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Effective 3-D GPR Survey for the Exploration of Old Remains

Jung-Ho Kim[1]*, Myeong-Jong Yi[1], Jeong-Sul Son[1], Seong-Jun Cho[1] and Sam-Gyu Park[1]

[1]*Engineering Geophysics Group, Korea Institute of Geoscience and Mineral Resources*

유적지 발굴을 위한 효율적 3차원 GPR 탐사

김정호[1]* · 이명종[1] · 손정술[1] · 조성준[1] · 박삼규[1]

[1]한국지질자원연구원 지반탐사연구실

Abstract : Since the buried cultural relics are three-dimensional (3-D) objects in nature, 3-D survey is more preferable in archeological exploration. 3-D Ground Penetrating Radar (GPR) survey based on very dense data in principle, however, might need much higher cost and longer time of exploration than other geophysical methods commonly used for the archeological exploration, such as magnetic and electromagnetic methods. We developed a small-scale continuous data acquisition system which consists of two sets of GPR antennas and the precise positioning device tracking the moving-path of GPR antenna automatically and continuously. Since the high cost of field work may be partly attributed to establishing many profile lines, we adopted a concept of data acquisition at arbitrary locations not along the pre-established profile lines. Besides this hardware system, we also developed several software packages in order to effectively process and visualize the 3-D data obtained by the developed system and the data acquisition concept. Using the developed system, we performed 3-D GPR survey to investigate the possible historical remains of Baekje Kingdom at Buyeo city, South Korea, prior to the excavation. Owing to the newly devised system, we could obtain 3-D GPR data of this survey area having areal extent over about 17,000 m^2 within only six-hours field work. Although the GPR data were obtained at random locations not along the pre-established profile lines, we could obtain high-resolution 3-D images showing many distinctive anomalies, which could be interpreted as old agricultural lands, waterways, and artificial structures or remains. This case history led us to the conclusion that 3-D GPR method is very useful not only to examine a small anomalous area but also to investigate the wider region of the archeological interests.

Keywords : 3-D GPR, Archeological exploration, Continuous data acquisition system

요 약 : 역사유물은 지질구조와는 달리 일정한 방향성이 없이 매몰되어 있는 경우가 많으므로 고적지 탐사를 위해서는 근본적으로 2차원 보다는 3차원 물리탐사가 바람직하다. 그러나 3차원 GPR 탐사는 매우 조밀한 측선설정과 아울러 대단히 많은 자료를 획득하여야 하므로 자력, 전자탐사와 같이 유적지 탐사에 많이 응용하는 다른 탐사방법에 비하여 상대적으로 현장탐사기간이 길어질 뿐만 아니라 많은 경비가 소요된다. 이 연구에서는 두 조의 송, 수신 안테나와 안테나 이동 궤적을 연속적으로 자동 기록할 수 있는 측량 시스템을 이용하여 소규모의 3차원 GPR 자동연속 탐사 시스템을 구성하였다. 3차원 측선을 미리 측량함 또한 상당한 기간과 경비가 소요되므로 미리 설정하지 않은 임의의 경로를 따라 자료를 취득하는 개념을 도입하였다. 이와 병행하여 개발한 자료취득 시스템으로 획득한 자료를 효율적으로 전산처리하고 영상화하는 소프트웨어 또한 개발하였다. 개발한 시스템을 이용하여 부여 외곽 백제 유적지로 추정되는 지역에서 3차원 GPR 탐사를 수행하였다. 약 17,000 m^2에 걸친 지역의 3차원 GPR 탐사에 약 6 시간의 현장작업시간이 소요되었으며 이는 개발한 시스템의 효율성을 입증한다. 미리 설정한 격자망 측선이 아닌 임의의 측선 경로를 따라 자료를 획득하였음에도 불구하고 고분해능 3차원 지하 영상의 획득이 가능하였으며, 이로부터 경작지, 수로, 인공 구조물 또는 유물 등의 존재를 알려주는 이상대들을 파악할 수 있었다. 이 연구를 통하여, 3차원 GPR 탐사 또한 국부적인 이상대의 규명뿐만 아니라 광역적인 유적지 조사에도 다른 물리탐사와 마찬가지로 쉽게 활용될 수 있다는 결론을 얻을 수 있었다.

주요어 : 3차원 GPR 탐사, 유적지 탐사, 자동연속 탐사 시스템

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*Corresponding author
E-mail: jungho@kigam.re.kr
Address: Engineering Geophysics Group,
Korea Institute of Geoscience and Mineral Resources,
30 Gajeong-dong, Yuseong-gu, Daejeon, 305-350 Korea

Introduction

Since the buried cultural relics are three-dimensional (3-D) objects in nature, the 3-D or areal survey is more preferable in archeological exploration. Ground Penetrating Radar (GPR) can give us images of shallow subsurface structure with very high resolution, thus 3-D GPR technology has been actively used in archeological exploration (Evangelistar *et al.*, 2002; Goodman *et al.*, 2004; Oh and Shin, 2004). 3-D GPR survey based on very dense data in principle, however, might need much higher cost and longer time of exploration than the other geophysical methods. This is one of the main reasons why 3-D GPR has not been commonly applied to the archeological exploration as one of routine procedures at a relatively wide area. Therefore, it is important to devise an effective way of 3-D GPR survey.

