

ENHANCING DAM MONITORING: UTILIZING THE CR-INDEX FOR ELECTRONIC CORNER REFLECTOR (ECR) SITE SELECTION AND PSI ANALYSIS

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ABSTRACT

Traditional methods for monitoring embankment dams and gravity dams typically rely on on-site geodetic measurements, such as pendulum devices, trigonometry, and Global Navigation Satellite System (GNSS) technology. However, the feasibility of these instruments is often constrained by factors such as cost and accessibility. In such cases, satellite remote sensing, particularly Persistent Scatterer Interferometry (PSI), can offer a valuable alternative. Despite its cost-effectiveness in measuring deformations, PSI is not universally applicable to all dams due to various geometric factors. To address this limitation, the CR-Index provides insights into the suitability of PSI for monitoring specific structures. This study focuses on the development and application of the CR-Index for embankment dams and gravity dams in Western Germany. Based on the results, well-suited dams were equipped with innovative electronic corner reflectors to enhance their visibility in radar imagery and enable a more effective PSI analysis.

Index Terms— Sentinel-1, Dam monitoring, CR-Index, MTInSAR, PSInSAR

1. INTRODUCTION

Persistent Scatterer Interferometry (PSI) [1] can provide valuable additional information for the monitoring of dams, as various studies have already shown [2, 3]. This is also demonstrated by the freely available online results of ground motion services [4, 5, 6]. However, as indicated by the different number of resulting PS points for various dams, not every object can be observed with equal effectiveness. This variability can be attributed, on one hand, to the division of dams into embankment dams and gravity dams, and on the other hand, to the specific geometric factors at the site. These factors may include the orientation of the dam in geographical space or disruptive influences such as slopes or

vegetation. To assess the applicability of the PSI technique, the so-called CR-Index was developed [7, 8].

This index considers both geometric information and land use data. In this study, the CR-Index is adapted for use on dams to subsequently assess the applicability of the PSI technique for different dam objects. This adaptation is applied equally to embankment dams and gravity dams. Furthermore, the CR-Index will also be used to determine whether the observability of certain dams can be improved by installing electronic corner reflectors. Thus, a comprehensive observation strategy for various dams will be developed, which includes not only the well-represented class of embankment dams in the literature [2, 9, 10] but also gravity dams that have been less observed so far [2].

2. STUDY AREA AND DATA

2.1. Study area

In this study, we focus our investigation on two dams operated by the Ruhrverband in North Rhine-Westphalia, Germany. Both are illustrated in Figure 1, in addition to their approximate locations in Germany. The Möhne Dam is a gravity dam, measuring 650 meters in length and 40 meters in height, oriented from northeast to southwest [11]. The reservoir, situated southeast of the dam, holds nearly 134.5 million cubic meters of water. It collects water from a 436 square kilometer catchment area, playing a crucial role in the water supply for the entire Rhine-Ruhr region [12, 13].

The Bigge Dam, located south of the Möhne Dam, is a rockfill dam and the second object of investigation. It features a crest length of 640 meters, with its greatest height above the valley floor being 52 meters [14] and has a total storage capacity of almost 171.7 million cubic meters of water, a portion of which is also impounded by the Lister Dam (21.6 million cubic meters) [15]. The catchment area of the Bigge Dam spans 287 square kilometers.



Figure 1: Möhne Dam (top) and Bigge Dam (bottom) as well as their approximate locations in Germany.

2.2. Data

A substantial number of input parameters are required for the computation of the CR-Index, which were derived from three primary components. Given that this study focuses on the observability of dams using Sentinel-1 data, geometric information such as the local incidence angle as well as metadata are necessary. These parameters can be directly extracted from the Sentinel-1 dataset. The specifics of the data are presented in the table below.

Table 1: Attributes of the Sentinel-1 data used in this study.

Flight direction	Ascending	Descending
Type	SLC	SLC
Beam Mode	IW	IW
Path	15	139
Frame	164	421

In addition to the Sentinel-1 data, a Digital Elevation Model (DEM) is required for the processing. For this purpose, the high-resolution LiDAR DEM provided by the Geodata Infrastructure North Rhine-Westphalia (GDI NRW) is utilized [16]. Additionally, land cover information from the GDI NRW, which is derived from the official topographic-cartographic information system of the state of North Rhine-Westphalia (ATKIS), is integrated into the processing of the CR-Index [16].

