

# InSAR 기술을 활용한 콘크리트 궤도 침하 계측의 정확도 평가

## Accuracy Evaluation of InSAR-Based Concrete Track Settlement Measurement

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**Abstract** Concrete tracks experience greater usability degradation and have more limited maintenance options compared to ballasted tracks when settlement occurs. Therefore, to ensure track stability, the allowable residual settlement of the subgrade is strictly regulated to be within 25 mm. In South Korea, settlement pins are installed at 5 to 10 m intervals along both up and down tracks of high-speed lines, and settlement is measured using leveling surveys. Recently, Interferometric Synthetic Aperture Radar (InSAR) technology, which enables precise measurement of ground surface displacement over large areas, has gained attention, and efforts are being made to apply it to concrete track settlement monitoring. However, to replace conventional leveling surveys, it is essential to verify the accuracy of InSAR-based settlement measurements. In this study, InSAR technology was used to measure settlement in the embankment section of the Honam high-speed rail, and the results were compared with leveling survey data to assess accuracy. Through this analysis, the applicability of InSAR-based concrete track settlement monitoring was evaluated, and a quantitative comparison with the conventional leveling method was conducted.

**Keywords** : InSAR, Concrete track, Settlement, Leveling

**초 록** 콘크리트궤도는 침하가 발생하였을 경우 자갈도상궤도에 비해 궤도의 사용성 저하가 크고 보수 방법이 제한적이기 때문에, 노반의 허용 잔류 침하량을 25 mm 이하로 규정하고 엄격하게 관리하고 있다. 침하 관리를 위해 국내에서는 고속선 선로를 따라 매 5 ~ 10 m 마다 상·하선 궤도 중앙에 침하핀을 설치하고 레벨측량을 통해 궤도 침하를 계측한다. 최근 넓은 영역의 지표면 변위를 정밀하게 측정할 수 있는 간섭 합성 개구 레이더(InSAR, Interferometric Synthetic Aperture Radar) 기술이 주목받고 있으며, 이를 활용한 콘크리트궤도 침하 모니터링이 시도되고 있다. 그러나 기존 레벨 측량을 대체하기 위해서는 InSAR 기반 침하 계측의 정확도를 검증하는 연구가 필수적이다. 본 연구에서는 호남고속선 토공 구간의 콘크리트 궤도 침하를 InSAR 기술을 이용하여 계측하고, 이를 레벨 측량 결과와 비교하여 정확도를 분석하였다. 이를 통해 InSAR 기반 콘크리트 궤도 침하 모니터링의 적용 가능성을 평가하고, 기존 측량 방식과의 정량적 비교를 수행하였다.

**주요어** : InSAR, Concrete Track, Settlement, Leveling

### 1. Introduction

Track settlement is a critical issue in railway infrastructure, as it can degrade train safety and ride comfort. In particular, concrete track systems require strict settlement management because maintenance is more difficult than for ballasted tracks, and even small settlements can lead to significant reductions in serviceability. To mitigate these issues, Korean high-speed railways specify a maximum allowable residual subgrade settlement of less than 25 mm; however, in cases of basin-shaped residual settlement, the allowable value may be increased to up to 60 mm by correcting the large vertical curve radius[1]. Continuous monitoring is therefore conducted to ensure compliance with these criteria.

At present, the settlement of concrete tracks in Korea is primarily measured through periodic leveling surveys. Settlement pins installed at intervals of 5–10 m along high-speed railway lines are used to perform precise leveling measurements, enabling accurate quantification of settlement. Despite its high accuracy, the leveling method has inherent limitations,

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including sparse spatial coverage and substantial labor and time requirements. Moreover, it is difficult to achieve continuous and wide-area monitoring of settlement using conventional leveling surveys alone.

In recent years, satellite-based Interferometric Synthetic Aperture Radar (InSAR) technology has attracted considerable attention as a powerful tool for high-resolution measurement of ground surface deformation over large areas. InSAR utilizes multi-temporal satellite SAR images to quantify surface displacements and offers the advantage of cost-effective, wide-area monitoring compared to traditional ground-based surveying techniques [2,3]. Owing to these advantages, InSAR has been widely applied to the monitoring of land subsidence, seismic deformation, landslides, and infrastructure-related ground movements. Qiao et al.[4] employed Sentinel-1 imagery and the persistent scatterer InSAR (PS-InSAR) technique to monitor land subsidence across a broad area of the Texas Gulf Coast from 2016 to 2022 and analyzed the primary causes of subsidence. Kobayashi et al.[5] used ALOS/PALSAR data and InSAR analysis to investigate crustal deformation induced by the Mw 7.0 earthquake in the Fukushima–Hamadori region and proposed corresponding fault models. Macchiarulo et al.[6] proposed a GIS-integrated InSAR time-series analysis framework for infrastructure monitoring and applied it to road networks in Los Angeles and highway networks in Italy to evaluate deformation of roads and bridges.

In Korea, efforts have also been made to develop monitoring systems for infrastructure under construction and operation using InSAR technology. Kim et al.[7] monitored surface displacement occurring during the construction of the Manduk–Centum underground road connecting the east–west axis of Busan Metropolitan City using Sentinel-1 A/B SAR data. Kim et al.[8] applied the PS-InSAR technique to monitor time-series displacement of Yongdam Dam and evaluated dam stability by analyzing localized deformation characteristics. In addition, ground surface deformation along the Honam High-Speed Railway and its surrounding areas has been monitored, and the results have been used to conduct risk assessments and to provide baseline information for railway safety and maintenance management[9].