For this purpose, we developed a continuous data acquisition system which consists of two sets of GPR antennas and the precise positioning device for tracking the moving-path of GPR antenna automatically and continuously. Besides this hardware system, we adopted a concept of data acquisition at arbitrary locations not along the pre-established profile lines, because establishing many profile lines itself would make the field work much more difficult, which results in the high cost of field work. Considering the characteristic feature of the data acquisition method, we also developed software to edit, to process, and to visualize 3-D GPR data. Using the developed 3-D GPR system, we performed 3-D GPR survey to investigate the possible historical remains of Baekje Kingdom at Buyeo city, South Korea, prior to the excavation. The principal purpose of the investigation was to provide the high resolution images of subsurface for the archeological excavation of the area. Besides this, another purpose was to investigate the applicability and effectiveness of the developed continuous data acquisition system. Through the case history discussed in this study, we want to report that we can acquire the 3-D GPR image with high resolution even though it will be difficult to distribute survey lines evenly in space because of the lack of pre-established survey lines.

3-D GPR system and field work

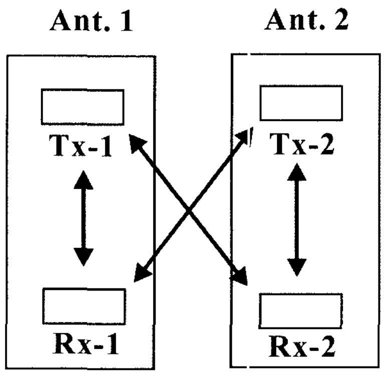
In order to improve the efficiency of 3-D GPR field work for the archeological exploration, we devised a continuous data acquisition system, where GPR antennas are installed in a small towing device and data are obtained continuously. To construct correct 3-D images of subsurface structure, it is desirable to make the measuring field points be distributed evenly and densely. A common approach will be to obtain GPR data along the profile lines laid in grid-form, but establishing numerous survey lines itself would lower the efficiency of field work. In this study, we established a hardware and software system assuming that the data will be measured along the arbitrary lines which will be determined by the operator during data acquisition.

This way of data acquisition essentially requires a real-time positioning system to track the path of antenna movement automatically with very high accuracy of the measurement error less than a few centimeters error. Self-tracking laser theodolite system (Lehmann and Green, 1999; Birken *et al.*, 2002) or Real-time Kinematic (RTK) system using the base station operation may be the ones satisfying this requirement. The former has an advantage that more precise positioning is possible but has a disadvantage that it can be only applied within the visible range. On the other hand, the latter has an advantage that it can be also applied to the area out of sight, while it cannot be used where GPS signal is too weak. Considering advantages and disadvantages of these two systems, we adopted both of these two systems as automatic positioning methods. Accordingly, we can select a proper method between these two positioning systems considering the field condition.

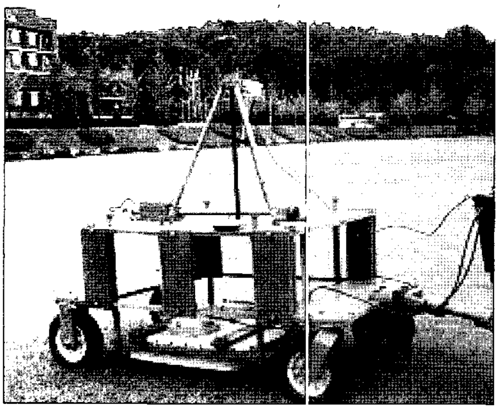
Birken *et al.* (2002) adopted multi-channel antennas (9 transmitters and 8 receivers) to perform 3-D GPR surveys effectively for mapping the 3-D distribution of infrastructures beneath paved roads. Multi-channel antenna array has important meaning not only in improving the efficiency of field work but also in distributing measurement points evenly in space. A large-scale multi-channel antenna system commercially available, however, may not be appropriate for the archeological exploration since the survey area may be unpaved and/or too narrow to apply such a large-scale antenna array. We established a small-scale system using two sets of 250 MHz antenna made by Mala Geoscience Co., as shown in Fig. 1. The spacing between two antenna sets is 0.5 m.

Buyeo city where the survey area was located had been the capital city of Backjäe Kingdom from A.D. 538 to A.D. 660. Thus the entire city can be regarded as a great historic site. According to the trench investigation, the survey area has been cultivated a paddy field since Baekje Kingdom period (Baekejae Kingdom Research Institute, 2003), and the cultivation is now temporarily suspended.

