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# Smartphone-Based Close-Range Photogrammetry for Monitoring Heritage Deformation under Extreme Subsidence: A Case Study of the Old Basilica of Guadalupe, Mexico City

## *Fotogrametría de corto alcance con teléfonos inteligentes para el seguimiento de la deformación del patrimonio en condiciones de hundimiento extremo: un estudio de caso de la Antigua Basílica de Guadalupe, Ciudad de México*

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**Abstract.** Smartphone photogrammetry offers a low-cost and accessible solution for monitoring surface deformation in urban environments. Subsidence, often caused by excessive groundwater extraction, leads to structural damage, ground fracturing, and long-term risks for cities like Mexico City. In the city center, average subsidence rates range from 9 to 10 cm per year, significantly affecting infrastructure and heritage sites. One of the most affected monuments is the Old Basilica of Guadalupe, a major historical and religious landmark built in 1709 and located in northern Mexico City. The basilica is part of the larger shrine complex dedicated to Our Lady of Guadalupe, one of the most visited Catholic pilgrimage sites in the world. It has suffered ground settlement since the early 20th century, with structural damage exacerbated by repeated seismic events, especially after the 2017 earthquake. This study evaluates the effectiveness of close-range digital photogrammetry using smartphone imagery to detect fracture evolution in the building. Two sets of images were acquired with a mid-range smartphone in April 2022 and March 2023, before

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and after the September 2022 earthquakes. The images were processed using Structure from Motion (SfM) techniques to generate 3D models for visual comparison and analysis of deformation patterns. Results show that, despite limitations in image resolution and lighting conditions, smartphone photogrammetry can effectively capture fracture propagation and tilt in architectural features. This method provides a practical and non-invasive tool for structural monitoring in sensitive or restricted-access sites. Its successful application in a major heritage building demonstrates the potential of smartphone-based photogrammetry to support routine damage assessments and long-term preservation strategies in subsidence-prone urban areas, particularly where conventional equipment is not feasible.

**Keywords:** Land subsidence, Cultural heritage, Anthropology, 3D monitoring, Close-range photogrammetry, Structure from Motion (SfM), Ground-based survey, Low-cost documentation.

**Resumen.** La fotogrametría con teléfonos inteligentes representa una solución accesible y de bajo costo para el monitoreo de deformaciones superficiales en entornos urbanos. La subsidencia, causada con frecuencia por la extracción excesiva de agua subterránea, provoca daños estructurales, fracturas en el terreno y riesgos a largo plazo para ciudades como la Ciudad de México. En el centro de esta urbe, las tasas promedio de subsidencia oscilan entre 9 y 10 cm por año, afectando gravemente tanto a la infraestructura como a las edificaciones históricas. Uno de los monumentos más afectados es la Antigua Basílica de Guadalupe, un importante sitio histórico y religioso construido en 1709, ubicado al norte de la ciudad. Esta iglesia forma parte del santuario dedicado a la Virgen de Guadalupe, uno de los destinos de peregrinación católica más visitados del mundo. La basílica ha presentado hundimientos desde principios del siglo XX, y su deterioro estructural se ha visto agravado por repetidos eventos sísmicos, en particular tras el de 2017. Este estudio evalúa la eficacia de la fotogrametría digital de corto alcance mediante imágenes tomadas con teléfono celular para detectar la evolución de fracturas en el edificio. Se capturaron dos conjuntos de imágenes con un celular de gama media en abril de 2022 y marzo de 2023, antes y después de los sismos de septiembre de 2022. Las imágenes fueron procesadas mediante técnicas de Structure from Motion (SfM) para generar modelos 3D y analizar visualmente los patrones de deformación. Los resultados muestran que, a pesar de las limitaciones en la resolución de imagen y condiciones de iluminación, la fotogrametría con celulares puede identificar de forma efectiva la propagación de fracturas y la inclinación de elementos arquitectónicos. Esta metodología representa una herramienta práctica y no invasiva para el monitoreo estructural en sitios sensibles o de acceso restringido. Su aplicación exitosa en un edificio patrimonial emblemático demuestra el potencial de la fotogrametría con teléfonos inteligentes para apoyar evaluaciones periódicas de daños y estrategias de preservación a largo plazo en zonas urbanas afectadas por subsidencia, especialmente donde el uso de equipos especializados no es viable.

**Palabras clave:** hundimiento del terreno, patrimonio cultural, antropología, monitorización 3d, fotogrametría de corto alcance, estructura a partir del movimiento (sfm), levantamiento terrestre, documentación de bajo coste.