3. METHODOLOGY

The R-Index, which preceded the development of the CR-index, was processed according to the model outlined in [7]:

$$R_{Index} = -\sin\{[S * \sin(A_{Asc})] - \sin(\gamma)\}. \quad (1)$$

In this context, S represents the slope inclination, A_{Asc} denotes the local slope orientation angles of the ascending trajectory, adjusted to the north direction, and γ symbolizes the Sentinel-1 incidence angle.

However, this step encompasses only purely geometric information. Given that the performance of the PSI technique is also significantly influenced by land cover, it is logical to incorporate corresponding information. This is achieved by augmenting the R-Index to form the CR-Index [8], which includes ATKIS data from the state of North Rhine-Westphalia [16]. This data facilitated the development of a Land-Use-Index (LUI), based on methodologies found in the literature [8, 17]. The LUI provides insights into the identifiability of PS points based solely on land use characteristics. The table below presents examples of various land use classes, whereas higher values represent a higher possibility to identify PS points:

Table 2: Examples of Land-Use-Index classes in this study.

Class	LUI
Forest	0
Water	0
Railway	0.5
Mixed-used area	0.8
Transportation infrastructure	0.8
Residential Area	1

4. RESULTS AND DISCUSSION

Figure 2 displays the CR-Index results for the Bigge Dam in both flight directions, while Figure 3 presents the results for the Möhne Dam, also in both flight directions. Areas exhibiting high CR-Index values are noticeable on the crest of the Bigge Dam for both flight directions, suggesting the suitability of the PSI technique for observation in these areas. However, it is important to note the contrast between the two flight directions, which is primarily due to the differing viewing angles of the satellite. In particular, the asphalt-covered water side of the dam is more easily observable, while the air side, covered with grass and partially with trees, exhibits poorer values. A building complex located in the middle of the dam displays high values in both flight directions. The Bigge Dam, with its extensive vegetation cover, generally shows lower values compared to the Möhne Dam. The gravity dam's construction, being a large structure made of quarry stone, ensures high values in both flight directions, though a contrast between both flight directions is still observable.

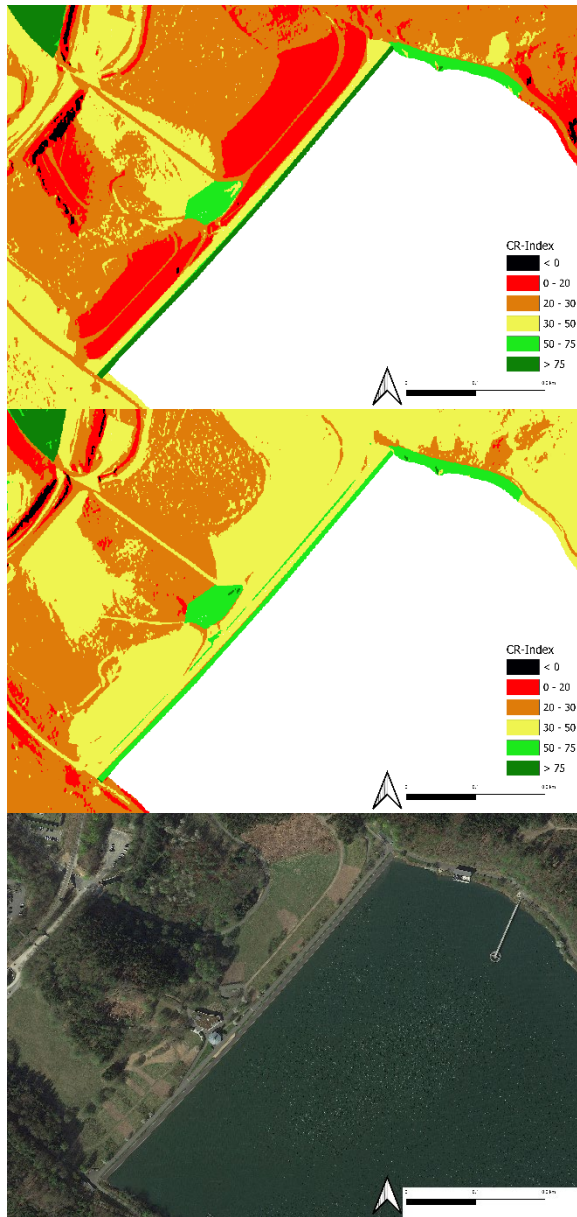


Figure 2: CR-Index results for the Bigge Dam. Top: Ascending orbit; Middle: Descending Orbit; Bottom: Google Satellite Imagery.

