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Review and rebuttal of the paper

Geophysical monitoring of large-scale levee overflow experiments with electrical resistivity tomography

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Editor handling the paper: Miguel Esteban

Reviewers remain anonymous

Reviewer B

The manuscript evaluates the use of electrical resistivity tomography (ERT) in monitoring subsurface changes during overflow field experiments conducted as part of Polder2C's. The experiments involved increasing overflow discharges on a damaged landward slope of a dike affected by animal burrowing. ERT was applied beneath road plates along the landward slope, providing insights into the internal dynamics of the subsoil, such as water content. The observed trends in the measurements were logically explained.

Major comments

Comment 1

From the introduction, it seems that the authors aim to investigate the internal dynamics of a damaged landward slope of a levee during overflow, particularly since animal burrowing caused unexpected failure in previous experiments. However, in this study, the animal burrowing was covered with road plates. It is not entirely clear how the hydraulic loading and internal dynamics were affected by the presence of the road plates. Could the authors clarify this point?

Response comment 1

We appreciate the reviewer's observation regarding the impact of road plates on hydraulic loading and internal dynamics during overflow. Indeed, the scope of this study was to monitor the internal dynamics of the levee subsurface during overflow, and our ERT monitoring results successfully captured and explained these processes.

The road plates altered the hydraulic loading and erosion processes by eliminating the shear stress that water would typically exert on the grass surface beneath them. This reduction in surface erosion likely decreased the magnitude and severity of internal erosion beneath the plates. Such load-reduction capability is one of the reasons road plates are considered a potential emergency measure during high-water events.

Quantifying the exact extent to which the road plates mitigated internal erosion requires further research. Ideally, future experiments should compare levee sections with similar designs and conditions, both with and without road plates, to isolate the plates' effect. However, such experiments are logistically challenging and rare, making it difficult to conduct such a study in the short term.

It is worth noting that a similar rigid covering was used during the Polder2C's project on another test section. In that experiment, a pre-existing scour hole (approximately 1.5 × 1.5 m in surface area and 50 cm deep) was covered with plywood and a plastic foil lining before being subjected to overtopping. The hydraulic load in that test was significantly higher than in our overflow experiment, with flow velocities reaching up to four times greater than the maximum velocities in our study. Despite these higher hydraulic loads and the vulnerable initial conditions, the rigid covering effectively mitigated further erosion.

This evidence supports the conclusion that rigid coverings like road plates can provide reasonable protection against erosion during high-water events. While road plates may be less robust than the plywood-plastic covering used in the Polder2C's experiment, their performance under lower hydraulic loads demonstrates their potential utility.

For further context, we invite readers to view the Polder2C's test video, which illustrates the effectiveness of such a rigid covering: https://www.youtube.com/watch?v=fezDbEyeLkU.

Comment 2

It is not clear why dataset 2 is incomplete, as it could have provided valuable insights into the internal dynamics without the road plates (or animal burrowing?). Did the cable fail when exposed to the overflowing water? If so, does this raise concerns about the suitability of ERT for overflow experiments (P8-194, P9-215)?

Response comment 2

The cables are robust to weather and overflowing experiments. In case severe flow speeds are expected, one should consider ever safer pin installations. The choice of not using it depends purely on the acquisition time. Each cycle of measurements takes some time to be measured and it heavily depends on the array used as also the number of pins deployed. Simply putting, double the number of pins requires (about) double the acquisition time. In our scope we wanted to have the highest frequency during the overflow experiment and thus we used measures from cable 1 only. The way to overcome is either to use system with more channels (we used 8 but there are systems with 12 or more channels available) in a way that for each injection of current we can measure more data points. Alternatively, someone can consider using multiple systems, as long as they are far away from each other, to avoid interfering with each other (typically at least 4 times the depth of investigation).

Some additions were made in P8-194 and relevant recommendations were added in the final discussion.

Comment 3

Within the manuscript, ERT is described as a 'non-invasive monitoring tool' (P1-8) and a ‘non-destructive’ technique (P17-466). However, Fig. 7 and P9-200 indicate that stainless steel pins with electrodes need to be inserted into the ground, and cables are required between the electrodes. Could the authors clarify whether this method of measurement affects the overflowing water? For instance, could the stainless steel pins potentially increase permeability in the subsoil? How does this align with the claim of being non-invasive/non-destructive?

