Juan Lorenzo · William Doll *Editors*

Levees and Dams

Advances in Geophysical Monitoring and Characterization

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Introduction

Only a third of the world's great rivers remain free-flowing—just 90 of the 246 rivers more than 1000-km-long flow without interruption. The world's rivers are interrupted by dams and levees, which constitute critical components of the infrastructures of most nations in the world. They serve indispensable functions—irrigation, water supply, flood control, electric generation, and recreation. Safe operation and maintenance of dams and levees are crucial for both sustaining these functions, and avoiding potential disaster and loss of life. Moreover, a substantial number of dams and levees in many countries are nearing the end of their life spans—requiring close monitoring of their structural safety.

Storm surge barriers of the Netherlands and New Orleans are two of the most extreme engineering works in the world. Much of the landmass of the Netherlands has been reclaimed from the North Sea by levees and dams built over the past two thousand years. The Delta Works in the Netherlands is the largest flood protection project in the world. This project consists of 13 surge barriers. The Oosterscheldekering is the largest surge barrier in the world—9 km long. The dam is based on 65 concrete pillars with 62 steel doors, each 42 m wide. It is designed to protect the Netherlands from flooding from the North Sea. The Maeslantkering is a storm barrier with two movable arms—when the arms are open, the waterway remains an important shipping route and when the arms close, a protective storm barrier is formed for the city of Rotterdam. Closing the arms of the barrier is completely automated without human intervention.

The Great Wall of Louisiana is a storm surge barrier constructed near the confluence of and across the Gulf Intracoastal Waterway and the Mississippi River Gulf Outlet near New Orleans. The barrier runs generally north–south from a point east of Michoud Canal to the Bayou Bienvenue flood-control structure. Navigation gates on the barrier reduce the risk of storm surge coming from Lake Borgne and the Gulf of Mexico.

Every four years, the American Society of Civil Engineers (ASCE) issues a report card for the American infrastructure. The report card depicts the condition and performance of American infrastructure in the familiar form of a school report card—assigning letter grades based on the physical condition and needed investments for improvement. The 2017 ASCE grade for levees and dams is D—a cause for concern and a call for action. The nationwide network of levees in the USA is more than 30,000 miles. As development continues to extend into floodplains along rivers and coastal areas, an estimated $80 billion is needed in the next 10 years to maintain and improve the nation's system of levees. There exist more than 90,000 dams in the country with an average age of 56 years. With an increase in population and thus development, the overall number of high-hazard potential dams has increased—with the number climbing to nearly 15,500 in 2016. It is estimated that it will require an investment of nearly $45 billion to repair aging, high-hazard potential dams.

Geophysical methods are indispensable to characterize the near-surface formation prior to planning and design of dams and levees, and monitoring their structural integrity during their lifetime. This volume is devoted to case studies for investigation of seepage risk and monitoring structural safety of dams and levees. In recent years, various types of fiber-optic sensors have enabled accurate and efficient structural monitoring in civil and geotechnical engineering. The fiber-optic technology is especially suitable for monitoring large or elongated structures, such as dams, dikes, levees, bridges, and pipelines.

The first chapter in this volume, entitled "Statistical Estimation of Soil Parameters in from Cross-Plots of S-Wave Velocity and Resistivity Obtained by Integrated Geophysical Method" by Hayashi et al., describes the application of an integrated geophysical and geotechnical borehole data analysis to derive cross-plots of S-wave velocity and resistivity and various geotechnical parameters for Japanese levees. Cumulative length of the geophysical survey line traverses is nearly 670 km on 40 rivers in Japan. The geotechnical borehole data were collected from about 400 boreholes located along the geophysical survey line traverses.

The second chapter in this volume, entitled "Application of Seismic Refraction and Electrical Resistivity Cross-Plot Analysis: A Case Study at Francis Levee Site" by Wodajo et al., describes a case study to assess the integrity of earthen embankment at the site affected by sand boil formations during the 2011 Mississippi River flood event. Results from seismic refraction and electrical resistivity surveys conducted at the Francis Levee site indicate seven distinct anomalies that might be associated with seepage. Specifically, using the seismic velocity and electrical resistivity values of the anomalies on the waterside as limiting values, a cross-plot analysis was performed to identify similar anomalies on the landside. The results indicate that preferential flow occurs within the sand layer in an old oxbow.

