A 3D ground penetrating radar imaging of the heavy rainfall-induced deformation around a river levee: a case study of Ara River, Saitama, Japan*

Toshiyuki Yokota1,3 Tomio Inazaki2 Shunsuke Shinagawa2 Takumi Ueda1

1National Institute of Advanced Industrial Science and Technology, 1-1-1-C7 Higashi, Tsukuba, Ibaraki 305-8567, Japan.
2Public Work Research Institute, 1-6, Minamihara, Tsukuba, Ibaraki 305-8516, Japan.
3Corresponding author. Email: yokota-t@aist.go.jp

Abstract. This paper describes a three-dimensional ground penetrating radar (GPR) survey carried out around a levee of the Ara River in Saitama, Japan, where deformation of the ground was observed after heavy rainfall associated with the typhoon of September 2007. The high-density 3D GPR survey was conducted as a series of closely adjacent four directional sets of 2D surveys at an area surrounding vertical cracks on the paved road caused by deformations induced by heavy rain. The survey directions of the 2D surveys were 0, 90, 45, and −45 degrees with respect to the paved road and the intervals between lines were less than 0.5 m. The 3D subsurface structure was accurately imaged by the result of data processing using Kirchhoff-type 3D migration. As a result, locations and vertical continuities of the heavy rainfall induced cracks in the paved road were clearly imaged. This will be a great help in considering the generation mechanisms of the cracks. Moreover, the current risk of a secondary disaster was found to be low, as no air-filled cavities were detected by the 3D GPR survey.

Key words: ground penetrating radar, high-density survey, river levee, 3D survey.

Introduction

Potential flood damage is an important issue in Japan because of both frequent typhoon events and frequent earthquakes. Global climate change may also affect the Japanese climate, potentially increasing the frequency of heavy downpours. Earthquakes may cut rivers by landslides, or may cause the destruction of river levees. Much of Japan’s population is concentrated on the coastal plain, and the floodplains are highly developed. Levees designed to withstand both floods and earthquakes are essential and their maintenance is a priority issue. Assessment inside and around the levee body is required to construct levee maintenance plans. It is essential to investigate groundwater distribution and to have a strong understanding of the hydrology surrounding the levee to plan proper maintenance.

Geophysical surveys are preferable to borehole measurements in many cases in groundwater research, because although borehole measurements are reliable, the limited number of drill holes can result in insufficient density of measurements. Therefore, datasets obtained by borehole measurements are often spatially interpolated by the use of geophysical data. Moreover, geophysical surveys are non-destructive. Geophysical surveys of river levees have become popular in the Society of Exploration Geophysicists of Japan (SEGJ) community with increased research and publication of case studies (e.g. Inazaki, 2006a, 2006b; Yokota et al., 2006; Hayashi et al., 2007; Inazaki and SEGJ Levee Consortium, 2007; Takahashi et al., 2007; Watanabe and SEGJ Levee Consortium, 2007).

Geophysical surveys related to groundwater such as river levee surveys often utilise electric and electromagnetic phenomena because these are sensitive to water. Ground penetrating radar (GPR) is suitable for the survey of large targets such as a river levee in relative detail because it has high spatial resolution and surveys can be conducted quickly.

Research on GPR surveys began in the 1920s (e.g. Stern, 1929) and a patent was issued at that time. Interest in GPR then waned until the 1950s (e.g. Cook, 1960). Thereafter, GPR surveys had been used in many research fields such as the measurement of glacier and ice thickness (e.g. Evans, 1963), gypsum and coal mine investigations (e.g. Cook, 1975), the search for air-filled cavities beneath paved roads or for pipes beneath roads (e.g. Nakauchi et al., 2005), and archaeology (e.g. Whiting et al., 2001). Recently, GPR surveys have been applied to new fields such as land mine detection (Arai et al., 2006; Sato et al., 2006), surveys over contaminated ground (Atekwana et al., 2000), and forensic targets (Nobes, 2000).

The conventional GPR survey is 2D and scans the subsurface along a given 2D line with a constant antenna offset. However, 3D surveys are useful or essential in some applications, for example, land mine detection. 3D surveys are conducted using multi-static (array) type antennas (Sato et al., 2004), which allow the use of several pairs of transmitter and receiver antennas simultaneously.

