Application of High-Density Resistivity Method in Emergency Detection of Embankments

Hailei Jia[1,*], Kai Zhang[1], Jun Li[1], Binbin Yue[2], Wenming Pan[1]

[1]Nanjing Hydraulic Research Institute, Nanjing, 210029, Jiangsu, China
[2]Jiangsu Huai-Shu Xinhe Management Office, Huaian, 211600, Jiangsu, China
*hljia@nhri.cn

Abstract. Aiming at the urgent need for rapid detection of seepage defects in embankments under high water level conditions during flood seasons, this paper explores the applicability and effectiveness of the high-density electrical resistivity method in emergency detection, so as to overcome the blindness and inefficiency of traditional manual patrols. Taking a section of the Yangtze River embankment in Jiangsu Province as the study case, under the background of sustained high water levels and piping and ponding already occurring on the land-side slope during the flood season, the high-density electrical method was employed, exploiting its high sensitivity to soil moisture content. Through inversion, the spatial resistivity distribution of the embankment was obtained, low-resistivity anomalous zones within the embankment body were identified, and the locations and depths of potential seepage defects were inferred. The detection and analysis successfully identified three low-resistivity anomalies, which were highly consistent with the field piping locations, and these were interpreted as the seepage pathways of the current emergency. The high-density electrical method can effectively identify seepage defects in embankments during flood seasons, provide precise targets for emergency response, reduce the blindness of on-site measures, and offer a basis for post-flood reinforcement works.

Keywords: levee; emergency rescue; high-density electrical method; low-resistivity anomaly; seepage

1 Introduction

Embankments are a critical component of China's flood control infrastructure, serving as a primary safeguard against river flooding. By 2024, China had constructed 317,702 km of river embankments of Grade 5 and above, with 257,633 km meeting the required standards; among these, the length of Grade 1 and 2 embankments reaching the standard is 40,776 km[1]. This extensive embankment network plays an indispensable role in protecting socioeconomic development and public safety.

Most of China's embankments were built decades ago under constrained technical conditions, resulting in generally poor construction quality, complex fill materials, and uneven compaction. Over time, functional deterioration has become evident, with frequent occurrences of toe scouring, cracking, animal burrows, and local loose zones that

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compromise structural integrity[2]. In recent years, extreme weather events have intensified, leading to prolonged high-water-level operation during flood seasons. Under sustained high seepage pressure, existing defects are prone to evolve into serious hazards such as seepage, piping, slope collapse, and even breach, posing severe threats to embankment safety. Currently, embankment safety inspection during flood seasons relies primarily on manual patrolling, which is both blind and inefficient—by the time anomalies are detected, hazards have often already developed rapidly, leaving emergency responses reactive and inadequate. Therefore, it is essential to conduct emergency detection of seepage defects during high-water periods or after hazard occurrence, enabling timely identification and treatment of potential risks.

There are various non-destructive detection methods for embankment defects, including high-density electrical resistivity, transient electromagnetic (TEM), ground-penetrating radar (GPR), pseudo-flow field, and elastic wave methods [3-4]. Xue et al. [5] used GPR to detect defects in the Yangtze River embankment at Dahekou, Nanjing, identifying 36 geological anomaly zones. Li et al. [6] applied the pseudo-flow field and TEM methods to successfully detect leakage inlets and pathways at the Jiyin Dam in Xinjiang. Jia et al. [7] used the high-density electrical method to predict piping zones during emergency response at the Shijiuhu embankment. Li et al. [8] employed shallow seismic and GPR methods to investigate seepage at the Yongding River flood detention reservoir embankment, ruling out large channels.

These methods can perform well under certain conditions for routine dam/embankment surveys. However, they are often unsuitable during flood seasons under high seepage pressure or when emergency detection is needed. GPR cannot accurately characterize defects in high-moisture clay layers, has limited depth insufficient to cover the embankment body and foundation, and is susceptible to electromagnetic interference. The pseudo-flow field method, which uses an artificial current field to simulate seepage and locates inlets by measuring current distribution, fails during floods because river flow velocities far exceed seepage velocities, making the two fields indistinguishable. TEM offers large depth but has a significant shallow blind zone, problematic for embankments within 15 m height. The elastic wave method requires an artificial source, suffers from vibration noise, and provides limited accuracy for shallow defects and restricted horizontal coverage.