However, for InSAR technology to serve as an alternative to conventional leveling surveys, rigorous validation of measurement accuracy is essential. This requirement is particularly critical for concrete track systems, where the allowable residual settlement is limited to 25 mm. Although InSAR-based settlement measurements are generally reported to achieve accuracy on the order of several millimeters, results can be influenced by atmospheric disturbances, spatial resolution limitations, and scattering characteristics; moreover, studies evaluating the accuracy of InSAR for linear infrastructure, such as railways, remain limited. Kim et al.[9] introduced an artificial vertical displacement of up to 35 mm to a cluster of corner reflectors installed at the Osong Railway Test Track. They reported discrepancies of approximately 2–12 mm in deformation measurements obtained using TerraSAR-X-based differential InSAR (D-InSAR). Sungkyunkwan University[10] installed 17 corner reflectors along the Honam railway line and confirmed that settlement values derived from PS-InSAR and leveling surveys generally fell within the error range of first-order leveling. However, these studies relied on corner reflectors, which are specifically designed to return incident electromagnetic waves directly back to the sensor, enabling highly stable displacement measurements at specific locations. As a result, the accuracy of InSAR-based measurements may be overestimated relative to practical applications involving natural scatterers along railway tracks.

Therefore, this study aims to quantitatively evaluate the accuracy of InSAR-based settlement measurements for concrete tracks by directly comparing them with conventional leveling survey results and to assess the applicability of InSAR for railway settlement monitoring. Using InSAR data, settlement of concrete tracks was measured over selected embankment sections of the operational Honam High-Speed Railway for approximately two years, from 2016 to 2018, and the results were systematically compared with leveling survey data. This analysis examines the potential of InSAR technology to complement or partially replace conventional surveying methods and discusses strategies to improve the efficiency of future railway track maintenance.

## 2. Settlement Measurement Data and Accuracy Validation Methods

### 2.1 Settlement Measurement of Concrete Track on the Honam High-Speed Line Using Leveling Surveys

Settlement is a critical factor affecting both train safety and maintenance costs in high-speed railway infrastructure. In embankment sections, settlement progresses rapidly immediately after fill placement and is generally known to stabilize approximately five years after the commencement of operation. However, excessive settlement may still occur at locally

vulnerable sections, making continuous settlement monitoring essential even during the maintenance phase. Accordingly, in Korea, leveling surveys have been employed to evaluate the settlement of concrete tracks precisely, and the results are continuously reviewed to assess settlement stability and maintenance requirements.

In Korean high-speed railways, continuous settlement measurements are conducted both before and after opening to operation to manage residual subgrade settlement. During the construction phase, settlement is measured at the original ground surface and at the top of the embankment, followed by a stabilization period of at least six months after completion of embankment construction to allow residual settlement to converge. However, due to practical constraints in domestic construction environments, sufficient stabilization periods are often not ensured, thereby increasing the importance of continuous settlement monitoring during the post-opening maintenance phase. During this phase, settlement measurements reflect the combined effects of train loads, climatic conditions, and topographic characteristics. While measurements may be discontinued if no additional settlement is observed over a certain period, continuous monitoring is required at locations where settlement persists until stabilization is confirmed. In the embankment sections of the Honam High-Speed Railway between Osong Viaduct and Gwangju–Songjeong Station (total length: 182.3 km), settlement plates and settlement pins have been used for settlement monitoring, with leveling surveys conducted accordingly. Settlement plates were installed at the original ground surface and the embankment surface, and measurements were performed at 1,118 locations beginning in September 2013. Additional measurements were subsequently conducted at 1,063 locations starting in December 2015. Following the opening of the Honam Line, responsibility for settlement management was transferred from the Korea Rail Network Authority to Korail, resulting in partial data gaps and inconsistencies in certain measurement records.

Settlement measurements of the concrete track using leveling surveys are performed with settlement pins installed at the center of the track slab between the rails for both the up and down tracks. A total of 13,279 settlement pins (T1: 6,927 locations; T2: 6,352 locations) were installed with varying spacing depending on site conditions. In sections vulnerable to settlement, such as bridge–embankment transitions and soft-ground areas, pins were installed at 5 m intervals; in general embankment sections, a spacing of 10 m was adopted. Settlement pins were fixed by drilling holes with a hammer drill, injecting adhesive materials (e.g., epoxy), and inserting the pins. To minimize measurement errors, all pins were installed at the track centerline.

According to the Guidelines for Track Maintenance and Management issued by the Korea Rail Network Authority [11], the accuracy of leveling surveys should be maintained within  $\pm 1$  mm, and measured values should be recorded with a resolution of 0.1 mm. Leveling measurements are conducted using round-trip observations with closure, and the allowable closure error is specified as  $1.5\sqrt{S}$  mm, where  $S$  denotes the observation distance in kilometers. The guidelines also stipulate that continuous settlement measurements should be conducted at locations where subgrade settlement is progressing or converging, and that measurements may be terminated once settlement stabilization is confirmed. During the study period, the Honam High-Speed Railway was experiencing ongoing subgrade settlement, and Korail increased measurement frequency to ensure continuous monitoring. The embankment sections were divided into 98 segments based on structural characteristics, and settlement management was implemented by adjusting the leveling survey frequency according to the magnitude of observed settlement, as summarized in Table 1.

**Table 1.** Frequency of settlement measurement by leveling.

| Classification  | Criteria       | Frequency of settlement measurement by leveling    |
|-----------------|----------------|----------------------------------------------------|
| Defect level    | > 30 mm        | 4 times / year<br>Needs maintenance of restoration |
| Critical level  | (20 mm, 30 mm] | 4 times / year                                     |
| Caution level   | (10 mm, 20 mm] | 3 times / year                                     |
| Attention level | < 10 mm        | 2 times / year                                     |

Leveling surveys remain the most reliable method for settlement measurement of concrete tracks within the current railway maintenance framework. Nevertheless, because leveling surveys are conducted at discrete locations, spatial

coverage is inherently limited, and the method requires substantial labor and time. In addition, it is challenging to perform continuous monitoring across large areas using leveling surveys alone. Therefore, it is necessary to explore approaches that complement conventional leveling surveys with InSAR-based settlement measurements in future applications.