There have been few applications of GPR to river levee surveys (e.g. Pipan et al., 2003). Those that are known have been reconnaissance surveys and employed conventional 2D GPR methods. This study presents a 3D GPR survey carried out to understand subsurface structures accurately with high resolution in three dimensions. This is essential for better understanding of the hydraulics and groundwater distribution around a levee.

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Field experiment

GPR surveys were carried out around a river levee in the vicinity of the Bunkaku River, a branch of the Ara River, ~62.5 km upstream from the river mouth (Figure 1). The survey area is located ~2 km south-west of the main stream of the Ara River. The area has been influenced by typhoons in the past (e.g. in 1981 and 2001) and was also affected by the typhoon of September 2007. The 2007 typhoon caused:
1. Deformation of the toe of levee slope,
2. Cracking to appear on the paved outer berm, and
3. Spring water to flow from the bottom of the Bunkaku River.

As it is difficult to image groundwater distribution by means of only one survey method, several kinds of investigation were carried out, and the groundwater distribution was revealed by combining their results. These methods included: groundwater analyses (water temperature, electric conductivity, pH, measurement of dissolved oxygen, and various ingredient analyses), well logging (resistivity and self-potential), radio isotope cone penetration tests, core examinations (geological core observation, grain size analysis), slingram type electromagnetic surveys, and GPR surveys. In this paper, we describe the GPR surveys carried out on the back of the berm, where cracks, which appeared after the typhoon, were observed on the paved road surface. In this area, there is a stabilised body to a depth of 2.45 m, which was constructed during ground improvement work in 2001, by filling an excavation beneath the road with a mixture of the original soil and quicklime.

Data acquisition using GPR was conducted on the paved berm of the river levee (Figure 2). Figure 3 is the photograph of the 3D GPR survey site, showing two lines of cracks on the paved road surface. This area will be used as a road in the future, and potential cavities beneath the cracks must be investigated in order to avoid a secondary disaster. In addition, the mechanisms leading to crack formation were investigated to further improve future river levees.

The direction of the access road to the levee top was taken as the x-direction. The survey area was approximately a rectangle of ~20 m by 8 m, with a missing corner. Figure 4 shows a schematic diagram of the plan view of the survey lines. Four-directional datasets were acquired: \( x, y, +45 \) degree, and \( -45 \) degree directions relative to the paved road. The line spacing of the \( x \)- and \( y \)-directional sets was 0.5 m, and of the \( +45 \) and \( -45 \) degree direction lines was 0.35 m. As shown by broken lines in Figure 4, cracks on the paved road occurred on the inside bend of the road, within the range of 5 to 9 m in the \( x \)-direction and 2.5 to 6 m in the \( y \)-direction. Note that the data acquisition was carried out after the paved road had been repaired. As a result, the surface topography was smooth and topographic correction during the data processing procedure was not necessary.

Data acquisition and processing

The Pulse-Ekko PRO system, a pulse-type GPR system with a multi-static type antenna and a central frequency of 250 MHz, was used for GPR data acquisition in this study. High and low cut-off frequencies are 500 MHz and 100 MHz, respectively. A bow-tie antenna is built inside an insulator box. The record length in data acquisition was 160 ns; therefore, assuming an electromagnetic wave velocity of 70 mm/ns, the possible survey depth was 5.6 m.

Data acquisition in this study was carried out in the similar manner to conventional GPR profiling, in that the distances between the transmitter and receiver antennas are kept constant. The main difference is the number of antennas: conventional GPR profiling uses a pair of transmitter and receiver antennas, whereas our method acquires data with more than two antenna-pairs by simultaneous use of more than three antennas. In our standard method, two transmitter antennas, four receiver antennas, and an odometer were dragged together by a car (Figure 5), acquiring eight lines of GPR data at 1 cm intervals. The method enhances positional accuracy and data acquisition efficiency because the eight lines of data are obtained...
at the same time, and the antennas precisely maintain their positions relative to each other. As shown in Figure 4, line spacing is $0.3–0.5$ m whereas inline data acquisition spacing is $0.01$ m. Such unevenness of the data density can give rise to artefacts during data processing. Multi-directional high-density data acquisition can reduce these artefacts and provide more accurate subsurface imaging after 3D migration processing. It took $\sim 2.5$ h to survey the study area of $20$ m by $8$ m, acquiring data along eight different directions.