In contrast, we consider the high-density electrical resistivity method to have distinct advantages for emergency detection under high water levels. Its physical basis is the resistivity contrast among different subsurface media; resistivity is closely related to soil moisture content—higher moisture gives lower resistivity. During floods, cracks, cavities, and loose zones in the embankment body, having poor impervious properties, lead to locally increased moisture or saturation. The method's high sensitivity to low resistivity rapidly identifies water-rich areas, thereby inferring leakage locations and depths. Its linear survey layout aligns with the embankment, providing broad coverage, and it offers large depth, good resolution, and strong anti-interference, making it suitable for rapid screening of internal defects [9].

Piping incidents are rare, influenced by rainfall, upstream inflow, water level, and embankment quality, but can cause severe consequences. Current case studies using the high-density electrical method before or during piping are scarce; Liu et al. [10] applied

it during the "23·7" flood in the Haihe basin for seepage detection on the Ziya River right embankment. This paper presents a detailed case study of emergency detection during a piping event at a Jiangsu embankment section in 2025, describing the layout scheme, result analysis, and summarizing the method's performance for emergency response, providing a reference for similar hazards.

2 Project Overview

A certain section of embankment in Jiangsu Province, downstream of the Yangtze River, was initially built in 1984 and underwent multiple expansion and renovation projects up to 2012. The embankment structure in this section is complex. The embankment is adjacent to the urban area, with the riverside facing the river and featuring a footpath. Part of the land side has been filled in, while other parts are occupied by factories, residential communities, or schools. Additionally, a river-crossing tunnel passes beneath the embankment.

The embankment is situated on a river floodplain with a thick overburden layer. The embankment height is approximately 5.0–6.0 m. The embankment body is mainly composed of miscellaneous fill and plain fill. Due to human activities, the artificial fill contains many broken bricks, crushed stones, concrete fragments, humus, etc., with hard material content reaching 40–50%. The soil has high compressibility and low strength, and overall uniformity is poor. The embankment foundation is mainly hydraulic fill, predominantly silty clay, interbedded with thin layers of fine sand and silt, with locally high sand content, containing humus and plastics. The layer thickness is 4.9–5.5 m, with poor uniformity and compactness. The main deposits are mucky silty clay and silty clay with a small amount of organic matter, locally interbedded with thin layers of silt and silty sand. Below the hydraulic fill layer, the foundation is mainly saturated soft soil, predominantly mucky silty clay and silty clay with a small amount of organic matter, locally interbedded with thin layers of silt and silty sand.

During a certain flood season, the Yangtze River basin experienced persistent heavy rainfall, and water levels in rivers, lakes, and reservoirs generally rose. The upstream inflow remained high. The measured maximum water level of this embankment section reached 9.96 m, which was 1.46 m above the warning level. Under the sustained ultra-high water level condition, piping and water gushing occurred on the land side of some embankment sections, and extensive ponding had accumulated at the toe. The management authority promptly took emergency measures on the seepage section to bring the embankment danger under preliminary control. However, the water level continued to rise, and the risk to the embankment kept increasing. Under these circumstances, the project team, in combination with on-site conditions, adopted the high-density electrical resistivity method for emergency detection of this embankment section, quickly delineating the high-risk seepage zones and identifying the locations and depths of weak seepage points, so as to provide important technical support for formulating emergency measures and mobilising emergency resources.

3 Survey Layout and Parameter Settings

Field inspection revealed extensive ponding at the toe on the land-side slope between K0+355 and K0+410, and local seepage (damp spots) near K0+320 on the land-side slope. Based on the seepage location and site conditions, one longitudinal survey line was arranged on the land-side crest of the embankment, parallel to the embankment axis, from chainage K0+220 to K0+550 (Fig.1). The instrument installation on site is shown in Fig. 2.

The high-density electrical method offers multiple electrode configurations (arrays), commonly including Wenner, Schlumberger, dipole-dipole, and pole-pole (or pole-dipole). The Wenner array provides balanced horizontal and vertical resolution, with regular anomaly patterns that are easy to interpret. The Schlumberger array offers higher vertical resolution, suitable for layered strata and deep targets, but has relatively lower horizontal resolution. The dipole-dipole array is sensitive to lateral resistivity variations, suitable for steep structures and local heterogeneities, yet suffers from weak signals and low SNR. The pole-dipole array achieves greater depth but is terrain-sensitive and rarely used in practice. Considering the embankment structure, site conditions, and target depth, the Wenner array was selected for this survey. The survey section parameters are listed in Table 1.

The measured apparent resistivity data were converted to true resistivity through inversion using the Res2DINV software, with a smoothness-constrained Gauss-Newton least-squares algorithm. The initial model was a homogeneous half-space with resistivity equal to the average of the measured apparent resistivities. Vertical and horizontal smoothing ratios were both set to 1.0, with an initial damping factor of 0.16 and a minimum damping factor of 0.015, adjusted adaptively during iterations.

