Archaeological Prospection with GPR Approaches: Case Studies in Xian and Shangqiu, China

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Abstract

During 1995 and 1996, three ground-penetrating radar surveys were carried out in conjunction with field archaeological investigations in China. The first survey was a detailed, high-resolution radar survey at the site of Hanyuan Hall, a ninth century palace. The latter two radar surveys were rapid, low-resolution reconnaissance surveys undertaken using the magnetic method and RS images as part of the Shangqiu Project. Geoarchaeological and geophysical teams worked jointly during the spring and fall of 1996. This paper will discuss several radar profiles with different patterns of anomalies and geological interpretation and compare them with the core profiles. The survey design, data acquisition and processing are also discussed. Ongoing work involves continuing to perform GPR and other geophysical surveys in the area surrounding and within the Eastern Zhou city to locate building structures, graves and ancient riverbeds.

1 Introduction

Archaeological geoprospection is about five decades old (eight decades, if aerial photographic survey of archaeological site is included). Several journals, such as Archaeometry, the Journal of Field Archaeology, the Journal of Archaeological Science, Archaeological Geology and Geophysics have published occasional papers on the subject since 1970s. Although special issues on this subject emerged during the second half of the 1980s (e.g., Wynn 1986), it is only with hindsight that Archaeological Prospecting and Remote Sensing (Scollar *et al*. 1990) , followed by Clark's remarkable book Seeing Beneath the Soil (Clark 1991), can be viewed as a watershed.The latter is the first book written for those trained in the physical science which provides detailed information on the theory and practice of archaeological geophysics. As a systematic outline of the physical and mathematical principles lying at the root of most of the currently employed methods, as a record of achievement of the early innovators within the field of archaeological prospection, and also as an indicator and enabler of future direction, "Archaeological Prospecting and Remote Sensing" stands alone. Following this publication the increase in the number of publications describing archaeological prospection has been steady both in Europe and North America.

Archaeological investigations in China, even today, are traditionally and mainly carried out with careful trenching and coring of sites having historical documentation, collection of surface artifacts, or analysis of surface morphology suggesting earlier human occupation. The traditional coring tool called a Luoyang spade was borrowed from grave robbers and has a long and successful history. The experienced coring technician can recognise traces of human culture by looking at the soil color, texture and material differences which are inclusions of a perceptible nature in a natural context. The Luoyang spade is so important in Chinese archaeology that it takes an outstanding role in newly published book Archaeological Investigations (Zhu 1996).

Despite the high profile of archaeological geophysics within Europe and North America, Chinese archaeological publications have had what can only be described as a disappointing impact elsewhere. Kaogu (Archaeology) and Kaoguxuebo (Archaeological Sinica), contain very few references to geophysics. Keji kaogu luncong (The Collected Essays of Archaeological Science and Technology) (Qiu 1991), which is the product of an Archaeological Lab Technology meeting and represents a global view of technology in Chinese archaeology, contains only one paper concerned with archaeological prospection (Ding 1991) which describes the use of aerial photograph and TM images on a city site. Although there are some other publications introducing geophysical methods (Jin *et al*. 1989; Liu *et al*. 1991) and their applications in archaeology (Liu *et al*.1991), as the use of geophysical methods in archaeology is known in Europe, none of the authors or archaeologists has a geophysical background or had used these techniques themselves before. This situation is not only due to the character of Chinese archaeological tradition mentioned above, but also related to the lack of communication between archaeologists and

geophysicists, and to some extent, the poor scientific training of Chinese archaeologists.

Since there have been lots of joint archaeological projects carried out in China during the last 5 years, and the practical need of rescue archaeology, including cultural heritage investigations within the world biggest Three Gorge Water Conservancy Project, things began to change with more and more archaeological surveys undertaken using remote sensing and geophysical methods. Geophysical methods were mainly used to search for graves (Zhang *et al*. 1995; Wang *et al* 1995; Qian *et al*. 1997), whilst RS image were used to locate city sites in desert (Liu 1995).