## 2.2 InSAR-Based Settlement Measurement of the Honam High-Speed Railway Concrete Track

InSAR (Interferometric Synthetic Aperture Radar) is a remote sensing technique that has been actively studied in recent years owing to its ability to acquire repeated observations over large areas using satellite platforms. Satellite-derived imagery can generally be classified into optical, infrared, and SAR data. Among these, SAR images are generated by transmitting microwave signals from a satellite-mounted antenna and recording the signals reflected from the Earth's surface and structures. Unlike optical imagery, SAR observations are mainly independent of weather conditions and solar illumination, making them particularly advantageous for detecting surface deformation over large areas. The wavelength of the transmitted microwave signal further categorizes SAR images. For infrastructure deformation monitoring, the ability to detect displacements at the millimeter scale is required. Consequently, shorter wavelengths, such as X-band SAR, are frequently used because they are more sensitive to small deformations. In contrast, C-band SAR is also widely employed for long-term time-series analysis.

SAR images are stored as complex-valued data containing both amplitude and phase information. InSAR analysis requires at least two SAR images acquired over the same area at different times. By analyzing the phase difference ( $\Delta\phi$ ) between two SAR images, displacement along the satellite's line-of-sight (LOS) direction can be estimated. When SAR image pairs with sufficiently large spatial baselines are available, three-dimensional topographic information can also be reconstructed using a Digital Elevation Model (DEM). However, when a single image pair is used, absolute displacement cannot be obtained directly due to phase ambiguity. To address this limitation, a DEM is commonly applied to remove the topographic phase component, after which relative surface displacement is estimated[12].

The fundamental principles of InSAR are conceptually illustrated in Fig. 1. The upper panel shows the SAR observation geometry, in which the satellite forms a synthetic aperture as it moves along its orbit, thereby improving azimuth resolution while observing the ground surface at a constant incidence angle ( $\theta_a$ ). The acquired SAR images contain backscattered signals within a given swath width. The lower panel illustrates how the phase difference ( $\Delta\phi$ ) between SAR images acquired at two different times is used to estimate displacement. By comparing the phases of the reference and reflected waves, LOS displacement can be derived and subsequently converted to vertical displacement by accounting for the

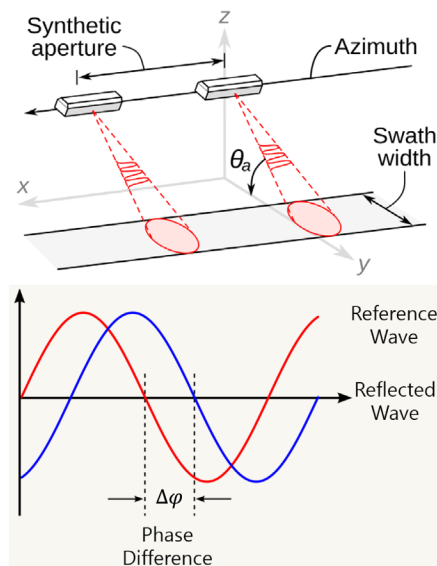


**Fig. 1.** SAR observation geometry (top) and principle of displacement measurement based on phase difference (bottom) (modified by authors [13]).

incidence angle [13].

InSAR can be implemented in various forms depending on the availability of persistent scatterers and image acquisition conditions. D-InSAR estimates displacement using two SAR images and is effective for detecting localized deformation. In contrast, PS-InSAR analyzes the time-series behavior of specific scatterers by integrating multi-temporal SAR images, offering significant advantages for long-term deformation monitoring. In general, surface displacement is investigated using 20–25 or more SAR images, although analysis with fewer than 12 images may be feasible depending on the study environment and data quality[14]. By generating multiple interferograms from multi-temporal SAR datasets, various error components—such as satellite orbit errors, DEM errors, and atmospheric delay effects—can be mitigated more effectively, thereby improving displacement accuracy. Unlike D-InSAR, which analyzes all pixels, PS-InSAR selectively processes only those scatterers that exhibit high backscattering intensity and stable phase behavior over time. By focusing on temporally stable scatterers, PS-InSAR effectively suppresses atmospheric effects and noise, enabling reliable long-term displacement analysis and precise deformation estimation[15]. Owing to these characteristics, PS-InSAR is particularly well suited to monitoring long-term deformation of infrastructure and has demonstrated strong potential for precise settlement measurements of linear infrastructures, such as railway tracks. Accordingly, PS-InSAR was adopted in this study to derive settlement information for the concrete track of the Honam High-Speed Railway.

In this study, PS-InSAR analysis was conducted using the SARscape module within the ENVI software environment to measure settlement of the Honam High-Speed Railway concrete track. After applying radiometric and geometric corrections to the SAR images, backscattering intensity images were generated. A master image and corresponding slave images were then selected, and interferometric processing was performed to generate coherence maps and interferograms. Using these products, persistent scatterers were identified, and displacements at the corresponding locations were analyzed. To achieve high accuracy, various parameter settings were systematically evaluated, and optimal parameters were selected for the final analysis. The detailed processing conditions and parameters used in this study are summarized in Table 2.