The third chapter in this volume, entitled "A Borehole Seismic Reflection Survey in Support of Seepage Surveillance at the Abutment of a Large Embankment Dam" by Butler et al., describes installation of a modern monitoring instrumentation at the Mactaquac Generating Station, a 660-MW hydroelectric facility located on the Saint John River—approximately 20 km upriver from Fredericton, New Brunswick, Canada. The objective of this study was to confirm the location of the steeply inclined interface between an embankment dam and a concrete diversion sluiceway as accurately as possible for installing seepage monitoring instrumentation. Specifically, installation of a fiber-optic distributed temperature sensing (DTS) cable as close as possible to the sub-vertical contact between the concrete diversion sluiceway and the clay till the core of the adjacent zoned embankment dam required an accurate knowledge of the dam's internal structure. Because of lack of detailed as-built drawings, a seismic reflection survey was conducted along a sub-parallel borehole, offset by approximately 1 m at the surface and by an estimated 4 m at the dam's foundation at a depth of 50 m. A wall-locking seismic tool with eight receivers was used in two different orientations to capture P- and S-wave reflections from the concrete–clay interface. Based on the S-wave image, which helped delineate the concrete–clay interface, two 50-m-long boreholes for seepage monitoring instrumentation was installed within an estimated 50 cm of the interface.

The fourth chapter in this volume, entitled "Self-potential Imaging of Seepage in an Embankment Dam" by Bouchedda et al., describes a case study to investigate seepage in Les Cèdres embankment dam in Valleyfield, Canada, by integrating self-potential tomography (SPT), electrical resistance tomography (ERT), thermometry, electromagnetic (EM) conductivity, and magnetic measurements. SPT consists of inverting self-potential data to retrieve the source-current density distribution associated with water flow pathways in embankment dams. The embankment dam is used to channel water from the Saint Lawrence River to a hydroelectric plant. The SPT inversion utilizes the resistivity model of the dam, which is obtained by ERT. EM conductivity maps allowed identifying two linear anomalies caused by metal-shielded electrical cables. The magnetic survey shows an important anomaly zone that is probably related to a metallic object. The SPT shows a few seepage locations on the upstream dam side at a depth interval of 4–5 m. Two of these seepages were confirmed by geotechnical testing. All observable seepage outlets on the downstream side can be related to the SPT anomalies and are observed as conductive zones in the resistivity model.

The fifth chapter in this volume, entitled "Optical Fiber Sensors for Dam and Levee Monitoring and Damage Detection" by Inaudi, describes the use of optical fiber sensors for monitoring dams and levees to detect damaged locations. Case studies for the surveys with various types of optical fiber sensors include (1) a water reservoir in Spain with plastic membrane to detect leaks through the membrane and the perimeter levee; (2) Nam Gum rockfill dam in Laos with concrete face where to detect leaks through the concrete plinth; (3) Luzzone concrete arch dam in Switzerland to monitor temperature evolution during concrete setting; (4) some levees in Louisiana to monitor movements between wall panels to detect anomalies and impending panel failure; (5) an earthen levee in the Netherlands to detect early signs of levee failure; (6) a river dam in Latvia with a hydropower plant to detect leaks across bitumen joints; (7) sinkholes affecting rail and road structures in Kansas to detect impending sinkhole formation; (8) embankment dam with clay core in Spain to monitor deformation of the clay core; (9) Val de la Mare reservoir in Jersey Island with mass concrete dam wall to monitor deformations induced by alkali silica reaction in concrete; and (10) El Mauro mining tailing dam in Chile to monitor long-term deformations and pore pressure.

The sixth chapter in this volume, entitled "Application of the Helicopter Frequency Domain Electromagnetic Method for Levee Characterization" by Smiarowski et al., presents two case studies using a HEM system for levee characterization and hazard detection at Retamal Levy, Rio Grande Valley in Texas and the flood-control levees of Sacramento Valley in California. Airborne remote sensing systems, such as HEM, can be deployed to survey large areas required by levee characterization. The HEM involves towing an electromagnetic transmitter and receiver that measure signals proportional to the electrical conductivity of the ground. The HEM provides electrical conductivity information about the earth from about the top 1 to 100 m below surface. Data are typically transformed to apparent conductivity, which removes variations in system altitude and allows easier interpretation of ground material. For levee characterization, the HEM-derived conductivity mapped in 3D gives an indication of the geometry of sand channels and clay layers. In one of the case studies presented, the HEM data enabled detection of sandy channels and delineation of their spatial extent, including old oxbows and buried river channels that provide seepage pathways under the levee, which may cause sand boils or levee collapse from foundation erosion. In the second case study, high-resistivity values from the HEM data indicated dry, sandy conditions, and led to the discovery of significant cracking in the levee due to desiccation of the levee material.