Probably the most important technical innovation in archaeological prospection in the last twenty years is ground penetrating radar (GPR). Though it is now over 20 years since the first reported use of GPR on an archaeological site (Vickers and Dolphin 1975), from then on there has been a small but regular stream of publications (Bevan *et al*. 1984; Vaughan 1986; Imai *et al*. 1987; Batey 1987; Daniel *et al*. 1988; Stove and Addyman 1989; Milligan and Atkin 1993; Goodman and Nishimura 1993; Goodman *et al*. 1994; Goodman *et al*. 1995; Meats 1996) on the successful use of GPR on other sites around the world. There are only two examples (Li *et al*. 1992; Qian *et al*. 1997) in China. Some unsuccessful experimental surveys were carried out by the Institute of Geophysics of the States Seismology Bureau in the Three George area, but details of the survey are not clear. People like to mention success and omit failure, this kind of tendency leads people to be overzealous about GPR or arouses suspicion when it doesn't work as effectively as expected, and hence to misunderstanding of this method. In a sense, failure is the most important stimulus of all in geophysical research.

I had opportunities to undertake GPR surveys in two collaborative archaeological projects during 1996. The data presented in this paper were obtained with pulseEKKO IV and 1000. This kind of digital radar systems has a programmable recording time duration, sampling interval, stacking; and interchangeable dipole antennas. There are seven parameters to define for a common-offset, single-fold GPR reflection survey (Annan and Cosway 1992). The details are survey-specific and are given for each of the case studies that follow. This paper reports successful results of radar data acquisition and processing in both of the projects and demonstrates GPR

techniques at the same level of sophistication as current near surface seismic exploration.

2 Case studies

2.1 The Reconstruction of the Hanyuan Hall

The first detailed, high-resolution radar survey took place during March 1996, at the Hanyuan Hall, a ninth century palatial architecture site, in Xian urban district, Shanxi province. The Hanyuan Hall , the main hall of Daming Palace, was built during the early Tang dynasty (618-709) and was demolished in the war-ridden years of the later Tang dynasty. The appearance and size of the original hall can be inferred from reconstruction studies based on evidence from a number of historical documents and a limited excavation carried out during 1959-60 by the Institute of Archaeology in Beijing.

During the spring and fall seasons of 1996, a full-scale excavation was carried out at this site. The principal part of the hall was built on a small mountain with a rammed earth platform about 5.5 m high. The present ground level is lower than the original building floor - a result of a thousand years of erosion by nature and human activities. Different opinions exist among researchers regarding whether or not there were stones to bear the column plinths. These kinds of stone structure, or cheng chu shi (plinth bearer) as they are called in China, have been found in some other ancient Chinese buildings. Radar was used here as a non-destructive technology to test and verify this and locate other building structures beneath the ground surface.

As a result of the large vertical variations of topography or where excavation was going on, GPR surveys focused on the principal part of the hall, an area about 35x55 m2. Radar was helpful in identifying and locating the anomalies caused by the undermining of the foundations.

2.1.1 Survey design and data acquisition

The GPR system used was pulseEKKO 1000 with a 225 MHz antennas. The modular design makes the system very transportable and field-portable. Forty lines with a separation of 1 m were surveyed in the west-east direction and six lines were surveyed in the north-south direction along the eastern and western edge of the building. Data were collected in a common offset configuration with an antenna separation of 0.5 m. For each recording, 128 source

excitations of the 200 volt pulsar were stacked to improve the signal-to-noise ratio. We recorded 220 samples with a time sample interval of 500 ps, for a total record time of 110 ns. For a typical radar propagation velocity in dry rammed earth of 0.08 m/ns, this total record time correspond to a possible depth of about 4 m, which is 2-3 times the target depth as expected.

An example of the data recorded along the west-east line is shown in Figure 1. This is an example of typical data recorded during this survey as it contains a number of strong reflections. It was verified by coring on-site that these reflections were caused by stone structures. When we plot the positions of the hyperbolic-like reflections along the profile lines on which they were recorded to produce a form of 'plan', the regular appearance of the location of the stone structures emerged immediately after examining the complete data set (see Fig. 2).
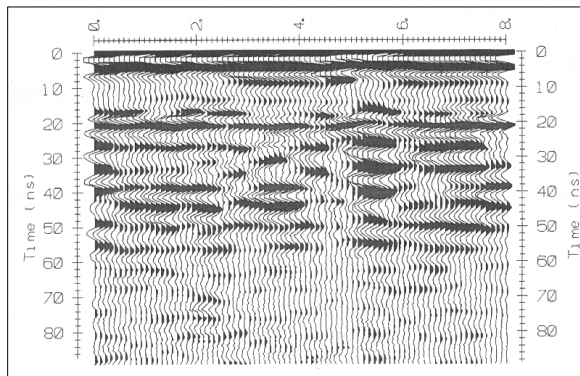

Figure 1. A typical example of the 225MHz data recorded during the first survey at Xian. The main reflective group at about 4m is associated with stone structures referred to as cheng chu shi (plinth bearer).