**Table 2.** Optimized PS-InSAR analysis parameters [16].

| Step                    | Parameter                             | Value                         |
|-------------------------|---------------------------------------|-------------------------------|
| Interferometric process | Looks[Azimuth, Range]                 | [2,2]                         |
| First inversion         | Sub-area coverage                     | 25 km <sup>2</sup>            |
|                         | Sub-area Overlap                      | 25 %                          |
|                         | Sub-area Coherence Threshold          | 0.60                          |
|                         | Minimum/maximum displacement velocity | -40 and 25 mm/yr respectively |
|                         | Number of reference point candidates  | 5                             |
| Second inversion        | Low pass filter                       | Adaptive                      |
|                         | High pass filter                      | 1200 m                        |
| Geocoding               | GCP/DEM import                        | DEM only                      |
|                         | Product coherence threshold           | 0.65                          |

### 2.3 Methodology for Accuracy Validation of InSAR-Based Settlement Measurements

Because the true settlement at a specific location of a concrete track is unavailable, this study evaluates the accuracy of InSAR-based settlement measurements by using precise leveling survey results as a reference benchmark. The accuracy assessment was conducted for four embankment sections of the Honam High-Speed Railway by quantitatively comparing settlement values derived from PS-InSAR analysis with leveling survey measurements obtained over the same period. S-InSAR-based settlements were obtained over an approximately two-year period from August 2016 to September 2018 and compared with leveling survey results from the same period. The PS-InSAR dataset consisted of SAR images acquired at an average interval of approximately 22 days, whereas leveling surveys were performed at approximately three-month intervals. To enable direct comparison between the two measurement methods, PS-InSAR-derived settlement values were

extracted from SAR images acquired within  $\pm 10$  days of each leveling survey date. Based on this temporal matching criterion, 12 corresponding epochs were identified during the study period and used for comparative analysis.

Spatial correspondence between the two datasets was established by matching each leveling-survey location to the nearest persistent scatterer (PS). Specifically, the vertical displacement of the closest PS located within a radius of approximately 2.5 m from each leveling settlement pin was selected as the InSAR-derived settlement value for that location. If no suitable PS was identified within the specified distance, the corresponding leveling point was excluded from the accuracy assessment. When multiple PS points were present within a 2.5 m radius, the average vertical displacement of those PS points was used to represent the InSAR-based settlement value. Through this preprocessing procedure, one-to-one matched pairs between leveling and InSAR measurements were constructed. Once the one-to-one correspondence was established, the difference between the leveling-based settlement ( $s_{level}$ ) and the corresponding InSAR-based settlement ( $s_{SAR}$ ) at each location was calculated. The mean error for each embankment section was then computed as expressed in Eq. (1).

$$\overline{\Delta s} = \frac{1}{N} \sum_{i=1}^N (s_{level,i} - s_{SAR,i}) \quad (1)$$

Here,  $\overline{\Delta s}$  denotes the mean difference in settlement between the two measurement methods for a given section,  $N$  is the number of settlement pins included in that section,  $s_{level,i}$  is the leveling-based settlement at the  $i$ -th location, and  $s_{SAR,i}$  is the corresponding InSAR-based settlement. A positive value of  $\overline{\Delta s}$  indicates a tendency for InSAR to underestimate settlement relative to leveling, whereas a negative value indicates overestimation. However, because positive and negative differences can cancel each other out, the mean error alone may underestimate the overall magnitude of discrepancies between the two methods. To address this limitation, the mean absolute error (MAE) was additionally calculated as defined in Eq. (2). The MAE represents the average of the absolute differences between leveling and InSAR measurements and provides an intuitive measure of the overall error magnitude. Lower MAE values indicate greater agreement between the two measurement methods.

$$MAE = \frac{1}{N} \sum_{i=1}^N |s_{level,i} - s_{SAR,i}| \quad (2)$$

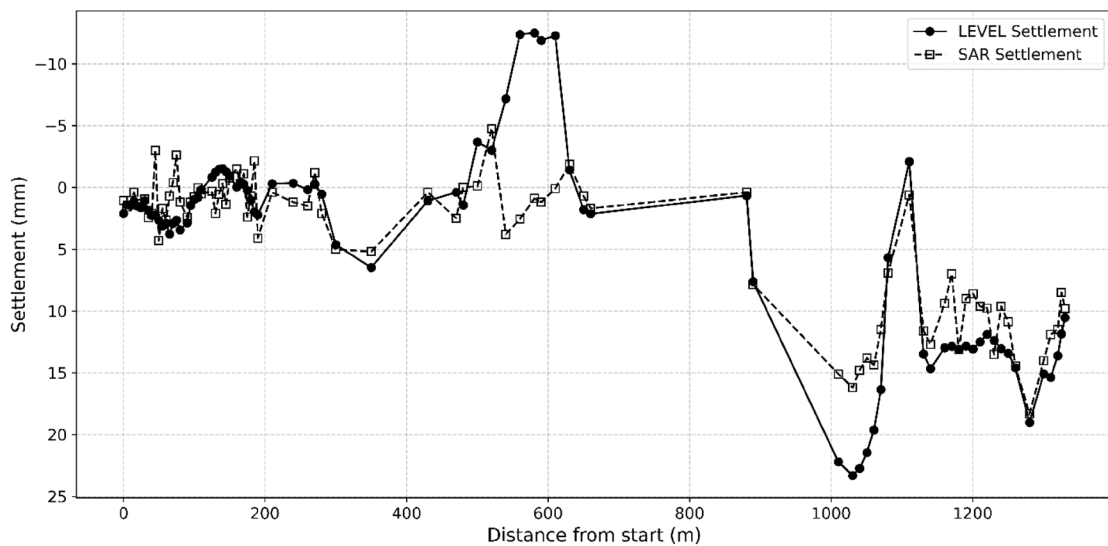
Discrepancies between leveling and InSAR measurements can vary from point to point. Mean error and MAE alone do not fully capture the distribution of these differences. To describe this, the standard deviation of settlement differences,  $\sigma_{\Delta s}$ , was calculated for each section, as shown in Eq. (3). The standard deviation shows how much individual differences deviate from the mean error. Smaller values indicate greater consistency and reliability in the agreement between the two measurement methods.