The survey area was flattened prior to the field work so as to apply the developed GPR system systematically and to enhance the ground coupling condition of GPR antennas. RTK system with the base station operation was adopted as a real-time positioning device since the survey area was open and GPS signal would be strong enough to get the accurate



(a)



(b)

Fig. 1. (a) Four channel data can be acquired using the two sets of transmitting and receiving antenna. (b) Two sets of GPR antenna are installed in the non-magnetic cart, and GPS antenna and omni-directional prism reflector for a self-tracking theodolite are also installed at the top of the cart.

positioning data of antenna movement. We acquired 20 traces per one pair of transmitting and receiving antennas every second. The speed of the survey vehicle could not be constant, but the average trace interval was about 5 cm. The average spacing between two adjacent antenna tracks was about 0.4 m, less than the spacing between two sets of antennas. Fig. 2 shows the track chart showing the movement of antenna system. The survey area was 300 m × 90 m, and the total length of the survey lines was about 35.2 km. It took only six hours to complete the field work including the extra work such as charging and exchanging batteries etc., which implies the efficiency of the data acquisition method adopted in this study.

Data processing

GPR data were processed and visualized by RADPRO and GPR3DSlice, software packages developed by the Geoelectric Imaging Laboratory of Korea Institute of Geoscience and Mineral Resources. GPR3DSlice was coded for editing and visualizing the 3-D GPR data obtained through the way developed in this study. The first step of "Pre-Processing" in Fig. 3 is to check and edit bad positioning data. The central blank part in Fig. 2 corresponds to the area where data were acquired when the GPS signal temporarily became too weak to get the correct positioning data. Since we are using time as the reference for positioning and acquiring GPR data and the trace interval is not uniform accordingly, we should convert the data into the ones having a regular trace interval. This is also done in "Pre-Processing" stage and is important for the data processing schemes assuming equi-spaced data such as migration and filtering in wave-number domain. The average trace interval was about 5 cm, and the field data were

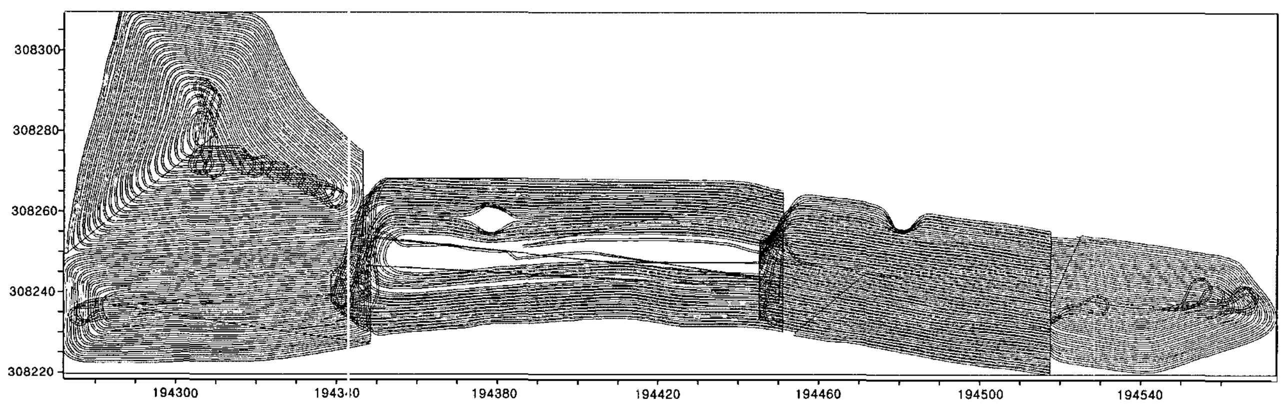


Fig. 2. Track chart showing the moving path of GPR antenna.

converted to have the trace interval of 10 cm.

After the data editing and conversion in "Pre-Processing" stage, signal processing was applied to enhance signal-to-noise ratio. Because diffracted waves from discontinuous reflectors or point reflectors can distort the overall 3-D GPR image, migration processing should be included in the processing sequence to focus the scattered energy and to move dipping events into their true subsurface positions. The left part of Fig. 3 shows the flow of the signal processing determined through various kinds of test processing.

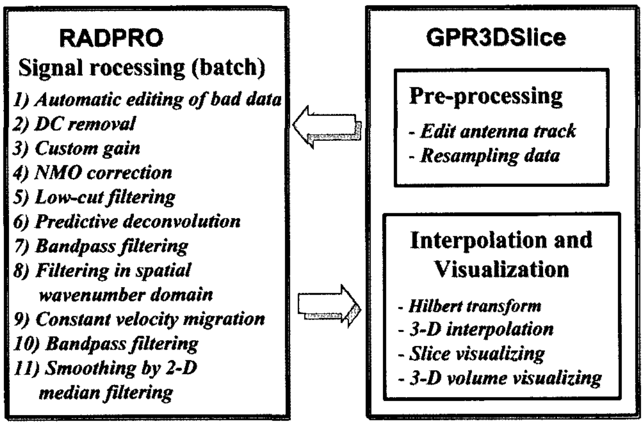


Fig. 3. Processing flow of 3-D GPR data.