The positions of the two lines of columns at the centre were located by 1960's excavations, but the stone structure beneath the building floor were not been mentioned; the two other lines of stone structures are new discoveries. These stone structures, in the same elevation, about .5 m beneath the present ground level, were used to bear the column plinths (see Fig. 3). Figure 4 shows another kind of anomaly caused by a brick structure. These reflections are from the western road surface of the cloister. Excavation of the wall-foot of the hall provided nothing, except some colour traces of the white lime, whilst the brick structure of apron can causes strong anomaly in the radar images.
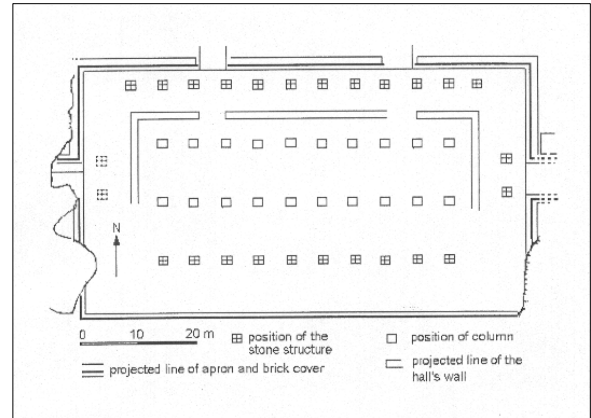

Figure 2. A plan of the principle part of the Hanyuan Hall showing the position of the stone structures and the projected lines of the hall and cloister inferred from the excavation results and GPR surveying.
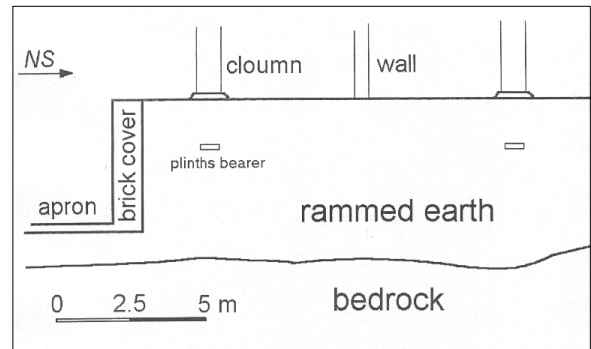

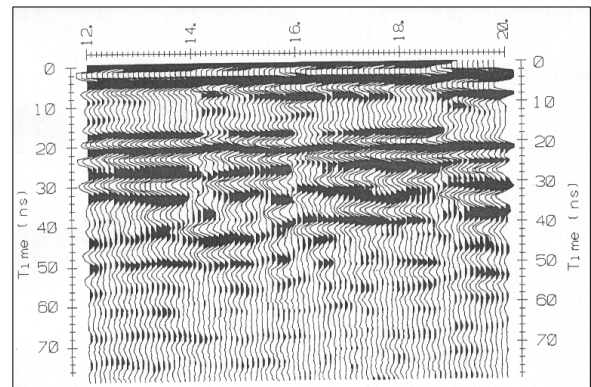Figure 3. A sketch map showing the northern part of the building structure.

Figure 4. An example of the 225MHz data recorded during the first survey at Xian. A lowpass filtering of the data has been carried out in order to remove the background noise. The main reflective group at about 14 m is associated with western apron of the Hanyuan Hall.