The orientation of the dams in geographic space significantly influences the CR-Index values, particularly for the descending direction, which tends to yield better results. In the ascending direction, the air side of the dam, which faces away from the reservoir, consistently shows lower values. Generally, slopes that are directly facing the satellite sensor provide lower values compared to those that are slightly angled away from the sensor [8]. These findings offer vital insights into the topographical and geometrical characteristics of dams on site.

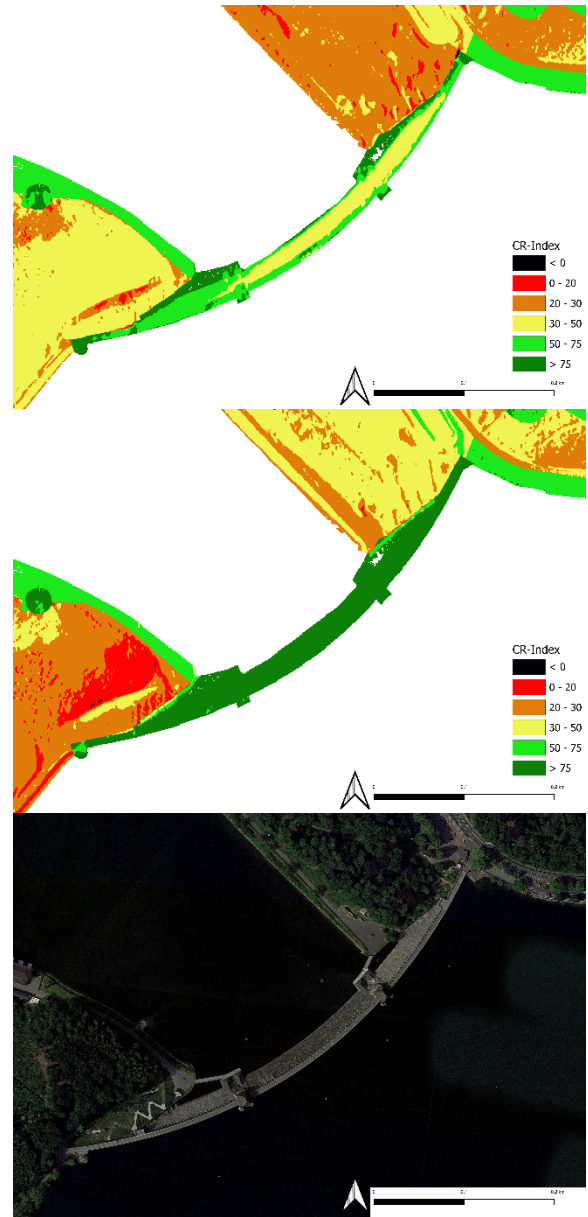


Figure 3: CR-Index results for the Möhne Dam: Top: Ascending orbit; Middle: Descending Orbit; Bottom: Google Satellite Imagery.

The results clearly demonstrate how topography and geographical orientation impact the observability of embankment dams and gravity dams when utilizing PSI. Prior to conducting a more intricate PSI analysis, an initial assessment with the CR-Index can be highly beneficial. This approach allows for preliminary conclusions about the observability of individual segments of the dam structures.

Due to the on-site geometric conditions, observability using PSI can be particularly challenging, especially in the case of dams. Consequently, the index is employed in conjunction with other parameters to identify optimal

locations for installing electronic corner reflectors (ECR). This strategy aims to enhance the effectiveness of PSI in observing dams, as will be explored further in an extension of this study.

5. CONCLUSION AND OUTLOOK

The CR-Index has proven to be an effective tool for developing an operational observation strategy for dams. Given that each dam presents unique geometrical and topographical conditions, it's crucial to estimate their observability beforehand. In this case study, the CR-Index was applied to two dams managed by the Ruhrverband.

This approach was part of a broader investigation that encompassed a total of five different dams. Moving forward in the study, the index was also utilized to pinpoint appropriate sites for the installation of electronic corner reflectors. This current study sets the stage for a subsequent analysis, wherein these ECRs were deployed on the dams and monitored over time for stability. Following this, a PSI analysis will be conducted to evaluate the effectiveness of the ECRs in enhancing the monitoring of dam objects while utilizing the PSI technique.

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