$$\sigma_{\Delta s} = \sqrt{\frac{1}{N} \sum_{i=1}^N [(s_{level,i} - s_{SAR,i}) - \overline{\Delta s}]^2} \quad (3)$$

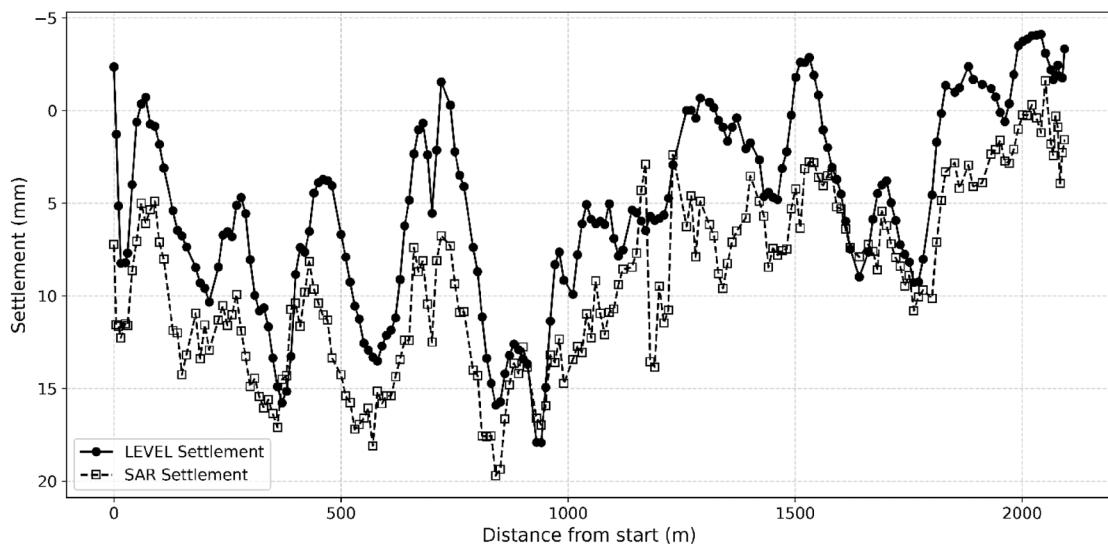
### 3. Results of Accuracy Validation

This section presents the results of the accuracy assessment conducted by comparing PS-InSAR-based settlement measurements with precise leveling survey results for four embankment sections of the Honam High-Speed Railway. Fig. 2 illustrates the comparison of cross-sectional distributions of total cumulative settlements derived from leveling surveys and PS-InSAR measurements for each embankment section (A–D) over the analysis period. At all locations, the overall shapes of the settlement profiles along the longitudinal direction are generally consistent between the two methods, and the locations of major settlement zones are commonly identified by both techniques. This indicates that PS-InSAR reliably reproduces the spatial settlement pattern along the track alignment and effectively detects zones of significant settlement.

In Section A, not only the shape of the settlement profile but also the magnitude of settlement closely agrees with the leveling results. However, sparse data points or gaps are observed in the interval between approximately 650 and 1000 m. This is attributed to radar shadow effects in this section, which prevented the acquisition of sufficient stable persistent scatterers (PSs), thereby limiting the estimation of settlements around the leveling pins using the PS-InSAR approach. In the remaining sections (B–D), the overall profile shapes show good agreement with the leveling results, while systematic biases are observed. In Section B, PS-InSAR generally yields larger settlement values, suggesting an overestimation bias, whereas in Section C, smaller settlement values are obtained than with leveling, suggesting an underestimation bias. Additionally, relatively large cumulative differences between the two methods are observed in certain sections. These discrepancies are interpreted as resulting from insufficient PS density, residual errors in DEM and atmospheric delay corrections, or systematic offsets related to reference point selection. To mitigate such discrepancies, measures such as reinforcing scatterer availability through corner reflector installation and utilizing high-resolution DEMs and external atmospheric correction