2.2 Shanqiu Project

The second and third radar surveys were carried out during June and November 1996 in the Shangqiu area, Henan province. Both of the latter two surveys were rapid, low-resolution reconnaissance surveys undertaken using the magnetic method and RS images as part of the Shangqiu Project.
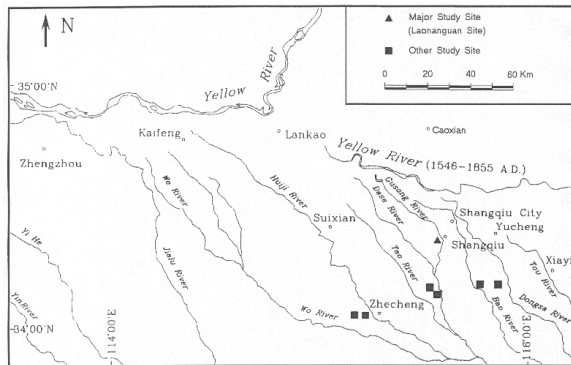

Figure 5. Location of Shangqiu area on the eastern Henan plain. This area was flooded frequently by the Yellow River from the early 12th through to the middle 19th centuries. The abandoned Yellow river course shown on the map was active between A.D. 1559 and 1855. The local rivers and streams shown on the map are currently contributive tributaries of the drainage basin of the Huai River to the south. But many of them served as distributive tributaries of the Yellow River between the early 12th and the middle 19th centuries. The east part of the map is often called the Yellow River Flooding Region (after Jin).

The Shangqiu area, situated on the south-eastern part of the alluvial plain of the lower Yellow River (see Fig. 5), is traditionally considered the homeland of the pre-dynastic and early Shang culture. It is the location of Great City of Shang, the political and religious centre during the pre-dynastic Shang period (2000-1750 BC), and the sacred cult centre throughout the Shang dynasty (1750-1100 BC) (Chang 1983; 1986; 1989). As the single most important element of regional physiography, the changing position of the lower Yellow River has greatly influenced the physical appearance and hydrologic conditions of the Shangqiu area. Archaeological remains dating to the pre-dynastic and dynastic Shang periods, however, have remained elusive, mainly due to the heavy late-historic flood plain alluvium from the Yellow River. The land surface of the time period to which early Shang and pre-dynastic Shang remains should be attributed was

buried to a depth of, on average, 10 meters (Jin *et al.* 1995).

The collaborative program of archaeological survey and excavation in the Shangqiu area began in earnest in 1991. The overall area of interest of this project is extremely large, an area encompassing roughly 10,000 km2. Our field survey focused on a 6x6 km2 area located to the south and southwest of the present town of Shangqiu. It was determined that geophysical surveying in selected areas would be the most cost- and labour-efficient method to locate areas of possible archaeological interest within this large region, based on the anticipation that the large hangtu, or rammed earth wall platforms, and building foundations would cause anomalies in the geophysical data.

Hangtu, a typical construction technique in ancient China, still commonly seen today in various parts of China, involves the erection of a wooden frame which is filled with soil, sometime mixed with a sandy liquid. This is then tightly packed down with repeated blows from wooden or stone pounding tools. The frame is then disassembled and moved to the next part of the structure, where the process is repeated. In this way, rammed layer upon rammed layer are combined to create walls and foundations many hundreds of meters long. Geophysically speaking, the exploitable physical properties of rammed earth, in a matrix of sandy loess deposited by alluvial processes, are the interesting higher density, dryness, and variation of solid particles.

The primary objective of geophysical survey was also to assess the local conditions in the Shangqiu area and to test the applicability of various geophysical methods for subsurface feature detection. Site exploration and the search for undiscovered sites can sometimes be accomplished with aerial photographs or digital imagery from aircraft-borne instruments. However, in localities such as the Shangqiu area where many meters of alluvial deposits blanket the underlying cultural features, the chance of observing any clues on the ground is greatly reduced. Initial processing of EOSAT Thematic Mapper (TM) satellite data of this area, taken on 23 August 1989 by the Landsat 4 satellite, revealed a curious light-coloured ring against the healthy vegetation of the area. A number of long magnetic survey lines were executed in order to look for subsurface anomalies when the "ring" feature was crossed, but no significant anomalies were detected on these lines. Aerial photographs of this area, used as base maps, have still proven to be very useful to the project.