Given the fact that levees and dams serve indispensable functions, including irrigation, water supply, flood control, electric generation, and recreation, safe operation and maintenance of dams and levees are crucial for both sustaining these functions and avoiding potential disaster and loss of life. The papers included in this volume demonstrate the successful application of geophysical methods to monitor the structural safety of levees and dams.

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Öz Yilmaz

Contents

Statistical Estimation of Soil Parameters in from Cross-Plots of S-Wave Velocity and Resistivity Obtained by Integrated Geophysical Method

Koichi Hayashi, Tomio Inazaki, Kaoru Kitao and Takaho Kita

Abstract Cross-plots of S-wave velocity and resistivity obtained by geophysical methods statistically estimated geotechnical soil parameters, *Fc*, *D20*, blow counts, and the soil types, of levee body and foundation for Japanese levees. The S-wave velocity and the resistivity were collected from surface wave methods and resistivity methods respectively. Total survey line length of the geophysical methods was about 670 km on 40 rivers in Japan. The *Fc*, *D20*, blow counts, and soil types were collected from about 400 boring logs carried out on geophysical survey lines. S-wave velocity and resistivity at the depth of the blow counts were extracted from two-dimensional geophysical sections. The total number of extracted data, blow counts and soil type, was about 4000. The data was grouped by levee body and foundation. A polynomial approximation estimated the soil parameters from S-wave velocity and resistivity. A least squares method optimized the coefficients of the equation. Accuracy of the estimation was statistically evaluated by comparing estimated and actual soil parameters. The correlation coefficients between estimated and actual parameters ranged between 0.43 and 0.8. The polynomial approximations with the optimized coefficients calculated soil parameters sections from S-wave velocity and resistivity sections.

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Introduction

Conventional levee assessments use invasive borings which provide useful and detailed information of levees. However, borings are expensive and cannot provide continuous information along a levee in heterogeneous environments. Non-invasive, rapid and spatially continuous investigation methods are needed to supplement traditional investigation techniques. Many researchers have been trying to apply geophysical methods to levee investigations (e.g. Dunbar et al. 2007). Surface wave methods (e.g. Ivanov et al. 2006) and resistivity methods (Liechty 2010) are often applied to such investigations because S-wave velocity and resistivity obtained by these methods are very valuable to estimate the soil condition of levees.

Both S-wave velocity and resistivity, however, reflect many physical properties and do not directly relate to engineering soil parameters such as cohesion, internal friction angle, grain size distribution, and permeability. We proposed an integrated geophysical method (Hayashi et al. 2009; Inazaki et al. 2009) to evaluate levee soil condition quantitatively. The proposed method mainly consists of the surface wave method using a land streamer and the resistivity method using capacitively-coupled resistivity equipment. The cross-plots of the S-wave velocity and the resistivity estimate the soil condition of levees in the method.

Geotechnical soil parameters, such as soil type (clay, sand or gravel), fine fraction content (*Fc*) and grain size (*D20*: diameter at which 20% of the sample's mass is comprised of particles with a diameter less than this value), are particularly important information for levee safety evaluation from an engineering point of view. Many engineering analysis methods such as slope stability, seepage flow, subsidence and liquefaction analyses use these soil parameters. In these types of analyses, the soil parameters are obtained by borings and laboratory tests. Geophysical properties obtained through the geophysical methods, such as S-wave velocity and resistivity, do not directly relate to the soil parameters. For that reason, geophysical methods have not been widely used for levee safety assessment. Several researchers have been trying to theoretically estimate the soil parameters from the geophysical properties in terms of a rock physics theory that is increasing in popularity in oil and gas exploration (Konishi 2014). In this paper, we estimate the geotechnical soil parameters, *Fc*, *D20*, blow counts, and the soil type, in terms of a statistical approach using geophysical and geotechnical data collected from a Japanese levee. The collected data in this study will play an important role in the theoretical study as well.