Conventional GPR data-processing procedures, including DC noise reduction, trigger-time compensation, clutter noise reduction, and normal moveout correction with spherical spreading compensation were applied. In addition, Kirchhoff-type 3D migration was applied. The velocity model used as input
for the migration process was obtained after interpolation of the results of a series of velocity analyses. The dataset obtained in this study has multiple transmitter-receiver offsets; hence it is possible to obtain a rough estimate of the EM wave velocity by assuming that the velocity structure is one-dimensional. Note, however, that this estimation is not correct in a strict sense, because the acquired dataset is not a common mid-point gather.

Survey results

Figure 6 shows results of the GPR survey as a depth slice at 0.7 m. Figure 7 shows y-z cross-sections for $x = 3.0, 6.0, 9.0$, and $11.0$ m. In both figures, positive reflection energy is indicated in black and negative in red, and cracks on the paved road are indicated by the broken line. The maximum survey depth obtained was over 3 m.

From 0 to 10 m in the $x$-direction, the reflected waves are relatively in phase and the horizontal continuity of the reflected waves is good, as shown by the same colours widely spread in the depth slice. At the location corresponding to the position of road surface cracks (e.g. at about $x = 5$ m in Figure 7b), a phase jump is observed in the reflected waves and the horizontal continuity of the blocks is disrupted by the surface cracks. From 10 to 15 m in

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**Fig. 5.** Photograph of the 3D GPR data acquisition technique. A car drags the Pulse-Ekko PRO system, with two transmitter antennas and four receiver antennas.

**Fig. 6.** Depth slice of the GPR survey results at a depth of 0.7 m. Positive reflection energy is indicated in black and negative in red. Cracks on the paved road are indicated by the purple broken line.

**Fig. 7.** Cross-sections in the y-z plane of the GPR survey results at a distance along the x-axis of (a) 3.0 m, (b) 6.0 m, (c) 9.0 m and (d) 11.0 m. Positive reflection energy is indicated in black and negative in red. Cracks on the paved road are indicated by the purple broken line.
the $x$-direction, the phase of reflected events is reversed for all depths between the river-side and back-side of the levee. The most probable interpretation of this phenomenon is dip of the strata, illustrated by the $y$-$z$ section at $x = 11$ m (Figure 7d).

The possibility of air-filled cavities beneath the stabilised body is of concern since they create potential for another disaster. From the GPR results, such an occurrence is not anticipated for this site, because no indicator of cavity existence, such as strong reflections and trapped multiples inside the cavity, were observed.

**Interpretation and discussion**

The geological column obtained from analysis of a borehole drilled in the region of the GPR survey is illustrated in Figure 8. The upper portion from the surface, to 0.25 m deep, consists of asphalt and rubble of the paved road. Below this lies the stabilised body, to a depth of 2.45 m. Beneath the stabilised body is the natural ground: a silt layer from 2.45 to 3.9 m shows low permeability with low water content, and overlies a fine sand layer. Confined groundwater was observed in this fine sand layer, because the water level was observed to rise when this layer was drilled, so convincing us that the groundwater in the layer is confined. The silt layer was inferred to be the seal of the confined groundwater in the lower fine sand layer as the elevation of the paved surface is 3 m higher than that of the Bunkaku River surface, so that the top of the fine sand layer is below the river surface.