Response comment 3

Electrical Resistivity Tomography (ERT) is a non-invasive geophysical technique used to map subsurface properties, such as soil composition and moisture content, without disturbing the environment. During ERT surveys, electrodes (or pins) are inserted into the ground to measure the electrical resistivity at various depths. These electrodes are typically placed at shallow depths, often no more than a few cm below the surface (in this case about 10-15cm), ensuring minimal disruption to the soil. The pins are designed to be small (diameter about 2-3 cm) and placed carefully, ensuring that the soil structure and ecosystem remain undisturbed. Since ERT does not require excavation or the removal of soil, it is considered environmentally safe, providing valuable data without compromising the integrity of the land.

When the pins used in Electrical Resistivity Tomography (ERT) are removed, the impact on the soil is typically minimal. The electrodes are usually inserted into the ground only a few centimeters deep, and their removal does not disturb the surrounding soil structure significantly. In most cases, once the pins are taken out, the small holes left behind close naturally due to the soil's cohesion and moisture content. This ensures that the surface remains largely undisturbed, and the integrity of the soil is preserved. Since ERT is non-invasive, there is little long-term environmental impact, and the site is generally safe after the procedure, with no lasting effects on the soil's physical or chemical properties.

A paragraph with relevant clarifications was added in the final discussion.

Minor comments

Page	Line	Comment
2	18	From P1-10 to P1-18, the applicability of field tests for understanding different failure mechanisms is discussed, while in P1-18, specific measurements for the overtopping/overflow failure mechanism are provided without mentioning it explicitly. Perhaps the authors could clarify that these measurements are particularly relevant to the overtopping/overflow mechanism. **Response:** Clarification added in lines 18-19.
2	37	In P1-37 to P1-50, the authors introduce the choice of the test section and outline the objectives. However, it is not entirely clear whether the ERT tests were a primary or secondary objective in these experiments. Clarifying this distinction could provide more context for some of the choices made in the experimental setup. **Response:** The ERT tests were a secondary objective, yet the primary focus of this paper. Clarifications added in lines 45 and 52-55.

3	58	The statement “Large-scale overflow experiments on levees have been carried out quite often over the past decades” appears to contradict P1-16, where it is stated, “Opportunities for in-situ tests are scarce.” It would be helpful to clarify whether the former refers to controlled experiments and the latter specifically to in-situ tests, as this distinction may resolve the apparent contradiction. **Response:** It was indeed an overstatement to say that large-scale overflow experiments took place quite often. ‘Quite often’ was replaced by ‘several times’ in the text to prevent misconceptions. Additionally the sentence in line 17 was adjusted as follows “Opportunities for such in-situ tests are scarce, especially for tests that can be continued beyond the onset of damage.”
3	73	The sentence starting with "The parameters … material composition" is a bit unclear and doesn’t flow well within the context. The authors might consider rephrasing it for better clarity and smoother integration with the surrounding text. **Response:** Sentence replaced by ‘The parameters that have the greatest influence are moisture content, followed by material composition’.
5	Fig. 1	For clarity, it might be helpful to indicate which side of the levee is the water side and which is the landward side. **Response:** Clarification added on the figure.
5	Fig. 2	Left figure: The red text is difficult to read and might benefit from a larger font size or a different color for better contrast. **Response:** Adjusted. Right figure: It is unclear what the red line represents. Could the authors clarify if it marks the crest of the dike? **Response:** Carification added in the caption of the figure.
6	144	The slope is indicated as 8/3. Does the author mean this the other way around (3V:8H)? Additionally, expressing the slope as 1/2.67 might be easier to understand. **Response:** 8/3 was replaced by 3V:8H in the text.
6	150	It would be helpful to specify what is meant by extreme loads and to clarify which types of loads the interconnected cavities are more vulnerable to (e.g. flow velocity, flow discharge, etc.) **Response:** It is yet unknown which load parameters the cavities are most vulnerable to. ‘Extreme loads’ was replaced by ‘overflow and / or overtopping conditions, although there are no studies that clarify specific load parameters that the cavities are most vulnerable to’.
6	Fig. 3	In Fig. 3, the test section is indicated on the hinterland, behind the dike. **Response:** Figure corrected.