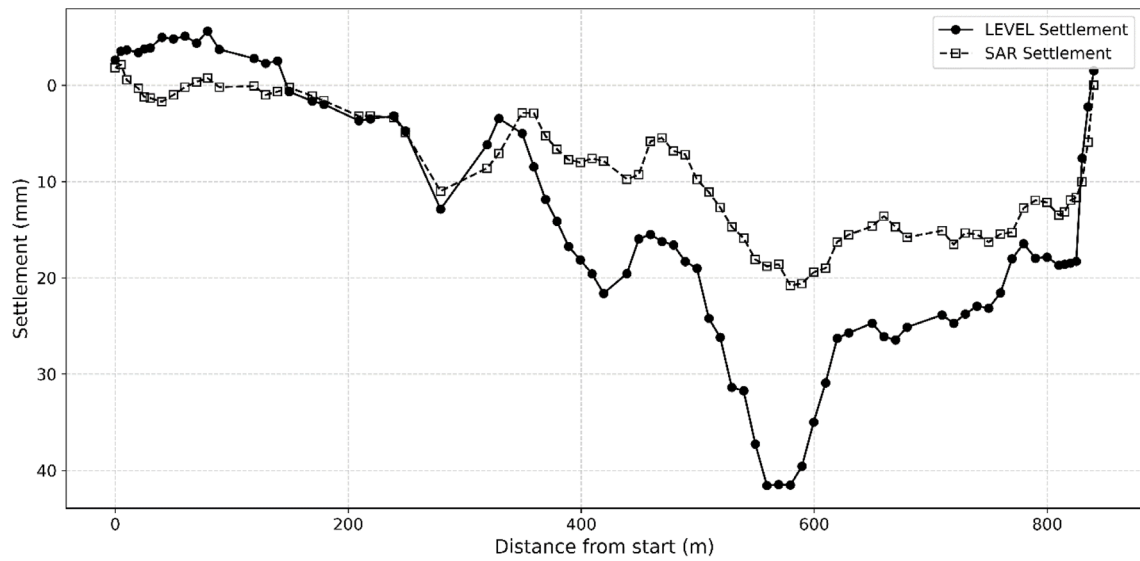


(a) Embankment Section A

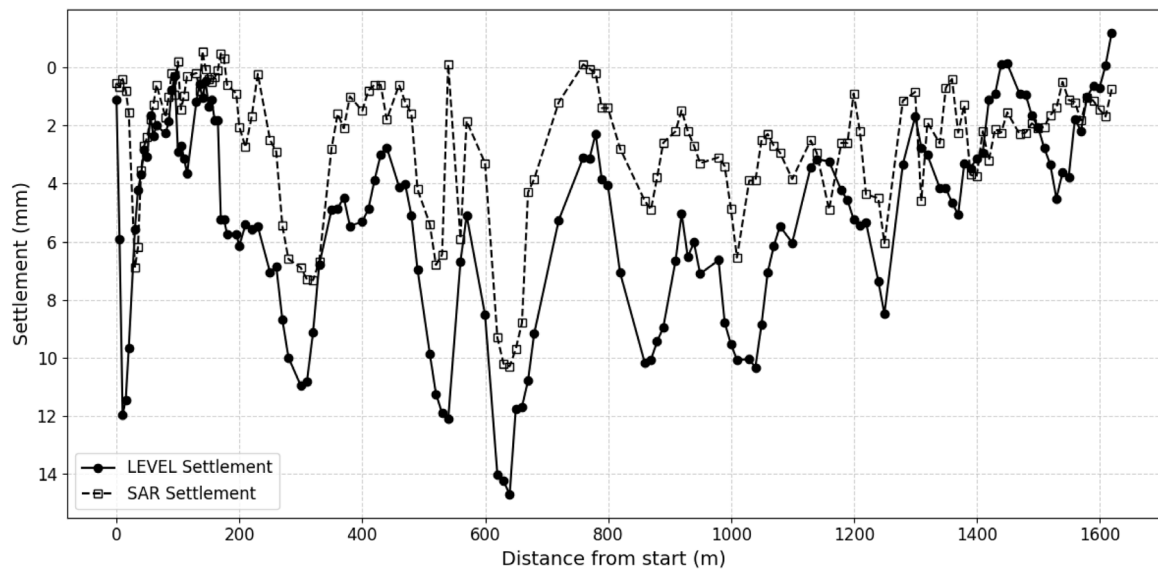


(b) Embankment Section B

Fig. 2. Cross-sectional profiles of cumulative settlement over analysis period from leveling and PS-InSAR.



(c) Embankment Section C



(d) Embankment Section D

Fig. 2. Continued.

data are required to further enhance the reliability of cumulative settlement estimation.

Next, the analysis was performed by averaging the settlement differences and their absolute values computed at each settlement pin over the 12 temporally matched epochs. Fig. 3 presents histograms of the settlement differences ( $\Delta s$ ) between the two measurement methods. For all sections, the differences exhibit approximately normal distributions centered around their respective mean errors. In Sections A and D, the differences are predominantly within  $\pm 5$  mm, demonstrating high agreement between PS-InSAR and leveling measurements. In contrast, Sections B and C show wider distributions within approximately  $\pm 8$  mm. In Section B, most differences are negative, indicating that the SAR-based method tends to overestimate settlement, whereas in Section C, the differences are predominantly positive, indicating an underestimation tendency. These section-specific biases and dispersions may be attributed to variations in PS density, atmospheric delay effects during SAR processing, or topography-induced interferometric phase distortions.