Magnetic surveying and Electromagnetic (EM) methods were selected for the initial phase of the exploration program during November 1992. With regard to the overall Geonics EM-34 conductivity measurements, no EM anomaly trends were defined with a rather narrow range of 35-45 millimhos/meter, due to the salinity and high conductivity of the local soils (Murphy *et al*. 1993).

The proton precession magnetometer surveys disclosed a number of anomalies and some of them are definitely caused by cultural features, such as tomb structures, while others could be due to either structures or to relatively localised erosive or excavated and backfilled features. Still others represent large lateral features, such as broad and extended river channels (Murphy *et al*. 1993) .

The GPR survey conducted for the first time in Shangqiu during the spring and fall field seasons of 1994, like the magnetic method, produced mixed results. The radar was successful in detecting some brick structures, but not as early as the late Neolithic and Shang materials of interest to this project. Most of the radar anomalies are due to the variation of alluvial deposits, and others are "false" anomalies caused by the root balls and leaves overhead of a particular variety of paotong (Paulownia) tree or the result of scattering from local power line poles (Cist *et al* 1995).

The earlier work highlights the fact that though magnetic survey can cover areas as fast as the operator can walk, there is a trade-off between rapidity and resolution. Coupled with this is the fact that the interpretation of total magnetic field data is sometimes very difficult. The GPR is a high-resolution technique that is best suited to focused areas rather than huge regions covering many kilometres of unknown character. The extreme depth of the early remains and the lack of a specific culture targ*et al*so made this immediate area a difficult one to carry out efficient geophysical exploration

This situation changed dramatically with the most important discovery of a buried rammed earth wall by systematic coring during the spring 1996 field season. The rammed earth walls have been tentatively identified as those of an Eastern Zhou (770-450 BC) city, based on pottery sherds taken from exposures of the walls.

Once the rammed earth wall had been located by coring, GPR lines were conducted to cross over known sections of the wall, in order to finally answer the crucial issue of whether or not GPR could "see" rammed earth structures in a matrix of alluvial loess deposits. The results was that these structures could indeed be detected (see Fig. 6 and 7), even with the poor working conditions in the spring of 1996. Then, the geophysical team, previously working across broad areas, could help the geoarchaeological team to locate the walls and focus its efforts on the more finite area immediately surrounding and within the Eastern Zhou city.
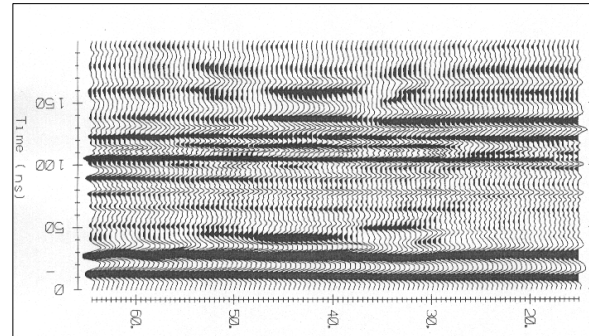

Figure 6. An example of the 100MHz data from profile across the south wall of the Eastern Zhou city. A SEC gain has be carried to the data. The hyperbolic-like reflection at about 40 m corresponds to a rammed earth structure.
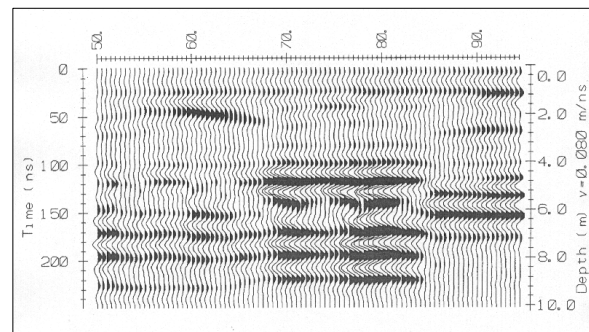