## INTRODUCCIÓN

Surface deformation due to land subsidence is a growing concern in many urban areas worldwide, particularly in cities built on unconsolidated sediments and subject to intensive groundwater extraction. This phenomenon can lead to structural damage, differential ground movement, and long-term risks for infrastructure, public safety, and cultural heritage. Non-invasive techniques such as remote sensing have become increasingly valuable for monitoring ground deformation and assessing its impact on the built environment.

Mexico City is one of the most densely populated metropolitan areas in the world. Its foundation dates back to the pre-Hispanic city of Tenochtitlán, which was built on Lake Texcoco. Over the centuries, the lake was drained to make way for urban expansion and flood control. As a result, large portions of the city are now built on soft, water-saturated clay soils. These weak ground conditions, combined with decades of groundwater extraction, have led to significant land subsidence across the basin. Government agencies such as INEGI and CENAPRED, along with academic institutions, have documented average subsidence rates of 15 cm per year in the city, with maximum rates reaching 40 cm per year along the northeastern boundary with the State of Mexico. These processes have caused damage to roads, buildings, and underground infrastructure. Among the affected structures is the Old Basilica of Guadalupe (OBG), a historic church built in 1709 and part of the Tepeyac religious complex in northern Mexico City. Located adjacent to the Tepeyac Hill, the basilica is crossed by a documented fracture caused by differential ground movement between the hill's consolidated material and the surrounding lacustrine sediments. Evidence of damage includes structural tilt, floor settlements, and visible cracks on walls and columns. Subsidence-related ground deformation in Mexico City has been extensively documented, drawing attention from both researchers and government agencies such as INEGI and CENAPRED. Approximately 24% of the city's surface area is undergoing continuous sinking, primarily due to its foundation on the former lakebed of Lake Texcoco. This area was progressively drained as the city expanded and as part of historical flood control strategies, exposing the lacustrine clays beneath (González Aparicio & Nájera Zamora, 1968). These soft, poorly consolidated sediments, in combination with decades of groundwater extraction, have led to significant soil compaction and vertical displacement.

The most affected boroughs include Azcapotzalco, Gustavo A. Madero, Miguel Hidalgo, Cuauhtémoc, Venustiano Carranza, Benito Juárez, Iztacalco, Coyoacán, Iztapalapa, Tlalpan, Xochimilco, and Tláhuac (Carreón-Freyre, 2017). Regional subsidence rates average around 15 cm/year, with localized areas —such as Iztapalapa and Nezahualcóyotl— reporting even higher values (Solano Rojas et al., 2020). In particular, the borough of Gustavo A. Madero, in the northern sector of the city, has been identified in its municipal risk atlas as having a high likelihood of subsidence-related damage, especially in areas adjacent to Tepeyac Hill (SEDATU, 2014). The location of Mexico City, the borough of Gustavo A. Madero, and the Villa de Guadalupe—where the study site is situated—is shown in Figure 1.

As context, the deformation rate was calculated with the InSAR technique, with Sentinel 1 satellite images in the period from March 2024 to January 2025, resulting in 5 short-term deformation models shown in Figure 13.

Monitoring damage to heritage buildings affected by subsidence is challenging, especially when access is limited or when traditional methods would require closing the site to the public. Close-range digital photogrammetry is a non-invasive technique that enables the documentation of structures through 3D reconstruction based on overlapping photographs. Although drone photogrammetry has proven effective in similar contexts, its use in central Mexico City is restricted by aviation regulations, such as NOM-107-SCT3-2019, which prohibits drone flights within a 9 km radius of the city's airport. The Old Basilica of Guadalupe falls within this restricted zone, making drone-based surveys unfeasible. As a result, efforts have been made to develop ground-based photogrammetric surveys using smartphones. These surveys involve capturing photographs from ground level using a mobile device to generate 3D models for fracture mapping and structural assessment.

The purpose of this study is to evaluate the potential of smartphone-based close-range photogrammetry for monitoring fracture evolution in a heritage building affected by subsidence. Two surveys were conducted using a mid-range smartphone, one in April 2022 and another in March 2023. The objective was to compare the resulting models and assess changes in structural damage following the earthquakes of September 19 and 22, 2022, with magnitudes of 7.7 and 6.9, respectively. This approach offers a practical, low-cost, and non-invasive alternative for damage monitoring in restricted heritage sites. The study also highlights the value of using everyday devices like smartphones to document structural changes over time, providing useful data for both conservation efforts and the development of accessible monitoring protocols in subsidence-prone areas.