6	Fig. 4	Clarifying these points could improve the interpretation of Fig. 4: The waterside of the dike is labeled as 'River side.' However, 'River' may not fully capture the intended meaning in this context, as the Western Scheldt is estuarine. **Response:** ‘River’ replaced by ‘Water’. The labels are missing of the small cross-section plot are missing. **Response:** Labels added. Additionally, the color of the outline of the dike in the cross-section is unclear. Does it correspond to the dike height? **Response:** Clarification added in the caption. Typo: in the legend of the larger figure: the ‘r’ is missing in interconnected. **Response:** Corrected.
7	168	The unit used for the amount of overtopping is m3/min, which does not account for the length of the test section. To ensure consistency with other literature, it is suggested to use m3/s/m (or m3/min/m) instead. **Response:** True, the **width** (not length) of the test section is not incorporated in this passage, dealing with the water supply system. This is not dependent on the width of the test section. Here, only one section, of 2 m wide, is described. Readers should be able to translate the 66 m3/min over a 2 m wide section to 66 m3/min/2 m = 33 m3/min/m = 550 m3/s/m (= 550 m2/s). Text adjusted accordingly.
8	Fig. 6	Vertically mirroring the bottom-right picture might improve alignment with the left picture, as it would place the crest at the top in both images, enhancing visual consistency. **Response:** Figure adjusted.
8	Fig. 7	In the figure, the numbers 1 and 82 appear quite small and are difficult to read. It might help to increase their font size or adjust their placement for better visibility. **Response:** Figure adjusted.
9	200	Could the authors specify the length of the stainless steel pins used in the experiments? Including this detail would help better understand the experimental setup. **Response:** The pins are 10cm long. Specification added in the text.
9	211	The authors might consider using the term “flow discharge” instead of “flow rate,” as it is more specific and aligns better with the units provided. **Response:** Agreed.

10	230	The reason provided for switching the protocol from “shallow” to “deep” is not entirely clear. Could the authors elaborate on the rationale behind this change? **Response:** The paragraph is adjusted to clarify this point better.
10	254	The authors might consider elaborating further on the methods used to filter out the erroneous measurements. Were these filtered manually or through an automated process? **Response:** Filtering is a rather complex procedure, especially considering time lapse data. There is no (easy) automated way to remove bad data points, thus a geophysist is always needed in the setup of a project. Someone has to consider the following: A) error from bad bin connection (coupled with the ground) B) random error from the measuring system C) error originated from modeling There are several steps needed to be addressed and it's an iterative process. We feel more details from the process does not fit in this work. Some relevant reference can be found in these references: Time-lapse three-dimensional inversion of complex conductivity data using an active time constrained (ATC) approach M Karaoulis, A Revil, DD Werkema, BJ Minsley, WF Woodruff, A Kemna Geophysical Journal International 187 (1), 237-251, 2011 4D time-lapse ERT inversion: introducing combined time and space constraints M Karaoulis, P Tsourlos, JH Kim, A Revil. Near Surface Geophysics 12 (1), 25-34, 2014 78 This answer was integrated in the data processing section.

11	276	The model’s accuracy is assessed using the RMS misfit, which quantifies the spread in a model. However, from this metric it does not capture potential biases in the model. **Response:** In this work to avoid bias to the model since the starting model is half space. As it has been shown in the past, the final results can be much better if a prior model is used. But we didn't do that in this work. A second bias comes from the regulazization parameter. In the references one can see the effect of the different regularization on the days and we have added this on the text. Our answer was integrated in the data processing section (last paragraph).
11	282	It is not clear whether the term “Experiment” here refers to the ERT experiment listed in Tab. 2. **Response:** Yes, the term refers to ERT experiment. A relevant clarification was added in the text.
11	287	It appears that P11-287 to P11-291 are identical to P11-282 to P11-286. **Response:** This was an oversight. We’ve deleted the repetition.
11	302	The statement “Since the top 60 cm of the soil is in a clay layer” may need further clarification. Since the top of the clay layer has a grass cover and roots within it, could this have an effect on the measured resistivity? It might be helpful to discuss how these factors could influence the results, if at all. **Response:** You are correct that the grass cover and root system in the top layer of the soil could potentially influence resistivity measurements. Grass roots and organic matter in the upper soil layer can introduce small-scale variations in resistivity due to their effects on soil structure, moisture retention, and ionic conductivity. However, in this study, we consider these factors to have minimal impact on the overall resistivity trends observed. The primary reasons are: A) Depth of measurement: The resistivity readings are influenced by the bulk soil properties over the entire measurement depth, which extends beyond the grass root zone. While grass roots can alter the very top layer of the soil, the influence diminishes as we go deeper into the clay layer, which constitutes the bulk of the resistive properties. B) Moisture distribution: Although the root zone may affect localized water retention, the experiments involved controlled overflow tests using fresh water, ensuring consistent saturation patterns. This limits the variability introduced by surface vegetation. C) Scale of influence: The study focuses on detecting significant resistivity changes associated with large-scale features such as saturated zones and voids. The grass and root effects are likely to be minor compared to these larger influences. To further clarify, we revised the sentence to reflect this consideration. Additional reflection of the topic was added in the discussion section.