This paper summarizes the integrated geophysical method, introduces a database storing the results of geophysical investigation, borings logs, and laboratory characterization of samples from the boring logs, describes a statistical estimation of soil parameters using cross-plot analysis of S-wave velocity and resistivity, and shows an application example at a Japanese levee.

S-Wave Velocity and Resistivity in Levee Investigation

Seepage and erosion, shear strength and soil types are examples of primarily important factors that must be used to evaluate the safety of levees. We will review the relationship between geophysical properties (S-wave velocity and resistivity) and geotechnical soil parameters (shear strength and soil types) in this section.

S-wave velocity is directly related to shear modulus which is particularly important to levee assessment. Small strain shear modulus (G_0) is a function of the S-wave velocity (V_S), according to:

$$G_0 = V_S^2 D \tag{1}$$

where, D is material density. It is well known that the S-wave velocity is mainly affected by shear stiffness or porosity. A considerable number of studies have been made on the correlation between the S-wave velocity and shear strength (e.g. Imai and Tonouchi 1982). Figure 1 shows a correlation between S-wave velocity and N-value (blow counts) obtained from standard penetration tests (SPT : JIS 2005) at many Japanese levees with soil classification. S-wave velocities in Fig. 1 were obtained by a surface wave method performed on the levee surface. The black line in Fig. 1 is a regression line obtained by the least squares method. It is clear that the N-value increases as the S-wave velocity increases although there is large scatter.

Resistivity is a function of many physical properties such as porosity, pore fluid resistivity, water saturation, and grain size distribution. The conductivity (inverse of resistivity) of a porous medium is expressed by an equation as follows (Imamura et al. 2007):

$$\sigma_R = \frac{1}{a} \cdot \phi^m \cdot S^n \cdot \sigma_W + \sigma_C \tag{2}$$

where, σ_R is conductivity of medium, σ_W is pore fluid conductivity, σ_C is conductivity due to clay minerals, ϕ is porosity, S is water saturation, a, m and n are constants. The first term on the right-hand side of Eq. (2) is known as Archie's equation and if fluid resistivity and water saturation are constant, resistivity is a function of porosity and resistivity decreases as porosity increases. A second term on the right-hand of Eq. (2) is the effect of clay minerals included in soils. It is well known that the effect of the second term cannot be neglected and may be dominant in saturated clayey unconsolidated soils. We may, therefore, reasonably conclude that the resistivity of soils mainly correlates to soil type. Figure 2 shows the example of correlation between resistivity and effective grain size (*D20*). Although there is large scatter, we can see that grain size increases and soil type is changing from clay to sand and gravel as resistivity increases.

Figure 3 (left) shows a schematic relationship between S-wave velocity and resistivity. The S-wave velocity indicates shear stiffness or degree of compaction and resistivity indicates soil type as mentioned above. Figure 3 (right) shows a schematic relationship between geophysical properties, S-wave velocity and resistivity, and the