We may occasionally encounter strong ringing which masks the deeper structure completely. If we do not remove this noise, the horizontal sliced images below a certain depth may show only the footprint of antenna movement. As illustrated in Fig. 4a, ringing appears as nearly horizontal events in a radargram, and thus it can be regarded as a component having infinite wavelength in wave-number domain. Accordingly, we can effectively eliminate the ringing by filtering in wave-number domain. We tested several approaches to remove ringing phenomena and concluded that the combination of filtering in spatial wave-number domain and predictive deconvolution would be most effective approach. In the processing sequence of Fig. 3, signal processing schemes 5), 6), and 8) are those for suppressing the ringing energy. Fig. 4 illustrates the effectiveness of our approach. Here, it should be pointed

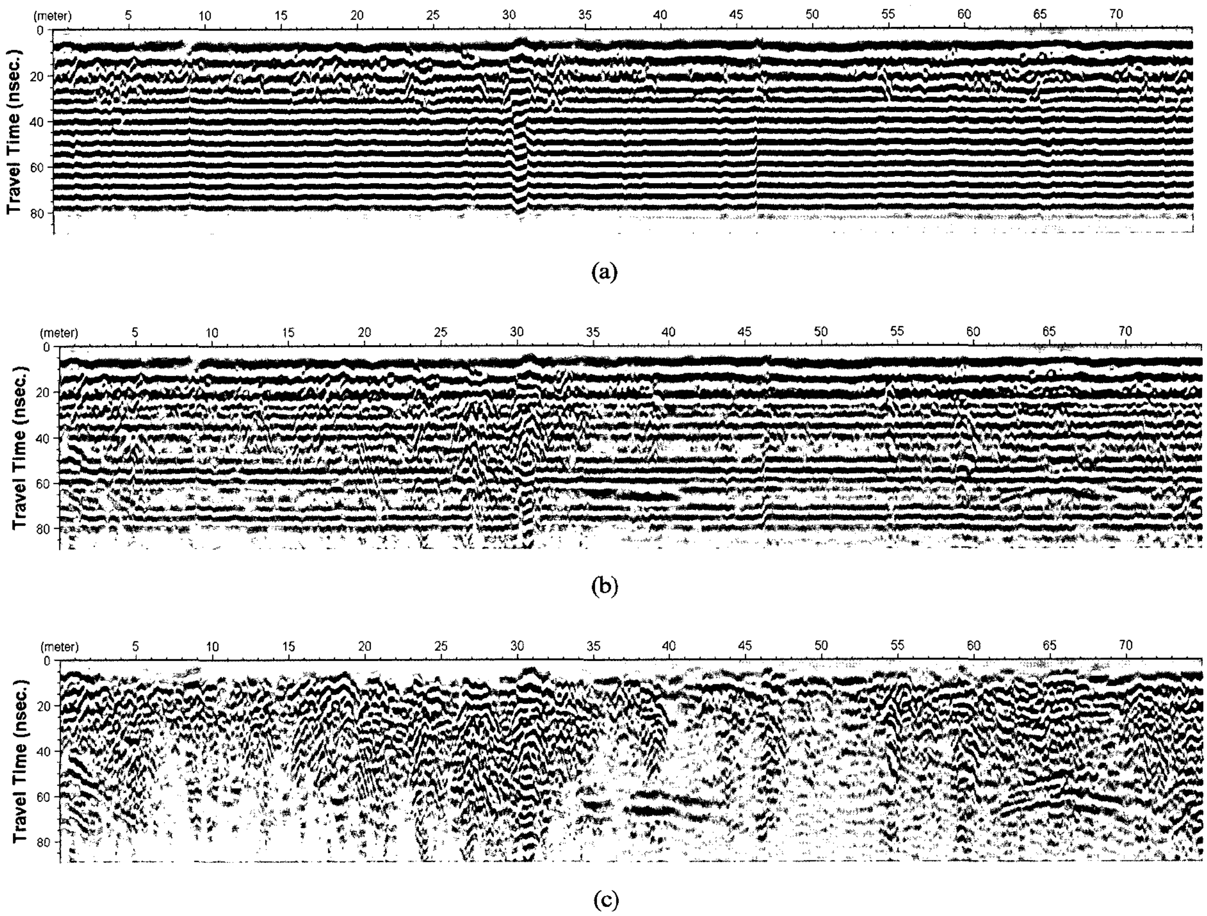


Fig. 4. Comparison of the images processed by different techniques. (a) Band-pass filtered image. (b) Deconvolved image. (c) Image after applying high-pass filter in wavenumber domain to (b). 30 meter was the cut-off wavelength.