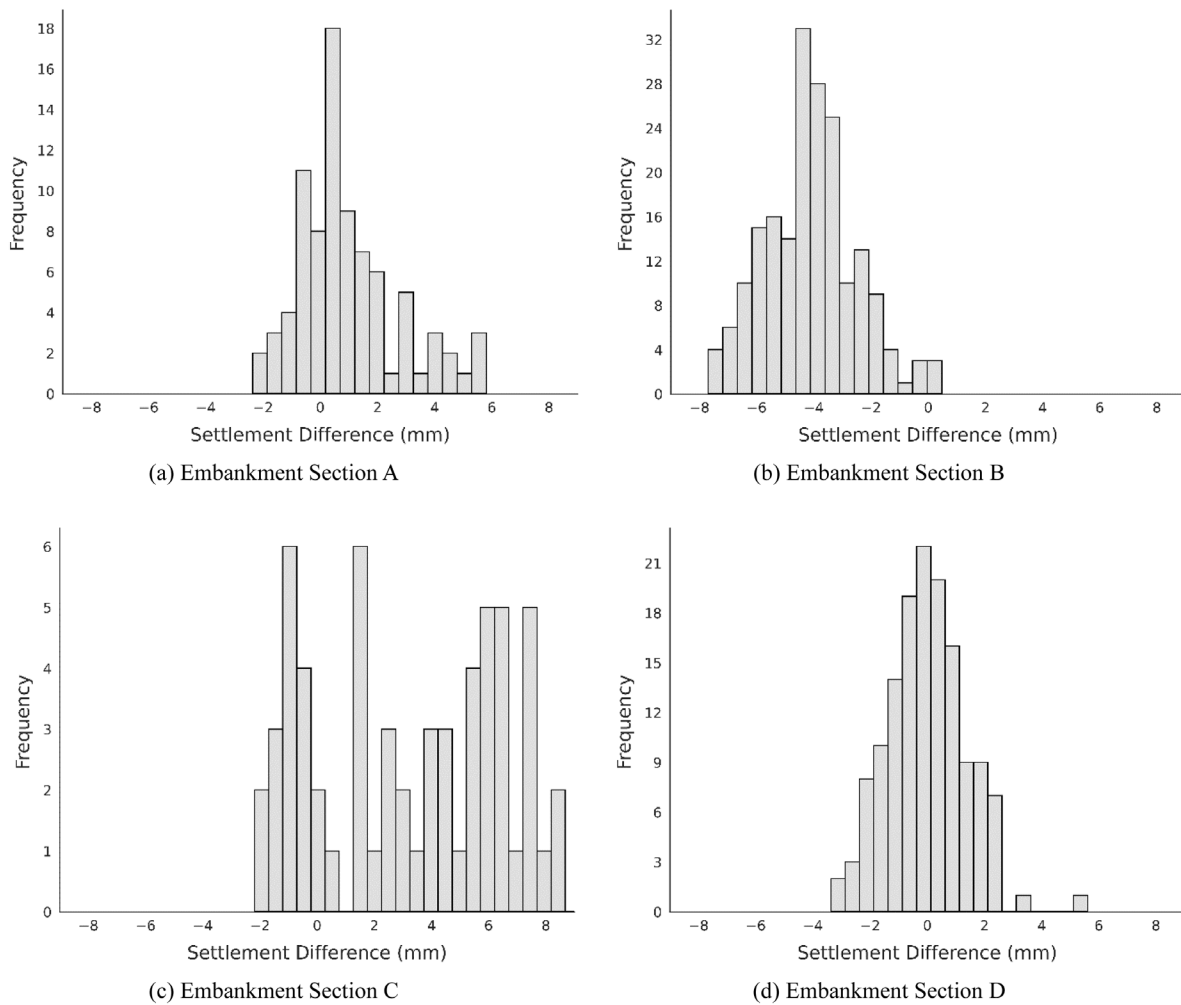


**Fig. 3.** Histogram of settlement differences estimated by leveling and PS-InSAR, averaged over 12 matched epochs.

Figure 4 shows histograms of the absolute settlement differences between the two methods. This approach allows direct evaluation of the magnitude of discrepancies without sign-cancellation effects. Most data points are distributed within 10 mm. Sections A and D show that errors below 5 mm are dominant. In contrast, Section C has a larger proportion of values exceeding 10 mm, suggesting reduced reliability of InSAR-based settlement estimation in this section. Sections B and C, which showed biased differences, exhibit distributions centered on the mean absolute error. Sections A and D, which have relatively small biases, display right-skewed distributions with longer tails toward larger error values.

Table 3 summarizes the mean error, mean absolute error, standard deviation, and the number of persistent scatterers per unit length for the four embankment sections. In Sections A and D, the mean errors are close to zero, indicating good agreement between PS-InSAR and leveling results. In contrast, Sections B and C show mean errors of  $-4.1$  mm and  $+4.9$  mm, respectively, revealing systematic biases in opposite directions. This suggests that PS-InSAR results may exhibit section-dependent systematic biases, underscoring the need for appropriate bias-correction strategies. The mean absolute error is highest in Section C at 6.0 mm, further indicating the relatively lower reliability of PS-InSAR measurements in this section. The standard deviation values for Sections A, B, and D are relatively low (1.78 mm, 1.59 mm, and 1.40 mm, respectively), indicating consistent differences between the two methods, whereas Section C exhibits a higher standard deviation of 4.7 mm, reflecting greater variability in errors.

The number of persistent scatterers per unit length is defined as the total number of PSs identified in each embankment