## STUDY SITE

This study focuses on the Old Basilica of Our Lady of Guadalupe, located within the Tepeyac Religious Complex in the borough of Gustavo A. Madero, at the foot of Tepeyac Hill. The basilica sits at approximately 19.4849° N latitude and 99.1169° W longitude (Figure 2), in a zone with a long history of ground instability. The site was built atop anthropogenic fills composed of weak, unconsolidated clay and silt layers, overlying sedimentary lacustrine deposits with low permeability (SEDATU, 2014). Beneath the structure, a large-scale ground fracture encircles Tepeyac Hill, attributed to differential subsidence between the hill's consolidated volcanic

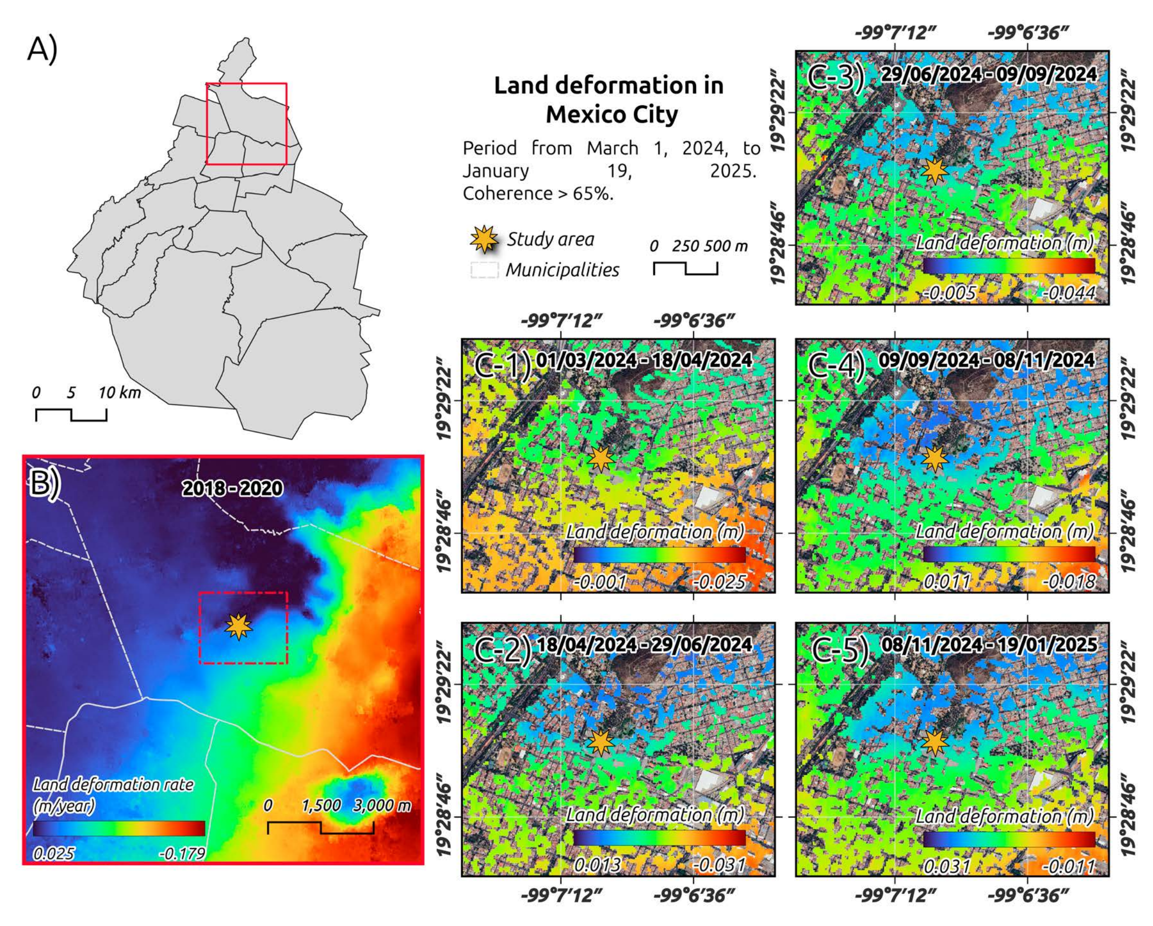

Figure 1. Regional ground deformation in Mexico City between March 2024 and January 2025 derived from InSAR data. The yellow star marks the location of the OBG, situated in a transition zone (~1 cm/month subsidence).

materials and the surrounding lacustrine basin. The spatial relationship between the fracture line and key structures in the area, including the basilica, is illustrated in Figure 2 (CENAPRED, 2017).