12	Fig. 9	Fig. 9 to Fig. 13 have the toe of the dike on the left side of the plot and the crest on the right side. The authors might consider horizontally mirroring these plots to align with Fig. 4. This left-to-right notation, from crest to toe, is commonly used in other publications related to wave overflow and wave overtopping. **Response:** This adjustment would be indeed helpful, but not essential for understanding the results. In the interest of time, we prefer to continue without this correction.
12	329	Only experiments 2 to 5 are described. Is this because experiment 1 is considered the initial measurement? **Response:** Yes. A relevant clarification was added in the text.
12	343	Are the blue areas entirely attributable to mole digging, or are these trends also visible in areas where the road plates overlap/provide an opening? **Response:** The blue areas are only attributable to mole digging. The configuration of the road plates does not influence the resistivity values along the line of measurements.
14	384	Within the manuscript, X is used to indicate the position on the slope. However, it is not clear how this position relates to specific locations on the slope. A figure, similar to Fig. 4, with X on the X-axis could help clarify the relationship between the described observations in Chapter 4 and the actual slope. **Response:** This would be indeed helpful, but not essential for understanding the results. In the interest of time, we prefer to continue without this adjustment.
16	433	The authors mention that the road plates affect the erosion. It would be helpful if the authors could elaborate on this and clarify how the road plates might influence the hydraulic loading and infiltration. **Response:** This is addressed in the answers given to Reviewer C. A relevant section was also added in the discussion.
17	456	The authors mention that the levee slope may reach a temporary state of equilibrium under sustained flow conditions (P17-456 to P17-462). What is the effect of the road plates on this? Do the authors expect the same interpretations if the road plates were not applied? **Response:** We do not expect the same results at all without road plates. Due to the road plates, there is much less flow directly on and inside the soil, leading to lower velocities and hence (much) less erosion. Clarifications were added in the text.
17	469	The authors associated a change in resistance to the water content of the soil (e.g. P12-312). Could deformation of the soil, such as the collapsing of cavities, also contribute to this reduction in resistivity? Can the authors distinguish between these two processes using ERT measurements? **Response:** The reduction in observed resistivity can be attributed not only to increased water content but also to soil deformation, such as the collapse of

		cavities. Soil deformation alters the pore structure, reducing air-filled voids and increasing water-filled pore connectivity, contributing to resistivity decreases. Distinguishing between these processes using ERT is challenging as both affect resistivity similarly, but three indicators could help. The first one is spatial patters. Resistivity drops localized around known high-resistivity areas (e.g., mole burrows) may indicate cavity collapse. The second indicator is temporal trends. Rapid changes might indicate water infiltration, while slower changes may point to soil deformation. The third indicator is depth variations. Water infiltration affects shallow layers, while cavity collapse may show deeper changes. While ERT provides valuable insights, distinguishing specific mechanisms like cavity collapse requires additional validation methods. It is recommended that future studies focus on integrating ERT with other techniques that allow relevant validations. This text was added in the discussion section.
18	492	The authors address several important points about the reliability of the ERT results. Could they provide suggestions or recommendations on how to validate these measurements in future studies? **Response:** Some approaches for validation of the measurements can be 1)benchmarking against independent techniques, controlled experiments, numerical modeling, repeatability studies, and post-experiment analyses. The section was expanded to elaborate on this.
18	510	In this study, the authors applied ERT below the road plates. Could ERT also be applied within the overflowing water itself, and if so, what challenges or considerations might arise? Yes. See response to reviewer's C first question.
18	511	It appears that P18-511 to P18-520 are identical to P18-493 to P18-502 **Response:** Indeed. This was an oversight. The duplication was removed from the text.
19	532	The manuscript describes ERT as a "non-destructive" technique (P17-466). However, Fig. 7 and P9-200 show that stainless steel pins with electrodes are inserted into the ground. How does this align with the claim of being non-destructive? Could the setup influence the overflow or erosion process or increase subsoil permeability? **Response:** Already addressed in our responses to the main comments.