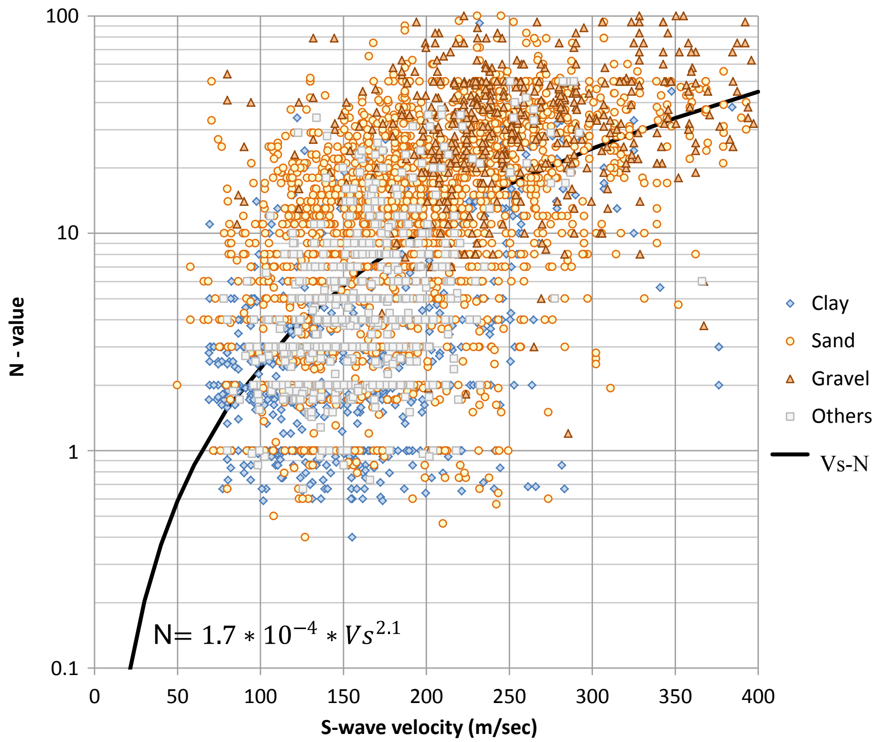

Fig. 1 Correlation between S-wave velocity and N-value obtained from standard penetration tests at many Japanese levees with soil classification. S-wave velocities were obtained by a surface wave method performed on the levee surface. The black line is a regression line obtained by the least squares method

vulnerability of levees. Loose and sandy levees are more dangerous compared with tight and clayey levees. Permeability is one of the most important parameters for levee safety assessment. It mainly relates to grain size distribution, such as clay or sand, and degree of compaction (Creager et al. 1944) although many other factors have an effect on the permeability. As mentioned above, the degree of compaction relates to shear modulus, and grain size distribution relates to resistivity. Through this it may be possible to qualitatively estimate the permeability from S-wave velocity and resistivity. Figure 3 shows the concept of cross-plots of S-wave velocity and resistivity on levee safety assessment. This implies that the geophysical methods can be used to evaluate the safety of levees.

However, Fig. 3 is quite qualitative and a more quantitative interpretation is required to apply the geophysical methods to levee safety assessment from an engineering point of view. Both S-wave velocity and resistivity reflect many physical properties. They do not directly relate to engineering parameters such as shear stiffness and permeability as well as other soil parameters such as grain size distribution. We have applied an analysis method in which soil parameters (*Fc*, *D20*, blow counts

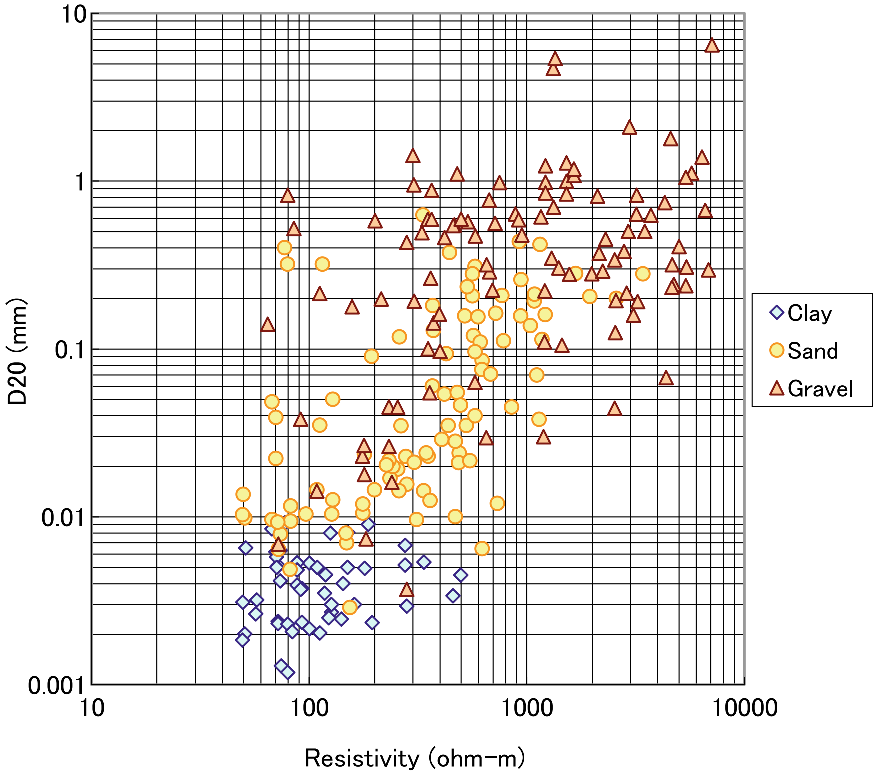

Fig. 2 Correlation between resistivity and effective grain size (*D20*) obtained from laboratory tests at many Japanese levees with soil classification

and soil type) are statistically estimated. Then we used a cross-plot of S-wave velocity and resistivity in order to apply the integrated geophysical methods to levee safety assessment more quantitatively.