**Fig. 8.** The geologic column obtained by the results of borehole drilling.

Figure 9 shows cross sections along the two survey lines at $x = 6.0$ m and $y = 5.0$ m, which run beside the boreholes. The simplified geologic column shown in Figure 8 is also shown beside each section. The purple broken line in the plan view indicates the crack on the paved road. The borehole trace is indicated by the dot-dash line in the cross sections. As mentioned

**Fig. 9.** Cross sections of the GPR survey results for (a) $x = 5.0$ m and (b) $y = 6.0$ m. The simplified geological column shown in Figure 8 is attached to each section. The area surrounded by the red solid line is the zone of 3D GPR data acquisition. The purple broken line indicates the crack on the paved road. The blue dot-dash-dot line encloses the position of the stabilised body. The borehole trace is indicated by the dot-dash line in the cross sections.
in the Results section, the characteristics of the GPR sections differed on either side of the cracks, suggesting that individual blocky movement has occurred either side of the cracks. In the north–south cross section (Figure 9a), there are some horizontally continuous reflection events south of the cracks, but most of the events died out north of the cracks. The continuity of the shallower reflector at ~0.6 m observed in the south part can be observed but with a step down of ~30 cm at the crack position in the north side. The position of the sudden drop clearly shows the location of the crack. A similar phenomenon was observed in the east–west cross section (Figure 9b). East of the cracks, the continuity of the reflection events at the 0.6 m depth was good, but this decreased to the west. A 30 cm depression was also clearly observed in Figure 9b at the distance of 4.8 m; this depression corresponds the boundary of the east and west blocks. However, there was no transformation and displacement observed, even at the positions of the cracks, in the natural layer in the deeper part of the section.

Conclusions

After heavy rain due to typhoon storms in September 2007, ground deformation was observed around the levee of the Ara River in Saitama prefecture, Japan. We investigated the region around cracks on the paved road to understand their formation mechanisms, in order to construct an efficient plan for protective measures against the effects of heavy rainfall. We adopted 3D GPR as the survey method because of the high-speed survey capability and the ability to provide 3D subsurface images, which assist in understanding the subsurface hydraulic structure.

High density data with line intervals of less than 0.5 m were acquired along four survey lines, at 0, 90, +45, and –45 degrees to the road direction. The method used was non-destructive and fast, appropriate for a river levee. The time required for data acquisition of the 20 m by 8 m area was ~2.5 h.

Data processing, including Kirchhoff-type 3D migration, enhanced the GPR images. In addition, utilising the high-density 3D survey volume enabled inspection of the survey results from various viewpoints, and improved the understanding of the 3D subsurface structures.

As a result, locations and vertical continuities of cracks induced by the heavy rainfall on the paved road were clearly imaged. This will be of great help in considering mechanisms of generation of the cracks. In addition, air-filled cavities below the road surface were not observed and a secondary disaster from this cause is not likely.

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豪雨による河川堤防周辺変状の三次元地中レーダイメージング:
埼玉県荒川における研究例
横田俊之1・豊崎富士2・品川俊介2・上田 匠1

1 産業技術総合研究所 地質資源環境研究部門
2 土木研究所

要 旨： 本研究では、2007年9月の台風に関連する豪雨による変状が見られた、荒川河川堤防周辺での三次元地中レーダ（GPR）探査について述べる。変状の一つである、舗装路面上に発生したクラックの周辺を調査領域として、0°、90°、45°に加え、±45°方向の測線でのデータを取得し、測線間隔を0.5m以下とする簡易な三次元GPRデータ取得がなされた。三次元解析ソフトウェア中のマイグレーションを含むデータ処理により、正確な地下構造が三次元的にイメージされた。それらの結果、豪雨に伴う変状の一つである舗装路面上に発生したクラックは、その地表での空間的な位置および、その影響の深度方向への連続性が正確に把握された。また現状では、クラック発生位置近傍に地下空洞は存在せず、今後新たな被害が起きる可能性は低いこともわかった。

キーワード：地中レーダ探査, 高密度探査, 河川堤防, 三次元探査

 Wolffに, 2007年9月に発生した豪雨で舗装が破壊された地域において、三次元地中レーダデータを取得した。データ処理により、正確な地下構造が三次元的にイメージされた。その結果、豪雨に伴う変状の一つである舗装路面上に発生したクラックは、その地表での空間的な位置および、その影響の深度方向への連続性が正確に把握された。また現状では、クラック発生位置近傍に地下空洞は存在せず、今後新たな被害が起きる可能性は低いこともわかった。

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Toshiyuki Yokota1, Tomio Inazaki2, Shunsuke Shinagawa2, and Takumi Ueda1

1 日本国際大学
2 日本建築学会

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