Figure 7. An example of the 100MHz data from a profile across the south wall of the Eastern Zhou city. After subtracting the average trace of the data with SEC gains. The strong reflections at about 69-84 m are associated with a rammed earth structure.
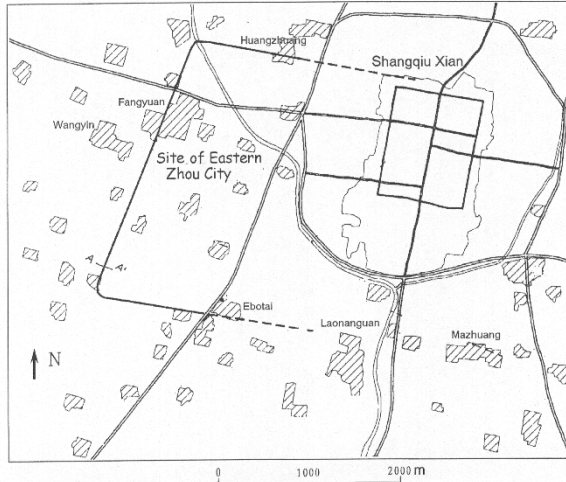
Figure 8. Map showing the location of the Eastern Zhou city's walls (after Jin),

By the intimate integration of coring team and GPR survey during the spring and fall season 1996, we got the following picture of the site (see Fig. 8). The rammed earth structure appears to have been the protective wall of a fairly major city. The western wall measures some 3050 meters long. The southern wall and northern wall have been traced out to a length of about 1100 meters and 1500 meters, respectively. But their eastern ends have not yet been located. Most parts of the walls already found seem to be well preserved; coring indicates that the top of the walls lie only three to four meters beneath the present ground surface, and that the rammed earth continues down to a depth of about 10 to 12 meters with average width of between 12 and 15 meters (see figure 9.).
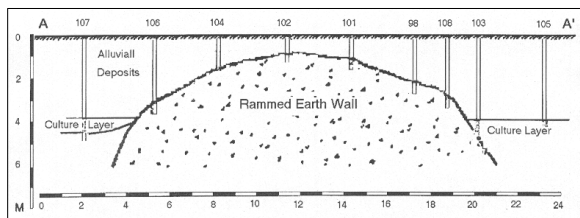

Figure 9. The coring profile across the west wall (after Jin). See Figure 8 for the location of AA'.

2.2.1 Survey design and data acquisition

The GPR system used was pulseEKKO IV with 100 MHz antennas and output voltages of 1000 v.

Three kinds of antenna deployment were employed in 1996: PL-BD and PL-EF were used in spring to overcome the impassability of the high wheat crop,

whilst the most common configuration of PR-BD was used in the fall.

Different antenna deployment results in different radiation patterns, and different critical refraction angle with maximum amplitude for propagation (Smith 1984). This angle decreases with depth due to downward refraction as the dielectric permittivity decreases with depth. In general, the antenna used for GPR are dipolar and radiate with a preferred polarity. But with the linear feature of our target and crossing profile line, the kinds of antenna deployment used in spring become unfavourable configurations. This conclusion is also supported by the comparison between our radar data recorded in the spring and fall 1996.

3 Data processing

One of the most convenient aspects of GPR is that profiles can be viewed as images on a computer screen and interpreted while the scan is being collected. This real-time on-site interpretation allows the operators to adjust their acquisition strategy to reflect new regions of interest suggested by the incoming data and maximise target coupling.

However, post-survey processing of the data is required to more accurately resolve the subtle details in the images. Annan (1993) has discussed the practical processing of GPR data. Many of the techniques now being used have been borrowed from the field of seismic interpretation as the kinematic properties of GPR are, under ideal circumstances, identical to those of scalar seismic waves (Lee *et al*. 1987; Fisher *et al*. 1992b). This is a consequence of the fact that displacement currents dominate conductive currents at frequencies where GPR is effective. The standard seismic processing sequence (filtering, static corrections, common-midpoint gathering, velocity analysis, normal- and dip-moveout corrections, stacking and depth migration) is well documented (Hatton *et al*. 1986; Yilmaz 1987). While all seismic processing can not be applied to GPR data, the vast majority can be used directly as evidenced by Fisher *et al*. (1992a), Maijala (1992), and Rees Glover (1992). The data manipulation becomes more and more processor dependent and hence more subjective because a particular end result is sought. Some of these processes are discussed in turn.

3.1 Velocity estimation

A crucial component of all migration algorithms and geological interpretations of the GPR profile is the estimation of the velocity distribution beneath the ground surface. There are at least four ways in which velocities may be estimated (Fisher *et al.* 1992b). For the examples below, we use a combination of coring profile, stacking velocity analysis, and iterative migration.