Surface Wave Method

Surface waves (Rayleigh wave) are elastic waves propagating along the ground surface and their energy concentrates beneath the ground surface. The velocity of surface wave propagation strongly depends on S-wave velocity of the ground. If a subsurface S-wave velocity varies with the depth, a propagating velocity varies with its frequency or its wavelength. This characteristic is called dispersion. A surface wave method is a seismic method in which sub-surface S-wave velocity structure is estimated by the analysis of the dispersive character of the surface waves (e.g. Nazarian et al. 1983; Park et al. 1999).

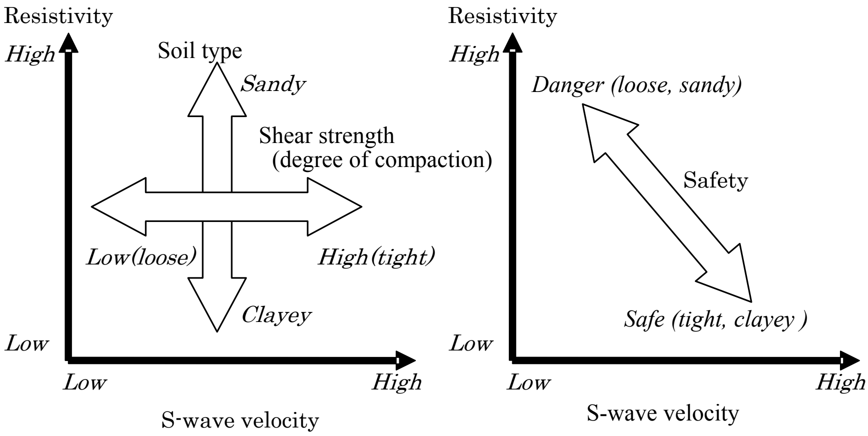

Fig. 3 Schematic relationship between geophysical properties and soil condition (left) and levee safety (right). The left figure shows a schematic relationship between S-wave velocity and resistivity. The right figure shows a schematic relationship between geophysical properties, S-wave velocity and resistivity, and the vulnerability of levees

In order to move receivers quickly, we use a land streamer (Inazaki 1999) comprising 24–48 geophones on aluminum plates, respectively, aligned in series at 1–2 m intervals by two parallel ropes on the ground surface (Fig. 4). In the land streamer, the geophones are not stuck in the ground surface and can be moved quickly.

In the analysis of the surface wave method, a CMP (Common Mid Point) cross-correlation (CMPCC) analysis (Hayashi and Suzuki 2004) is applied to waveform data firstly and a multi-channel analysis of surface-waves (MASW) developed by Park et al. (1999) is applied secondly. The CMPCC analysis is applied to raw shot gathers and CMPCC gathers are calculated in order to improve lateral resolution of S-wave velocity profiles. The MASW is applied to each CMPCC gather so that

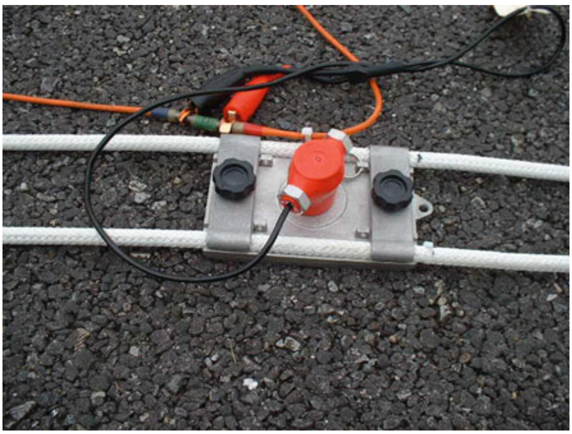

Fig. 4 A geophone on an aluminum plate of land streamer used in a surface wave method. The land streamer comprises 24–48 geophones on aluminum plates, respectively, aligned in series at 1–2 m intervals by two parallel ropes on the ground surface