The inversion was terminated automatically when the relative change in RMS error between two consecutive iterations fell below 5%, or when the iteration count reached 5. For this profile, the RMS error decreased to 9.8% after five iterations; further iterations did not significantly improve either the RMS error or the resistivity distribution, indicating convergence. The slightly elevated RMS error is attributed to the complex fill composition, strong electrical heterogeneity, and near-surface interference. Nevertheless, the 9.8% misfit remains within an acceptable engineering range, and the anomaly interpretations were highly consistent with the field seepage observations, further validating the reliability of the inversion results.

Table 1. Characteristic Table of High-Density Electrical Method Detection Profiles

Survey line No.	Start chainage	End chainage	Elevation (m)	Layout position	Array type	Electrode spacing (m)
Line 1	K0+220	K0+550	12.3	Embankment crest	Wenner	3.0

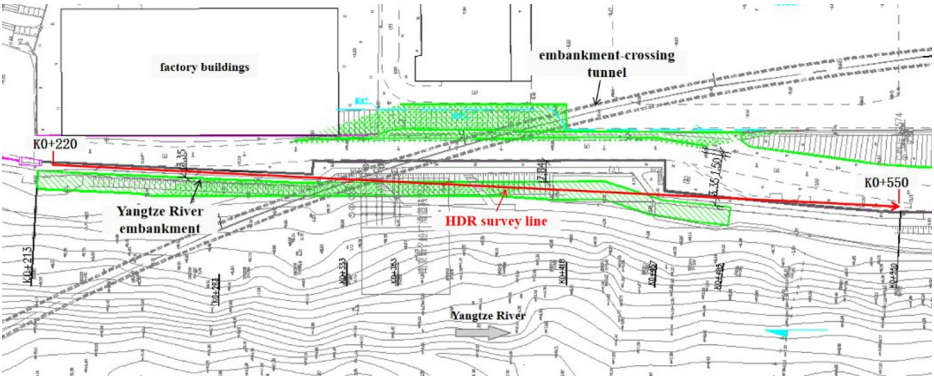


Fig. 1. Field arrangement of HDR survey lines



Fig. 2. Field deployment of detection instruments

4 Detection Results

At the time of detection, the river water level was 9.4 m, and the detection depth was 43 m. The two-dimensional resistivity section of the embankment obtained from inversion is presented in Fig.3. The overall resistivity distribution of the embankment shows no obvious regularity, which is directly related to the poor uniformity of the embankment body and foundation soils mentioned earlier. Under high water levels, the soil moisture content below the phreatic line is higher than that in the upper part of the embankment, so the resistivity of the embankment body is generally higher than that of the underlying foundation; this is consistent with the general law of seepage in embankments. Most of the soil in the embankment body exhibits resistivities higher than 160 Ω·m, appearing as a relatively high-resistivity zone, while most of the foundation soil has resistivities below 100 Ω·m, and the interface between the embankment body and the foundation is relatively clear.

In the vicinity of K0+340, a river-crossing tunnel passes beneath the embankment. The air in the tunnel should appear as a high-resistivity feature on the resistivity tomogram. According to the inversion results, in the range of K0+325–K0+348, below

elevation –2.5 m, a high-resistivity zone is displayed, which is generally consistent with the location of the tunnel.

Analysis identified three low-resistivity anomalous zones in the embankment, as follows:

(1) K0+258–K0+288, elevation 3.7 m to –5 m: soil resistivities range from 5 Ω·m to 15 Ω·m, differing from the surrounding soil, indicating a low-resistivity anomaly. It is inferred that the soil in this zone has a relatively high moisture content. This anomaly is located within the foundation and does not extend into the embankment body, so it is classified as a general seepage-risk area. The upper embankment body has resistivities generally >50 Ω·m; the shallower the depth, the higher the resistivity and the lower the moisture content.

(2) K0+310–K0+325, elevation 7.0 m to –2.5 m: this is a low-resistivity anomalous zone with soil resistivities of 1 Ω·m to 10 Ω·m, forming a closed low-resistivity loop that contrasts sharply with the surrounding soil. This indicates extremely high moisture content, and the zone includes the interface between the embankment body and foundation, making it a high-risk seepage area.

(3) K0+362–K0+367, elevation 10 m to 0 m: soil resistivities range from 5 Ω·m to 15 Ω·m, showing a vertical strip-like low-resistivity anomaly that penetrates both the embankment body and foundation. This indicates that, under high seepage pressure, a connected pathway has formed between the foundation and the embankment body, reflecting poor compactness of the soil in this area, and it is a high-risk zone for seepage. Moreover, this zone shows low-resistivity connectivity with the area below the foundation at K0+379–K0+398, with an obvious contrast to the surrounding soil.