3.2 Migration

It has long been recognised that a raw radar reflection time section often portrays a distorted, unfocused representation of the true subsurface structure due to apparent position shifts associated with dipping reflectors and diffractions from corners and edges (Harrison 1970). Furthermore, as the antenna of the pulseEKKO IV are not screened, radar data may be influenced by surface objects on the ground or above the survey line, such as power lines and poles, trees, and buildings. In a typical example at Shangqiu, noise events including scattering by trees are recorded in much lower part of the radar section even when the trees were 40m. away. The purpose of migration is to take a reflection profile and obtain improved results in spatial positioning and reduction of diffraction artefacts. It is also possible that an enhancement in signal-to-noise for target responses may occur. Not only do misleading events disappear, but new structures and continuities show up that were previously obscured. All these improvements to the radar section may allow the user to make a more reliable interpretation of the subsurface.

Generally, there are two types of migration: one method uses the principles of asymptotic ray theory, another type of routine based on the electromagnetic wave equation. A number of algorithms based on acoustic or scalar waves equation have been developed. Hogan (1988) uses Kirchhoff integral migration for GPR data; Fisher *et al.* (1992b) have successfully applied reverse-time migration to GPR data; whilst phase-field imaging, often referred to as downward continuation routines, the same as frequency-wavenumber (F-K) domain migration, which is applied to data shown below, can also be used (Lee *et al.* 1987; or Meats 1996).

Figure 10 shows the migrated image produced by F-K migration of the preprocessed data in Figure 6 using the Stolt (1978) algorithm with a constant velocity. In this example, the fairly flat hyperbolic wall response caused by diffraction is reduced and

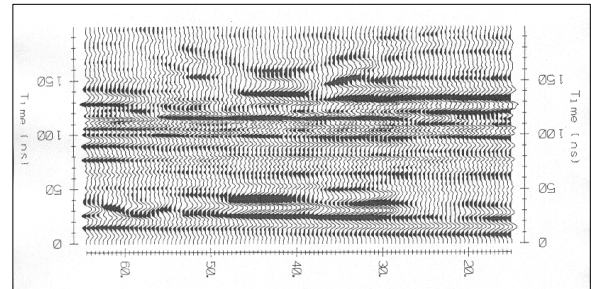strong amplitude concentrated at the edges of the wall.

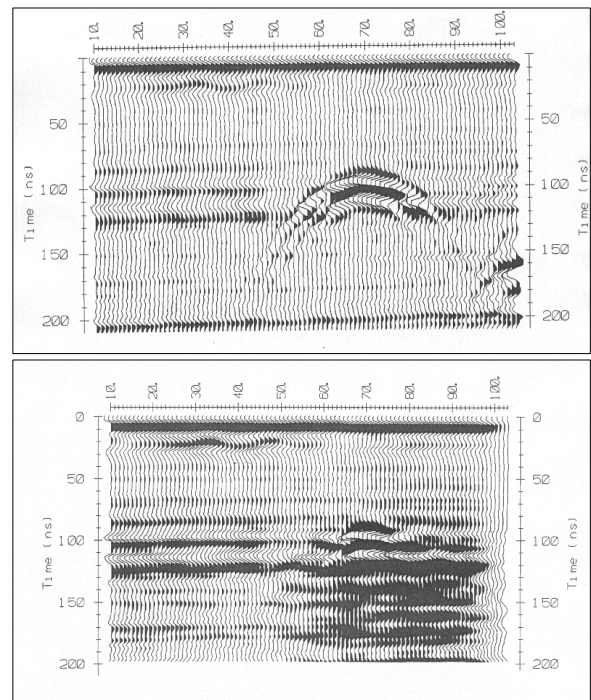**Figure 10. After F-K migration of the data in figure 6 using a constant v=0.08m/ns.**

Figure 11. Migration of the data from a profile across the west wall of the Eastern Zhou city. (a) Raw data showing surface scatters by trees and power line, (b) After F-K migration using a constant v=0.3m/ns, the radar velocity in air. The strong reflections at 70-90 are associated with a rammed earth structure.