Gustavo A. Madero concentrates about 2.3% of all mapped ground fractures in Mexico City (CENAPRED, 2017). The physical characteristics of the soil, especially the high plasticity clays, contribute to the development of fissures, settlements, and structural damage. When groundwater is extracted, these clays shrink, lose volume, and trigger uneven subsidence across the urban landscape (Carreón-Freyre et al., 2006). The subsurface at the basilica site reflects these conditions, marked by a desiccated aquifer and limited recharge capacity.

The spatial context of the studied structures and their relationship to a major subsidence-related fracture is illustrated in Figure 3. The image shows the location of the Old Basilica of Guadalupe, the adjacent Ex-Convent of the Capuchinas, and the New Basilica, all situated near the base of Tepeyac Hill. A red line marks the path of a suspected geological fault, as documented by CENAPRED (2017), which appears to follow a curvilinear path around the hill and intersects the zone occupied by the heritage buildings. The alignment of this fracture corresponds to areas where significant structural damage—such as tilting, cracking, and foundation settlement—has been observed, reinforcing the hypothesis that dif-

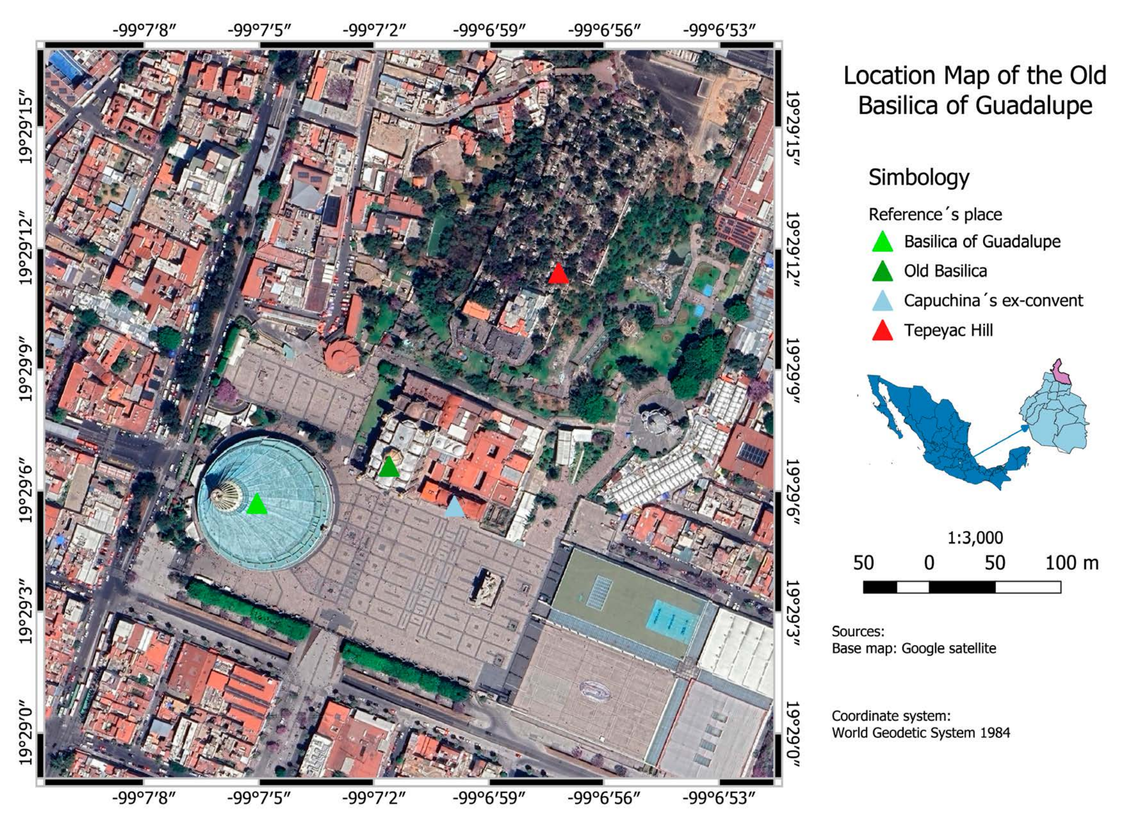

Figure 2. Location of the Old Basilica of Guadalupe. The panels show: a) the location of Mexico City within Mexico; b) the location of the borough of Gustavo A. Madero within Mexico City; c) the location of the Villa de Guadalupe within Gustavo A. Madero; and d) a detailed view of the Villa de Guadalupe.

ferential subsidence across heterogeneous subsoil conditions contributes to the ongoing deformation at the site.

