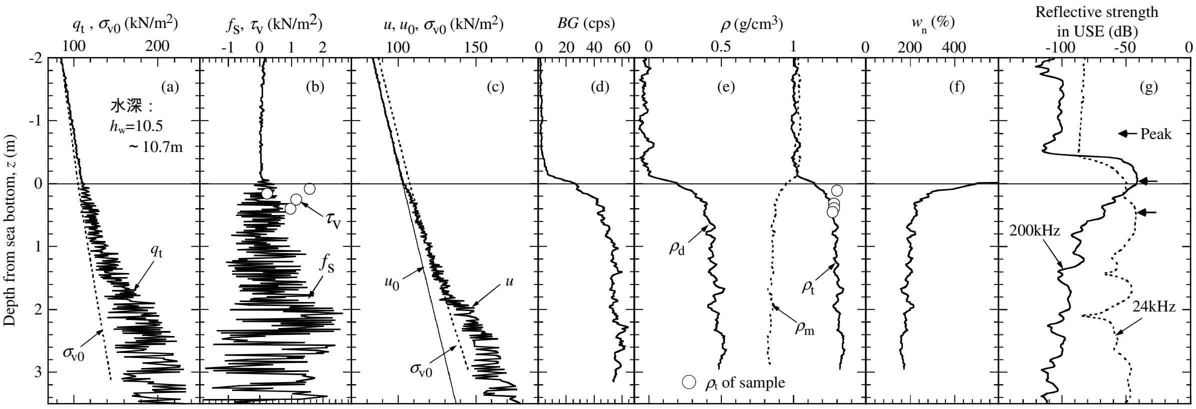


Figure 7. Results of RI-DL, CPT, (the Ariake Sea No. 1)

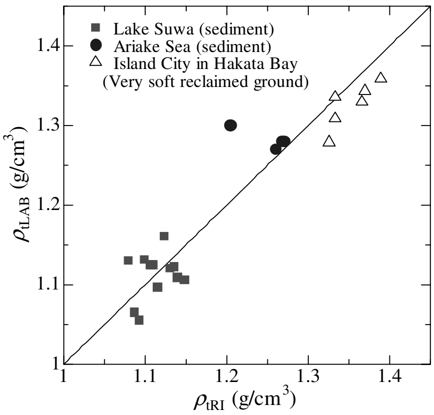


Figure 8. Comparison of wet density

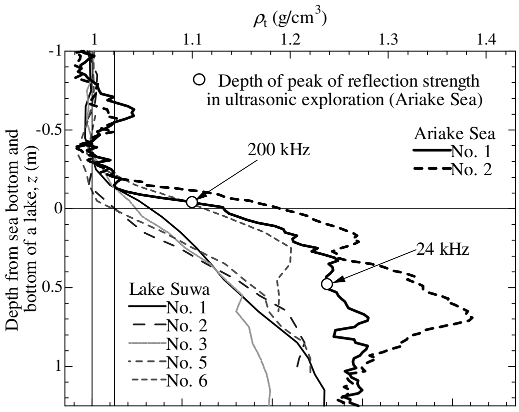


Figure 9. Distribution of wet density around bottom of water

Figure 8 shows a comparison of ρ_t obtained from RI-DL, ρ_{tRI}, and laboratory tests, ρ_{tLAB}. In this figure, data of an RI cone penetration test carried out at Island City under reclamation, which is very soft reclaimed ground in the Hakata Bay, Fukuoka City, are also shown (Umezaki et al. 2003). The values obtained from RI-DL have sufficient compatibility for a wide range, thus the feasibility of RI-DL is confirmed also in-situ test.

Figure 9 shows a zoomed image of ρ_t distribution near the sediment surface. At Lake Suwa No. 5, one part is smaller than the density of fresh water (ρ_w=1.00 g/cm^3). Moreover, the densities of the seawater section in Ariake Sea Nos. 1 and 2 vary ρ_t= 0.985–1.045 g/cm^3 and they differ from the seawater density of ρ_w= 1.025 g/cm^3. In clear water, the value of ρ_t differs because of disintegration of radiation sources, which is peculiar to RI. The values of ρ_t in the sediment surface (z=0 m) estimated from u distribution are ρ_t =1.02–1.13 g/cm^3 in Lake Suwa and ρ_t =1.14 and 1.21 g/cm^3 in the Ariake Sea. The thickness of suspension and fluid mud is 10–30 cm. Consequently, the values of ρ_t of the sediment surface (boundary surface of fluid mud and bed mud) and thickness of fluid mud differ among locations. In this figure, O marks signify ρ_t obtained from RI-DL at depth corresponding to the peak value of the reflective strength of USE at Ariake Sea No. 1.