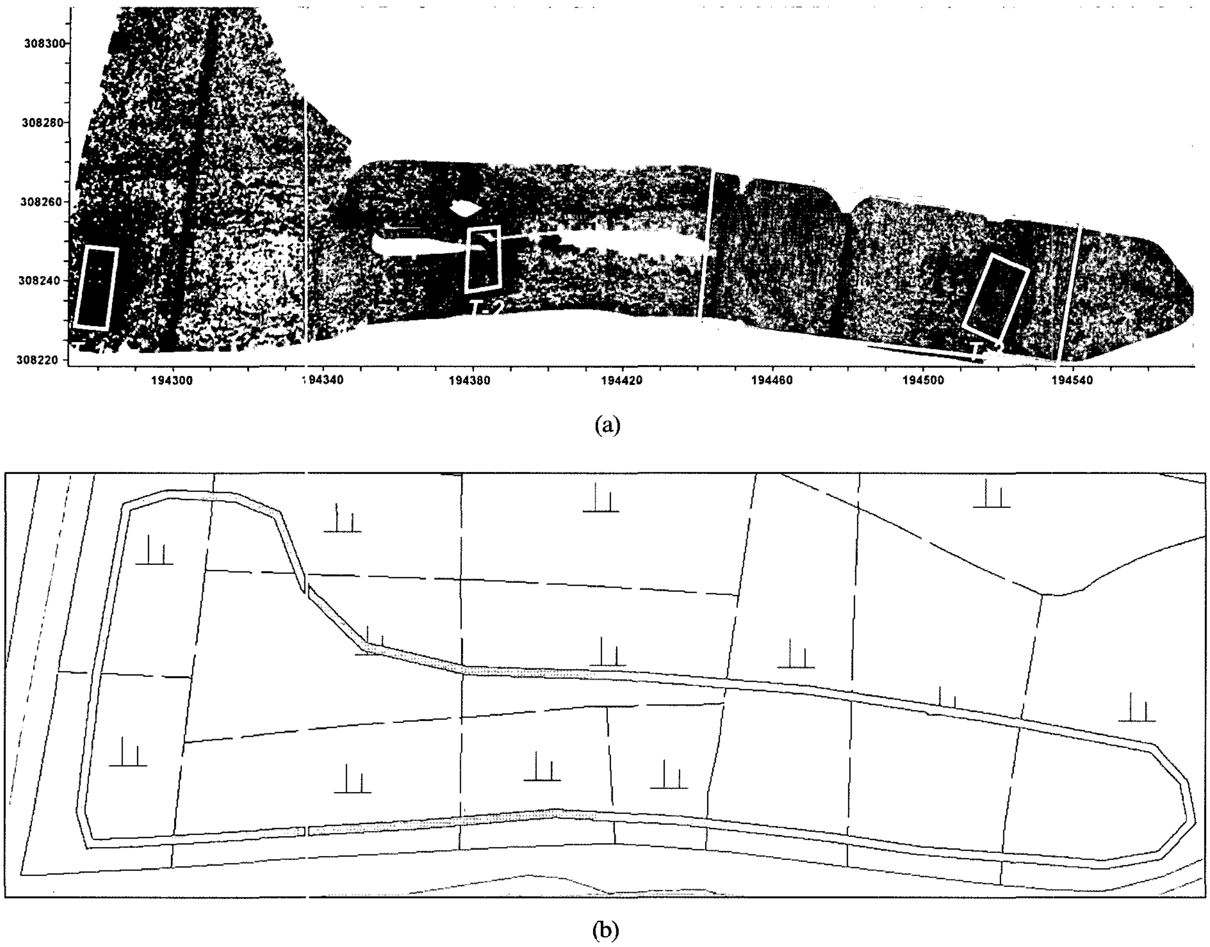


Fig. 5. Depth slice image of 0.3 m (a) and the topographic map showing the development of the ridges dividing the rice fields (b). Anomalous zones are marked on the image in (a). The central blank parts in (a) corresponds to the area acquired when the GPS signal was too weak to get correct positioning data.

out that the complete horizontal reflectors may be also filtered out by the filtering in wavenumber domain. However, we hopefully expected that the possibility would not be so high, since very long wave length, 30 m, was adopted as the cut-off wavelength.