Constructed between 1695 and 1709, the Old Basilica is a prominent cultural and religious monument. It was built near the site where Saint Juan Diego is believed to have encountered the Virgin of Guadalupe in 1531, making it a major destination for Catholic pilgrimage. Due to structural instability caused by subsidence, the building was declared unsafe in the 1970s, prompting the construction of a new basilica nearby. Today, the original structure exhibits visible tilting, cracks, and floor deformations, making it a critical site for testing low-cost, non-invasive monitoring technologies.

## METODOLOGY

### Materials

A close-range photogrammetric survey was conducted using ground-level images acquired with a mid-range smartphone. The device used was a POCO X3 Pro, equipped with a digital camera suitable for high-resolution image capture under daylight conditions. The camera's technical specifications are detailed in Table 1. Image processing and 3D reconstruction were performed in Agisoft PhotoScan Professional (version 1.4.5), using Structure from Motion (SfM) algorithms to generate the photogrammetric model from overlapping photographs.

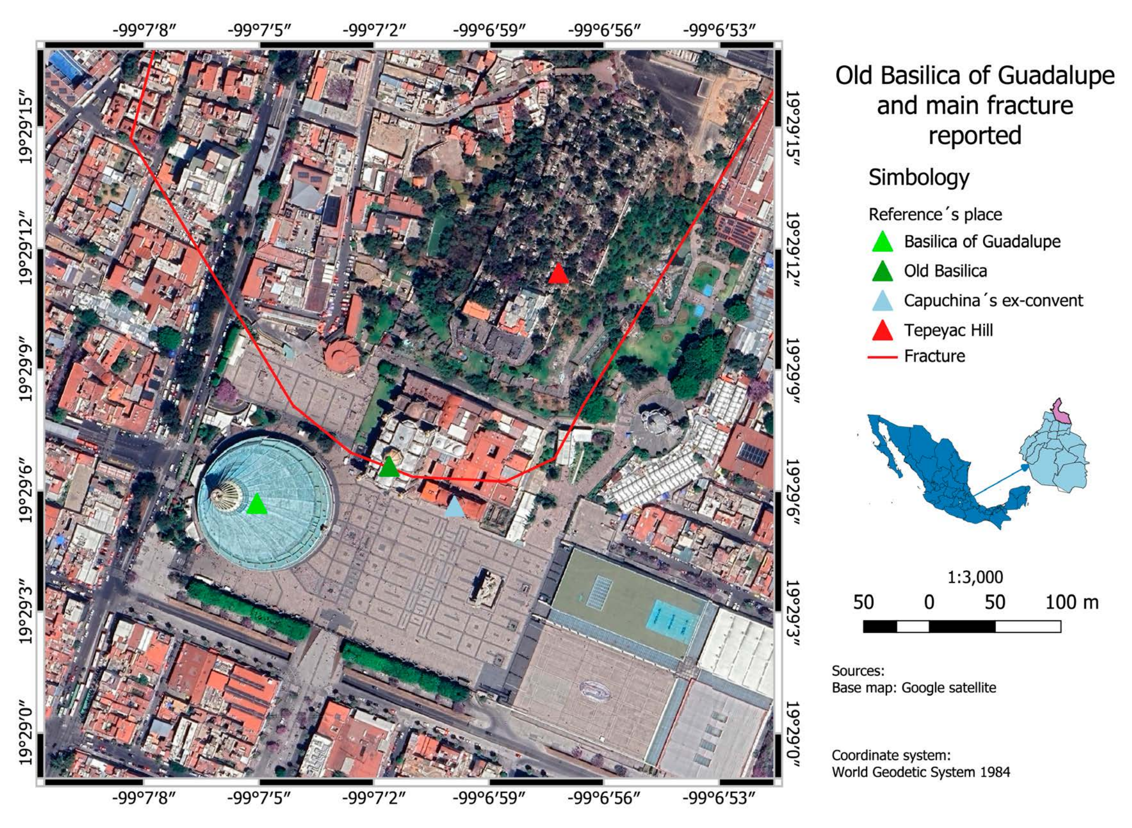

Figure 3. Location of the buildings studied, and the main ground fracture (red line) as reported by CENAPRED (2017). Images obtained from Google Earth.