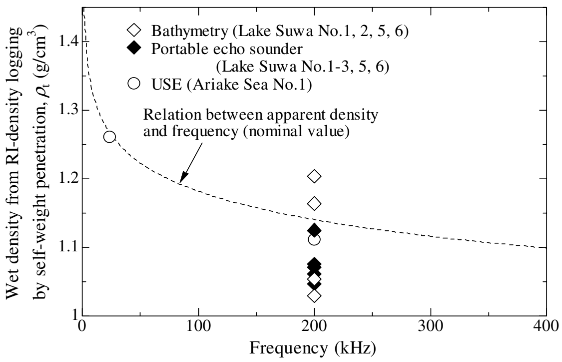


Figure 10 Compatibility of frequency and wet density (Lake Suwa Nos. 1–3, 5, 6 and Ariake Sea Nos. 1 and 2)

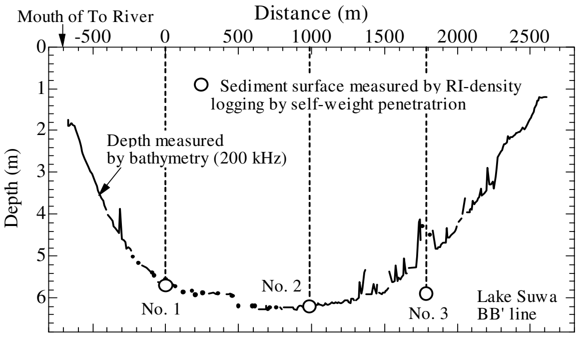


Figure 11. Typical bathymetry results

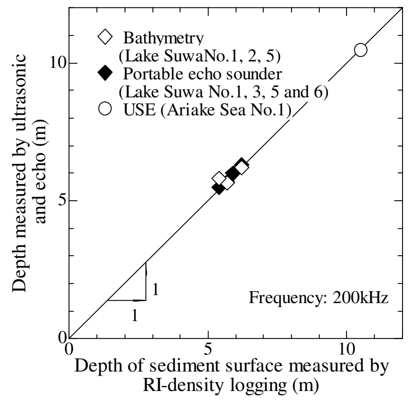


Figure 12. Comparison of depth of sediment surface

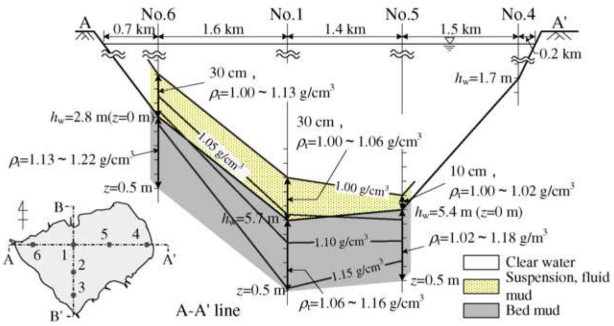


Figure 13. An example of deposition situation

The depth with ultrasonic frequency of 200 kHz is 4 cm above the sediment surface, as estimated by the *u* distribution.

Figure 10 shows the relation between ultrasonic frequency and ρ_t obtained from RI-DL. This figure also shows the relation between the apparent density and ultrasonic frequency (nominal value). If the errors of position data are disregarded and only the error of bathymetry is considered, the range of ρ_t corresponding to the frequency of 200 kHz is 1.03–1.21 g/cm^3. The values of ρ_t of 200 kHz differ in every location and no unique relation is observed between frequency and ρ_t.

Figure 11 shows a typical bathymetry result. At No. 3, because depth data obtained from bathymetry were missing for about 100 m, this point was excepted from consideration.

Figure 12 shows a comparison between the water depth measured using 200 kHz ultrasonic wave, h_{US}, and the water depth on the sediment surface measured using RI-DL, h_{RI}. Their difference, h_{RI}-h_{US}, is 4 cm at Lake Suwa No. 1, is -2 cm at No. 2, is -43 cm at No. 5, and is 4 cm in the Ariake Sea No. 1. For the portable echo sounder, h_{RI}-h_{US} is 0 cm at Lake Suwa No. 1, and -10 cm at No. 2, No. 3, and No. 5. Therefore, the water depth measured using the 200 kHz ultrasonic wave is interpreted as the depth of the sediment surface at which the sediment structure is fully developed in the lower part of the fluid mud layer. The USE and bathymetry are effective as investigations for elucidating long-term changes of the bed mud deposition situation.

Figure 13 shows an example of the deposition condition of suspension, fluid mud, and bed mud obtained from the ρ_t distribution. A line showing equal density is also presented. By carrying out RI-DL more widely, detailed sediment environments can be understood. In the dredged region, the dredge sediment amount was estimated quickly and easily. Moreover, the change was understood using periodic surveys.

4 CONCLUSIONS

Main conclusions from results of this study are the following.

(1) RI-density logging by self-weight penetration can be conducted rapidly and easily from a small boat.

(2) Wet densities of sediments comprising suspension, fluid mud, and bed mud can be measured with sufficient accuracy using the RI-density log.

(3) The lower limit of water, which is the sediment surface, is definable based on a pore water pressure distribution obtained from the cone penetration test. Therefore, fluid mud and bed mud are classifiable. The values of density at the boundary surface of fluid mud and bed mud obtained using the proposed method differ among locations. Bed mud and fluid mud are not classifiable according to their wet density.

(4) The values of wet density at the sediment surface, measured using both bathymetry and ultrasonic exploration at 200 kHz, are not constant. The measured depth is interpreted as the top surface of bottom sediment at which the sediment structure is fully developed in the lower part of the fluid mud layer.

(5) Outline of long-term changes in bottom sediment conditions can be estimated by bathymetry using an echo sounder of 200 kHz.

(6) RI-density logging by self-weight penetration is effective for detailed investigation of short-term changes of the conditions of suspension, fluid mud, and bed mud, all of which affect the water quality.

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