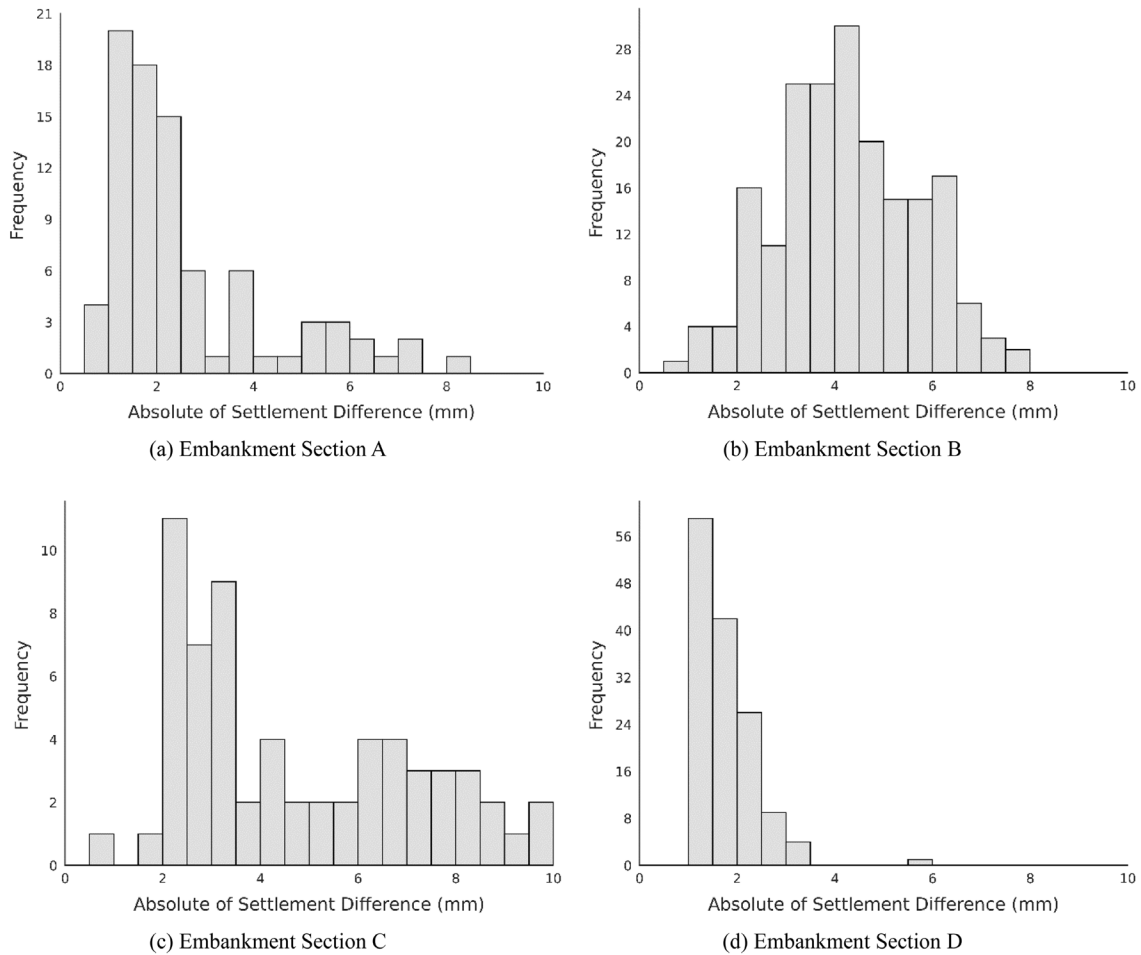


**Fig. 4.** Histogram of absolute settlement differences estimated by leveling and PS-InSAR, averaged over 12 matched epochs.

section divided by the section length and serves as a quantitative indicator of scatterer density. It is crucial for judging how reliable InSAR measurements are in each section. Typically, more scatterers yield more stable phase information, thereby making settlement estimates more accurate and consistent. Fewer scatterers make sections more likely to exhibit phase changes and to be affected by weather or noise, thereby lowering accuracy. As shown in Table 3, Section C has the lowest scatterer density at 0.24 points/m, suggesting insufficient scatterers, which reduced accuracy. Earlier studies found that the characteristics of a persistent scatterer depend strongly on the surrounding land cover [17]. Future work will examine additional areas and study land cover to understand its effects on settlement measurement accuracy better.

**Table 3.** Summary of analysis results on four embankment sections.

|                                        | Section A | Section B | Section C | Section D |
|----------------------------------------|-----------|-----------|-----------|-----------|
| Mean error (mm)                        | 0.978     | -4.102    | 4.859     | -0.006    |
| Mean absolute error (mm)               | 2.615     | 4.243     | 6.013     | 1.773     |
| Standard deviation of differences (mm) | 1.78      | 1.59      | 4.74      | 1.40      |
| PS per unit distance (points/m)        | 0.41      | 0.51      | 0.24      | 0.52      |

## 4. Conclusions

In this study, PS-InSAR was applied to measure settlements of concrete tracks in embankment sections of the Honam High-Speed Railway, and the accuracy of InSAR-based measurements was quantitatively evaluated by comparing them with precise leveling survey results. The main conclusions can be summarized as follows.

First, a comparison between leveling surveys and PS-InSAR measurements showed that both methods consistently reproduced the longitudinal settlement patterns along the track alignment. In particular, PS-InSAR successfully identified locations of sections with large settlements, demonstrating its effectiveness in detecting spatial settlement patterns along linear railway infrastructure.

Second, quantitative accuracy assessment indicated that the settlement differences between the two methods generally remained within  $\pm 8$  mm across all sections. Considering the allowable residual settlement criterion of 25 mm, this level of accuracy is deemed sufficient to support maintenance-related decision-making. However, section-dependent biases were observed, with PS-InSAR tending to overestimate settlement in Section B and underestimate settlement in Section C.

Third, comparison of the mean error, mean absolute error, and standard deviation revealed that PS-InSAR measurements exhibited larger bias and variability in certain sections. In particular, Section C showed relatively large errors, attributed to a low persistent scatterer density. This finding suggests that the accuracy of PS-InSAR-based settlement measurements is strongly influenced by the availability and stability of persistent scatterers.

Fourth, this study provides a practical validation case in which PS-InSAR was applied to an operating high-speed railway concrete track and rigorously compared with conventional leveling surveys. The results demonstrate that satellite-based settlement monitoring can be effectively used as a complementary tool within existing railway maintenance systems. In particular, PS-InSAR offers the potential to overcome the spatial and temporal limitations of leveling surveys by enabling wide-area and efficient monitoring.

Nevertheless, shadowed areas where settlements could not be estimated using PS-InSAR and sections where cumulative errors led to large discrepancies in total settlement were identified, and the measurement accuracy varied considerably among embankment sections. Therefore, when higher precision is required for embankment settlement management or when large local discrepancies are observed, PS-InSAR should be used in conjunction with leveling surveys. In addition, supplementary measures, such as installing corner reflectors to enhance scatterer availability and applying additional correction techniques, are recommended to improve the reliability of InSAR-based settlement monitoring.

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