Table 1. Smartphone camera specifications.

| Feature | Device Specifications |
|---|---|
| Camera resolution | 48 MP / 8 MP / 2 MP / 2 MP |
| Key features | Dual LED flash, Panorama, HDR photo, Night mode, Dual video |
| Aperture | f/1.79, f/2.2, f/2.4, f/2.4 |
| Number of cameras | 4 |

## Close-range photogrammetry workflow

A close-range photogrammetric survey was conducted twice around the Old Basilica of Guadalupe (OBG) and the adjacent Ex-Convento de las Capuchinas (Figure 3). The first campaign (PL1) took place on 30 April 2022 and produced 60 ground-level images; the second (PL2) was completed on 23 March 2023 and yielded 156 images. All photographs were captured with the POCO X3 Pro smartphone described in Table 1. Images were taken sequentially along the 3D meshing and sidewalls at an average stand-off distance of ~40 m, maintaining ≥ 60 % forward overlap to satisfy stereoscopic requirements. Spatial constraints prevented coverage of the rear elevations: the gap between the buildings and Tepeyac Hill is ≈5 m, too narrow for the camera to achieve convergent geometry. Additional obstructions—trees, kiosks and attached structures—were likewise excluded, concentrating acquisition on the areas that exhibit the most visible fractures and settlements.

The image set was processed in Agisoft PhotoScan Professional v1.4.5 following a standard Structure-from-Motion/ Multi-View Stereo workflow (Figure 4).

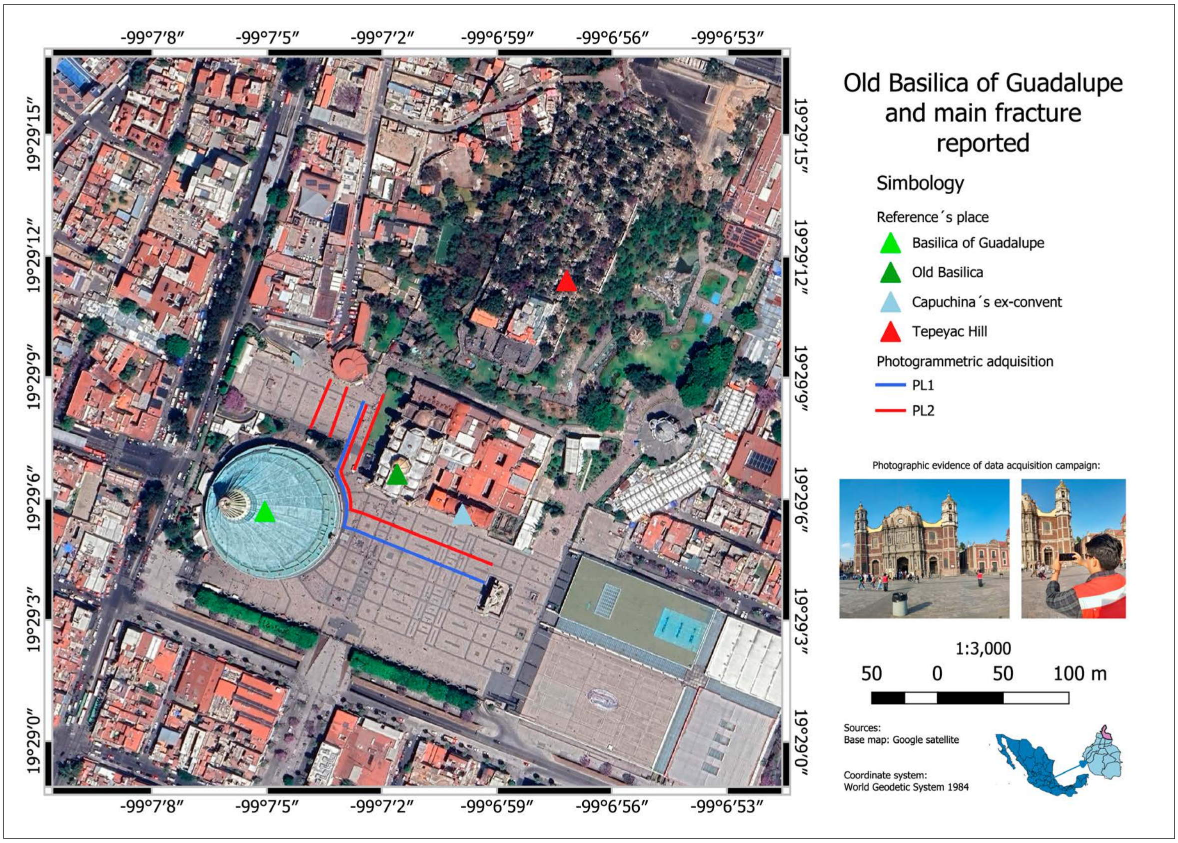

Figure 4. Survey routes used for image acquisition in each photogrammetric campaign. PL1 (blue line) and PL2 (red line). Image obtained from Google Earth.