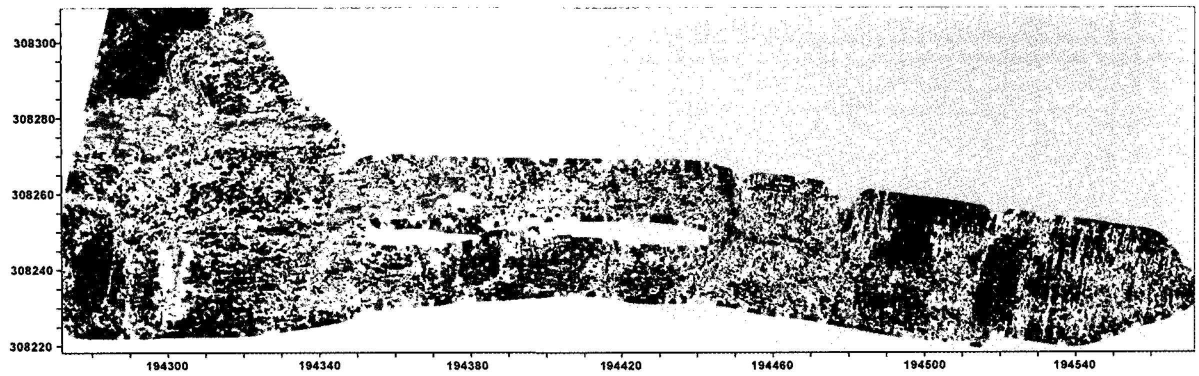
The processed results were converted into Hilbert amplitude data and interpolated in 3-D space. Using the 3-D interpolated data, we constructed various kinds of images such as horizontal and vertical sliced images and 3-D volume images.

Survey results

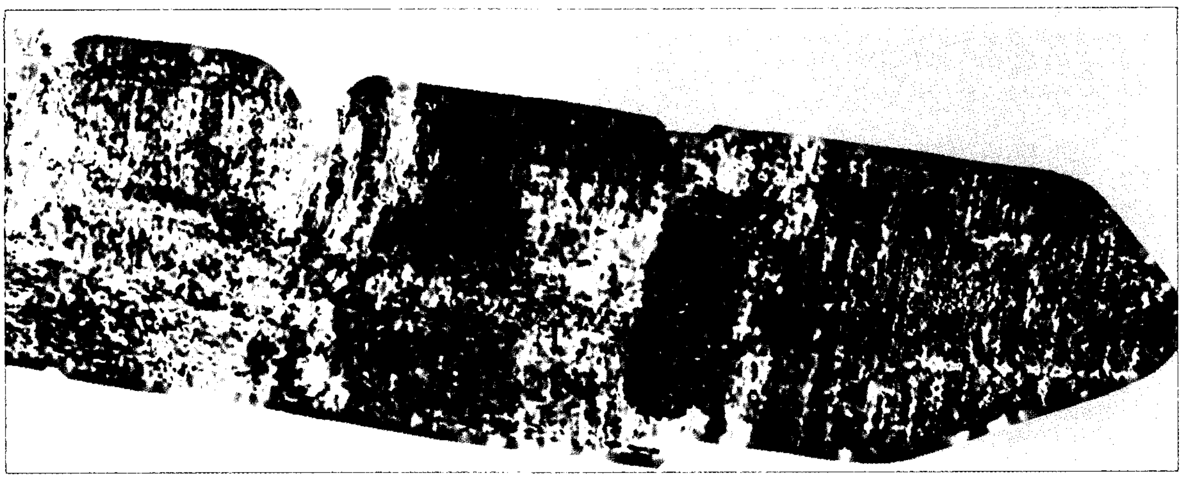
Many clear geometrical features can be identified in Fig. 5a of the depth slice image of 0.3 m. Among these features, we can recognize clear linear patterns with relatively higher reflection energy. Just prior to the commencement of the field work, the survey area was flattened so as to improve the efficiency of the field work. These distinct linear features are attributed to small levees of this rice field buried by flattening work or their substructures, which can be verified by the topographic map shown in Fig. 5b. This result implies that 3-D GPR can image ancient man-made structures such as roads, boundary of agricultural lands, waterway, and so on, although strong reflected waves cannot be expected from them.

Three rectangles T-1, 2, and 3 in Fig. 5a correspond to trench areas. Inside and near the rectangles, relatively stronger reflectors are irregularly distributed, which means that the material properties at these parts are different from those of the soil currently cultivated. This led to our interpretation that the soil of deeper parts had been moved to surface or shallower parts as a result of trench investigation and they were imaged in depth slice image in such ways.

As shown in Fig. 6a, much stronger reflectors are distributed with clear geometrical features in the depth slice image of 0.7 m. Among them, very strong reflectors expressed in red color show linear and curved features dividing the survey



(a)



(b)

Fig. 6. Depth slice image of 0.7 m (a), and enlarged view of its right part (b).