Observation of whether it is under-migrated (migration velocities are too low) or over- migrated (migration velocities are too high) (cf. Yilmaz 1987) allows appropriate velocity adjustments to be made, and in turn velocity estimation. The Migration at the air-wave velocity will focus surface-scattered events into small regions, and these phenomena will be very helpful in identifying surface scattering (Sun *et al.* 1995), especially when detailed field notes regarding

objects above the ground are not available (see figure 11a and b).

3.3 Interpretation

Radar reflection originates at a change in dielectric permittivity that tends to correlate with the porosity, degree of saturation, and clay content. The geological interpretation of GPR section, like the stratigraphic-lithologic interpretation of seismic data, usually involves comparison between the core profile and radar time section, and in advanced steps, the quantitative estimates of the spatial distributions of electrical properties from field profile based on the studies of forward synthetic profile (Cai *et al.* 1995). State-of-the-art approaches in current research include automotive interpretation of velocities, depths, and structure geometry by iterative inversion or linearized inversion.

Reflector identification and anomaly analysis are the basic interpretations of radar time sections. Reflectors are often picked up according to the continuity and similarity characteristic of the events, whilst anomalies are usually analysed based on the amplitudes, wave form, and pattern of the events.
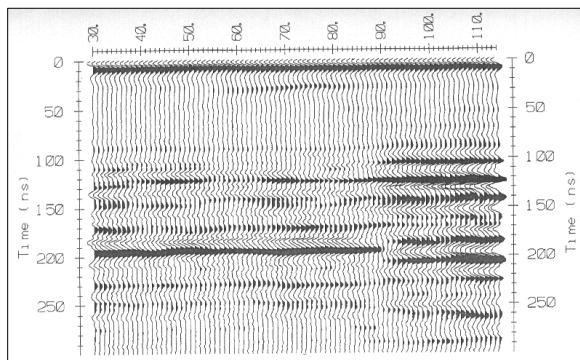

Figure 12. An example of data from profile across the wall of Eastern Zhou city showing that the stratigraphy "inside" the city is different from that of "outside" the city, thereby indicating the probable location of the walls, even though the rammed earth cannot be contrasted with the alluvial deposits enough to cause an anomaly in the radar image.

To produce a good visualisation of the radar data, Meats (1996) tries 'distance' slices, whilst Goodman *et al.* (1995) use 'time' slices. Our urgent problem at present is to trace out the city walls, so the simple determination of whether a rammed earth structure exists or not is enough. Both high-resolution GPR surveys and core profiles have revealed that the

stratigraphy of "inside" the Eastern Zhou city is different from that of "outside" the city (see Figure 12), thereby indicating the probable location of the walls. Consequently, even if the walls are no longer intact or the rammed earth structure doesn't contrast with the surrounding alluvial deposits, enough contrast can be determined from the anomalies apparent within the radar data.

4 Conclusions

High-resolution geophysical methods, including GPR, are suitable for intrasite volume mapping and are usually used to guide the excavation program within known sites. It should, therefore, not be used as an initial method of archaeological exploration or for investigating large areas of unknown character. However, prediction of whether GPR will 'work' for the problem at hand is not clear cut. In general it is easier to rule out situations where radar is totally unsuitable than to state with confidence that radar will be successful. This is not a unique feature of GPR, is a fact of life with all geophysical methods. The most important step in making a survey design for GPR is to clearly define the problem: what are the depth, geometry and electrical properties of the target? what are the host material and the survey conditions like?

While there are a wide range of geophysical techniques and aircraft- or spacecraft-acquired imagery for archaeological surveying which tend to complement each other as they measure different physical properties, so giving different information about the feature, it is also well worth mention that the combination of GPR with coring proved to be a fast way of surveying a location, since each technique directly and immediately informs the other of essential information it would not otherwise have. The value of having both coring and geophysical teams working in tandem was a major advantage in the field work of tracing the walls. The excitement and fun that comes from cross-cultural communication between scientists from different countries with widely divergent backgrounds and specialities makes the sweat and occasional failures inherent in this collaborative project worthwhile.

The rammed earth structure is typical archaeological remains in China, its contents and situation of conservation vary both spatially and temporally. The estimates of physical properties of rammed earth theoretically, in lab situations or in-situ field measurements, will improve survey design and data interpretation.

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Acknowledgements

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