Photographs were first imported with their embedded GPS tags, providing an initial spatial reference. Feature detection and matching relied on scale-invariant keypoints identified by SIFT (Lowe, 2004). PhotoScan estimated interior camera parameters and exterior orientations simultaneously, producing a sparse point cloud whose tie-points represent homologous image features (Börlin & Grussenmeyer, 2013). Redundant tie-points were merged to remove duplicates and strengthen network geometry (Fisher & Bolles, 1981). A high-quality, moderate-depth dense cloud was then generated using multi-view stereo algorithms that infer depth for each pixel (Furukawa & Ponce, 2009). The dense cloud was manually cleaned to eliminate vegetation, people and street furniture, retaining only points belonging to the basilica and convent. The filtered cloud served as the basis for surface meshing, after which a 16-bit texture was projected to enhance visual interpretation of cracks and surface wear. Finally, fracture traces, widths and wall tilts were measured directly on the dense cloud, providing quantitative descriptors for comparison between the 2022 and 2023 models. This integrated acquisition-and-processing sequence supplies a repeatable, low-cost workflow suited to restricted heritage sites where drone operations are prohibited and conventional surveying equipment is impractical.

## RESULTS

This study aimed to evaluate the potential of smartphone-based close-range photogrammetry to monitor fracture evolution in the OBG and its adjacent structures. Two photogrammetric surveys were conducted in April 2022 (PL1) and March 2023 (PL2) to assess structural deformation before and after the September 2022 earthquakes.

### General observations

At first inspection, the OBG shows a noticeable southeastward tilt, aligned with the main entrance axis. Evidence of restoration and mitigation measures is visible; however, structural damage continues to progress due to ongoing subsidence. The PL1 survey identified cracks and deformations already reported after the 2017 earthquake.

The characteristics of the filtered dense point clouds from both surveys are summarized in Table 2, while the specifications of the resulting textured 3D models are provided in Table 3. Figures 5 and 6 illustrate the models, highlighting that the inclusion of a larger number of images in PL2 significantly improved reconstruction quality compared to PL1. The enhanced resolution in PL2 provides a clearer depiction of the central temple's tilt and its connection to the adjacent building.

### Point cloud comparison

Figure 7 compares the dense point clouds from PL1 and PL2. The PL2 model (blue) extends beyond the PL1 model (red), suggesting a progressive displacement of the structure towards the east. This shift corroborates ongoing subsidence effects in the central nave and adjacent structural components.

### Fracture monitoring

Fractures identified in PL1 were tracked in PL2, and new fractures observed in PL2 were validated through site photographs. The western fade of the temple shows the greatest concentration of structural damage in both models. Figure 8 illustrates a newly detected fracture in PL2, located at the base of a load-bearing column. Measuring

Table 2. Specifications of the filtered dense point clouds for PL1 and PL2.

| Feature | Filtered Dense Point Cloud Specifications (PL1) | Filtered Dense Point Cloud Specifications (PL2) |
|---|---|---|
| Points | 9,329,518 | 10,651,669 |
| Spectral and radiometric resolution | 3 bands, uint 8 | 3 bands, uint 8 |
| Quality | High | High |
| Depth filtering | Moderate | Moderate |
| Depth map generation time | 1 hour 44 minutes | 20 hours 3 minutes |
| Dense point cloud generation time | 29 minutes 2 seconds | 3 hours 45 minutes |

Table 3. Comparison of point cloud and mesh density between PL1 and PL2.

| Feature | 3D Mesh Specifications (PL1) | 3D Mesh Specifications (PL2) |
|---|---|---|
| Faces | 207,322 | 2,126,589 |
| Vertices | 108,992 | 1,071,892 |
| Surface type | Arbitrary | Arbitrary |
| Interpolation | Enabled | Enabled |
| Quality | High | High |
| Depth filtering | Moderate | Moderate |
| Surface count | 207,322 | 2,126,590 |
| Processing time | 4 hours 18 minutes | 16 minutes 12 seconds |