Reviewer C

Comment 1

The work presented here has the potential to be super, but it is difficult to see what the utility of the work is when the dike surface was covered with plates, or at least, this must be better explained. The progression of dike morphology visualized in a vertical plane and varying in time is something I don't think we've been able to observe in the field before. Super technique and results. However, the presence of "road plates" covering the measurement area and preventing erosion there, is very confusing. How applicable are the results to real life? This needs to be quantified somehow, to show utility. Utility of the work must be clear in order for it to be publishable.

Response comment 1

We understand the reviewer’s concerns regarding the impact of the road plates on the erosion process and the resulting implications for the utility of the presented ERT monitoring system. While the road plates likely reduced the magnitude of surface erosion, they did not entirely prevent internal erosion processes, as evidenced by the resistivity changes observed during the experiments. This confirms the ability of the ERT system to monitor internal erosion dynamics even under these conditions.

The road plates provided a significant advantage for performing high-resolution ERT measurements by enabling continuous data collection during active flow conditions. This allowed us to create a dense time series of resistivity measurements (every 3–6 minutes), capturing the internal dynamics in real time. However, we acknowledge that there are alternative methods for securing the electrodes that could allow resistivity measurements during flow without the need for road plates. For example, stronger mounting points at the beginning of the cable and pins soldered directly to the cable could ensure that electrodes remain securely in place even under high flow velocities. Another possibility would involve suspending the pins from a platform, with the cable suspended in the air and the platform’s feet positioned outside the flow area. This design could weigh around 10 kg and would be relatively straightforward to implement. A third scenario involves operating the system under continuous flow conditions with the cable fully submerged. In such cases, the pins may not be necessary, as the current can flow directly from the submerged cable to the ground. The primary function of the pins is to inject current into the ground in configurations where the cable takeout is above the surface.

To address the influence of the road plates on subsurface dynamics, we recommend further research into alternative electrode configurations and sensor coverings that minimize interference with the hydraulic and erosion processes. A promising approach could involve flexible, watertight coverings such as ethylene propylene diene monomer (EPDM) foil. Small EPDM patches (e.g., 25–50 cm^2) could be used to cover individual sensors, isolating them from the flow while allowing measurements during overflow. These patches could be pinned to the ground in a manner similar to the road plates but with reduced interference on surface erosion. A potential challenge with this approach is that securing the EPDM patches would likely require metal pins placed closer to the sensors than in the current setup, which could introduce noise in the resistivity measurements. To address this, synthetic pins could be explored as an alternative. Further research is needed to optimize the configuration to ensure minimal noise while maintaining negligible interference with subsurface dynamics.

In summary, the presented ERT monitoring system offers valuable insights into internal erosion processes during overflow, even with the limitations posed by the road plates. The dense time series of resistivity measurements provides a unique capability to observe the progression of infiltration and cavity expansion under realistic testing conditions. While alternative setups such as improved electrode mounting or flexible coverings could enhance applicability, we believe the current findings demonstrate the system's significant utility and potential for advancing the understanding of internal erosion processes.

Comment 2

Fig 1. The axis titles and labels are not clear. Is this a spatial/elevation map? This needs to be stated/clarified. The colorbar also is not readable; I guess the colors show resistivity of a slice of the dike, but this is not clear.

Response comment 2

Clarification added in the caption.

Comment 3

Fig 4a. What is the meaning of the color along the dike surface? This should be stated.

Response comment 3

Clarification added in the caption.

Comment 4

Line 180. What are "synthetic road plates"? The purpose of these plates also is not clear. Do they prevent scour of the dike surface? How does this affect the processes occurring inside the dike?

Response comment 4

Synthetic – made of a kind of plastic. In essence, non-metal, therefore not having a low resistivity to electric flows. (The other questions are already addressed elsewhere.)