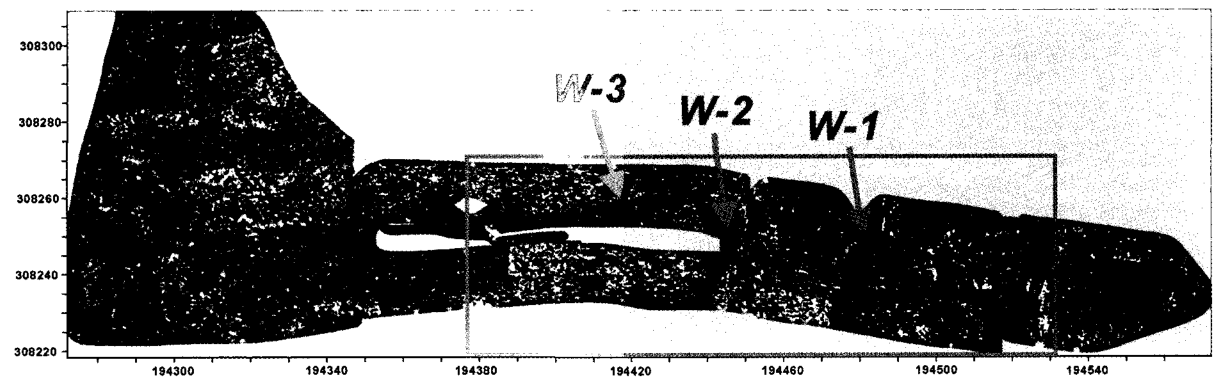
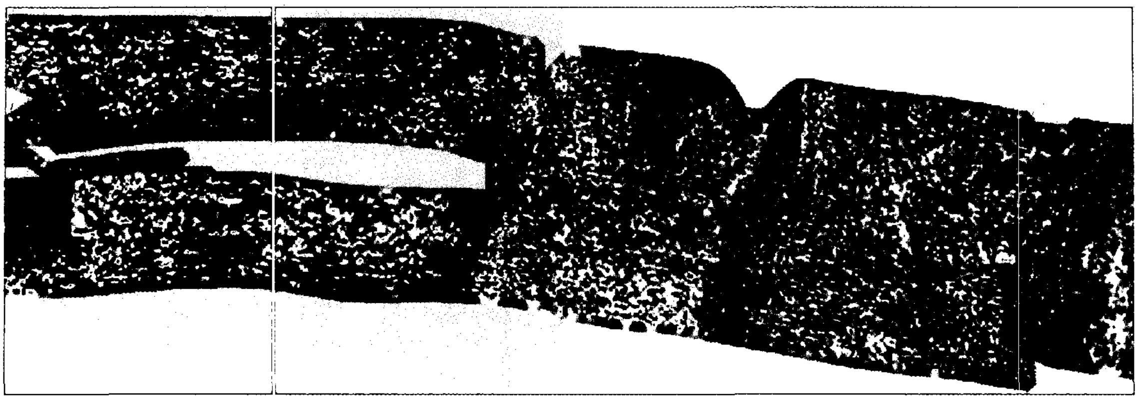


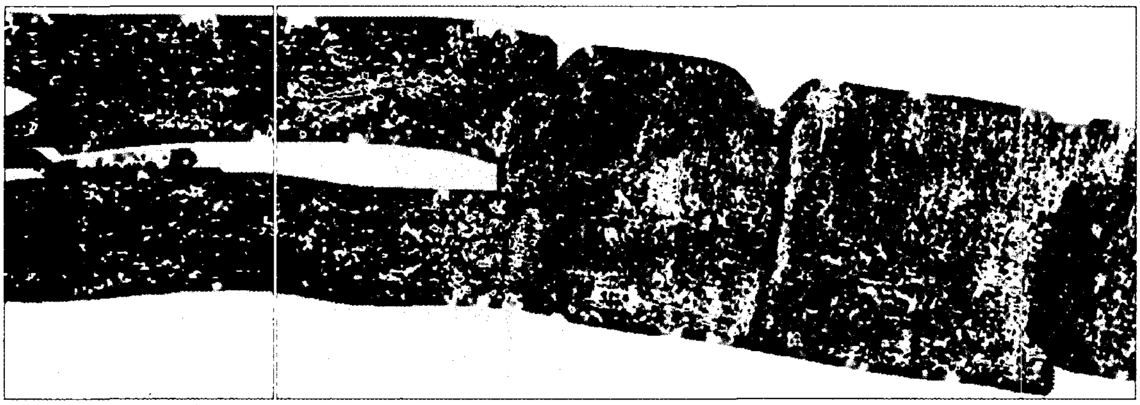
Fig. 7. Horizontally sliced image of 1.5 m depth.

area. They were interpreted as small-scale levees or artificial structures zoning the ancient rice field of Chosun Dynasty period (A.D. 1392-1910). Besides these reflectors, linear reflectors aligned in the same directions develop like the teeth of a comb throughout the whole image as illustrated in Fig. 6b. We interpreted that these reflectors were attributed to the long history of cultivation in this area.