Field inspection revealed extensive ponding at the toe on the land side of the embankment from K0+355 to K0+410, indicating that seepage failure had already occurred in this section. This is highly consistent with the location of the low-resistivity anomaly at K0+362–K0+367. The anomaly is relatively shallow and its upper part lies within the embankment body, which matches the situation where piping points appear on the embankment. It is inferred that this location is the piping outlet for the current seepage emergency. Meanwhile, sporadic seepage (damp spots) began to appear at the toe of the land-side slope near K0+320, which is presumed to be directly related to the low-resistivity anomaly at K0+310–K0+323. Under high seepage pressure, internal seepage channels within the embankment are developing and extending, and there is a high probability that this area will evolve into piping; immediate measures should be taken. The low-resistivity zone at K0+258–K0+288 shows clear water-rich characteristics, but its influence is mainly below the embankment body. No water gushing or seepage was observed on the embankment surface in this section, but it represents a weak point of the embankment, and the risk of seepage failure under extreme conditions remains relatively high.

It is worth noting that the current validation of anomalous zones relies primarily on the spatial correspondence between surface seepage manifestations and resistivity anomaly sections, without borehole verification or in-situ permeability tests, so a quantitative relationship between resistivity and moisture content cannot be established. This is mainly because: (i) drilling at high-risk seepage locations under high seepage

pressure may induce or exacerbate seepage failure of the embankment; and (ii) the complex site conditions during emergency response are unfavorable for drilling operations.

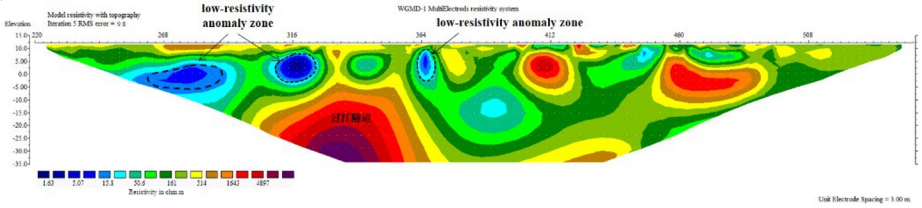


Fig. 3. Resistivity inversion image of Line 1

5 Conclusions

Based on the electrical characteristics of embankments under high water levels during flood seasons, and combined with the emergency seepage detection case of the Yangtze River embankment, this paper conducts a feasibility study on the application of the high-density electrical resistivity method for detecting seepage defects in embankments, and draws the following conclusions:

(1) Under high water level conditions during flood seasons, weak zones within the embankment – such as loose soil, cavities, and soft interlayers – exhibit increased moisture content and significantly reduced resistivity, forming electrical contrasts with the surrounding soil, manifested as closed low-resistivity loops or beaded low-resistivity zones. This is the fundamental basis for using the high-density electrical method to detect seepage defects. Compared with detection at low water levels outside the flood season, detection at high water levels is more favourable for identifying defects above the phreatic line.

(2) Through the emergency detection of the Yangtze River embankment, the location of piping was successfully identified, and the weak zones and high-risk seepage areas within the detection range were delineated, demonstrating that the high-density electrical method is relatively suitable for emergency embankment detection under high water levels. It can also provide early targeting for emergency flood-fighting efforts, reduce the blindness of "blocking wherever leakage occurs", make on-site responses more targeted, and provide a basis for post-flood reinforcement works.

(3) The high-density electrical method shows certain advantages in emergency embankment detection, but it is mainly used as a single-time detection during or after the occurrence of hazards, lacking continuity and comparative analysis of detection data at the same location. Therefore, this paper suggests that a feasible future development model is to install fixed high-density electrical resistivity monitoring systems on key embankment sections to achieve long-term dynamic monitoring of embankment electrical parameters, combined with hydro-meteorological data and water level monitoring information, to establish an early warning model for embankment seepage safety.The proposed technical route is as follows: (i) Establish a sensing system by installing permanent electrode arrays connected via multi-core cables to an automatic data acquisition unit. (ii) Set up a data transmission system that uses wireless modules to upload the collected resistivity data to a cloud database, with acquisition frequency adjustable

as needed. (iii) Develop a seepage risk prediction model by inverting the long-term resistivity time series, extracting characteristic parameters such as low-resistivity anomaly locations and resistivity variations, and integrating concurrent water level and rainfall data. (iv) Based on the risk probabilities output by the model, implement a multi-level early warning system, with alerts simultaneously pushed via SMS, mobile applications, and monitoring platforms to support flood-control decision-making and emergency deployment.

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