The boundaries of three trench areas can be clearly recognized in the slice image of Fig. 6 by the abrupt change of reflection energy, and the trench areas are imaged as reflection free zones. Soil layers deposited during the long history had been disturbed and mixed by the trench excavation and the soil in these zones became homogeneous; consequently, reflected electromagnetic waves in these zones should be



(a)



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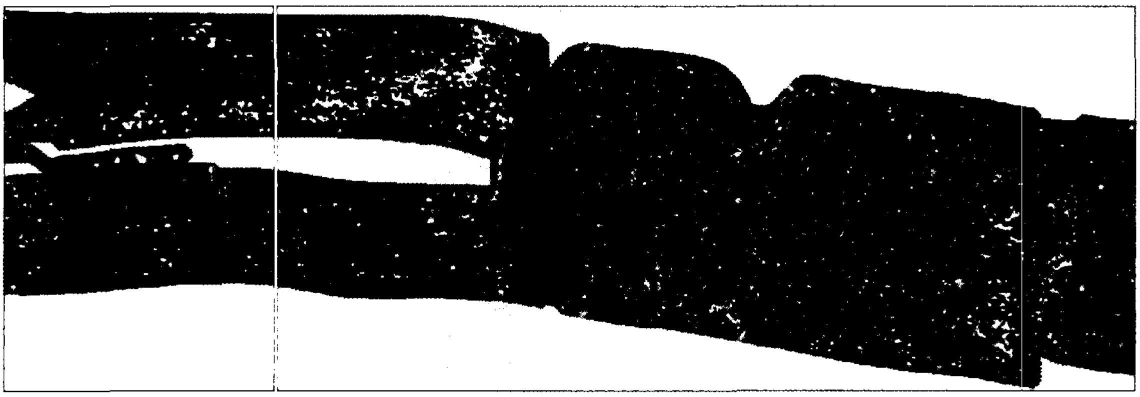

(c)

Fig. 8. Change of the depth slice images at the central part of the survey area. 1.5 m depth (a), 2.5 m, (b) and 3.5 m (c).

weaker than those in the undisturbed area.

The average reflection energy at 1.5 m depth becomes significantly reduced compared to the images of upper layers as shown in Fig. 7. We can recognize that narrow reflection free zones expressed in blue color develop with linear feature; they are designated as W-1, 2, and 3 in the figure. In depth slice images from 1.2 m down to 2.5 m depth, we can also observe the similar patterns, which means that relatively homogeneous materials are filled in the narrow bands of W-1, 2, and 3. We may interpret that these features reflect artificial excavation works in historical time or ancient waterways. Several evidences revealed by the trench investigation led us to the interpretation that these anomalous zones are more likely to be ancient waterways of 3 - 4 m width.

Enlarged horizontal slice images of different depths are illustrated in Fig. 8 in order to observe the change of reflection patterns at the central part of the survey area as depth increases. The images in this figure correspond to the zone of the rectangle in Fig. 7. While low reflection energy is the characteristic feature of the three anomalous zones in the horizontally sliced image of 1.5 m depth, rather stronger events develop along the same anomalous zones in deeper slice images. Very strong events develop in the depth slice image of 3.5 m at the same locations with the same spatial patterns of W-3 in the 1.5 m slice image. W-2 is not as distinct as W-3, but we can say that the same phenomenon occurs at 3.5 m depth. Concerning to the anomalous zone of W-1, we can also recognize the similar situation at near 2.5 m depth. Consequently, we could interpret that these anomalous patterns with strong reflection energy at deeper depths might be the bottoms of the three anomalous zones with weaker energy at the shallower depths marked by W-1, 2, and 3. The layer around 3 m depth was estimated to belong to Backje Kingdom period (Baekejae Kingdom Research Institute, 2003). If these anomalies are the images of ancient waterways, all the phenomena observed in the depth slice images imply that the history of utilizing these subsurface structures as waterways might go up to the Backje Kingdom period, about 1,500 years ago.

Conclusion

We developed a continuous data acquisition system of small scale for the effective 3-D GPR survey. The system consists of two sets of GPR antennas and the precise positioning device tracking the path of antenna movement automatically and continuously. Besides this hardware system, we also developed 3-D GPR data processing software for the data acquisition method designed in this study. Using the developed system, 3-D GPR survey was conducted to investigate the possible historical remains of Backje Kingdom at Buyeo city, South Korea, prior to the excavation. Owing to the newly devised system, we could acquire 3-D GPR data in this survey area having the areal extent over about 17,000 m^2 within six-hours field work. Although the GPR data were obtained at random locations not along the pre-established profile lines, we could acquire high-resolution 3-D images showing many distinctive anomalies, which could be interpreted as old agricultural lands, waterways, and so on. This case history led us to the conclusion that 3-D GPR method is very useful not only to examine a small anomalous area but also to investigate the wider region of the archeological interests.

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