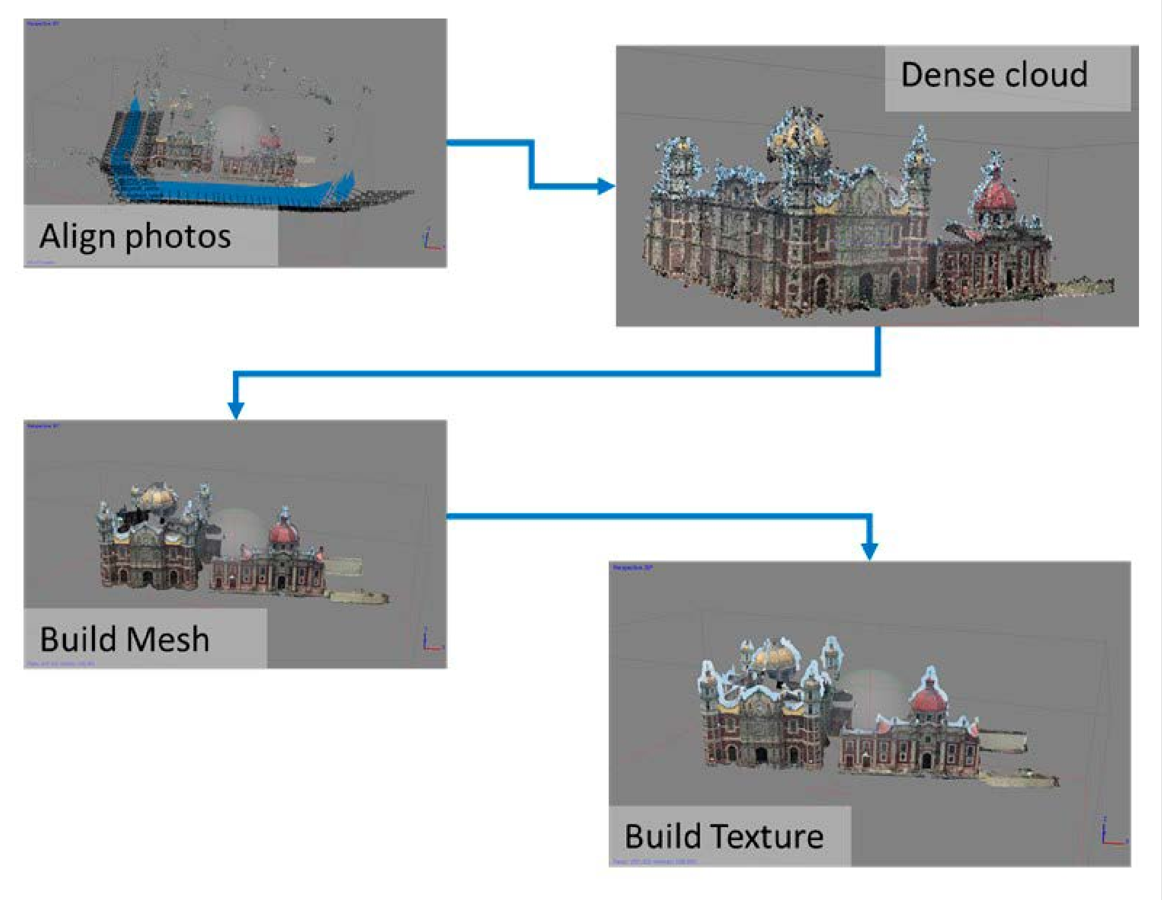

Figure 5. Diagram of the methodology carried out for the construction of 3D models in the Agisoft Photoscan software.

approximately 1.78 m, its position near a critical structural element requires special attention.

Additional fractures were documented in the decorative elements of the western access passage, as shown in Figure 9. One prominent fracture near an ornamental column follows an irregular geometry and spans approximately 11.2 m. Figures 10a, 10a1, and 10a2 provide a closer view of this section, highlighting two distinct fracture segments. However, Figure 10b shows that portions of this fracture are absent in the PL2 model, likely due to limited image coverage.

At the rear of the OBG, a corridor separates the temple from the adjacent Museo de la Virgen. Between these two buildings lies a fissure approximately 1.8 m long (Figure 12). This fracture spatially aligns with the regional fault line reported by Carreón Freyre (2014) and CENAPRED (2017), marking the boundary between the subsiding OBG structure and the apparently stable museum.

## Model improvements

PL2 shows a significant enhancement over PL1, achieved by increasing the number of photographs and strategically adjusting acquisition angles. These refinements improved lower façade coverage, allowing better documentation of basal fractures previously inaccessible. However, despite these improvements, not all fractures identified during fieldwork are visible in the PL2 model. Consequently, the fractures detected cannot be directly attributed to the 2022 seismic events. The findings

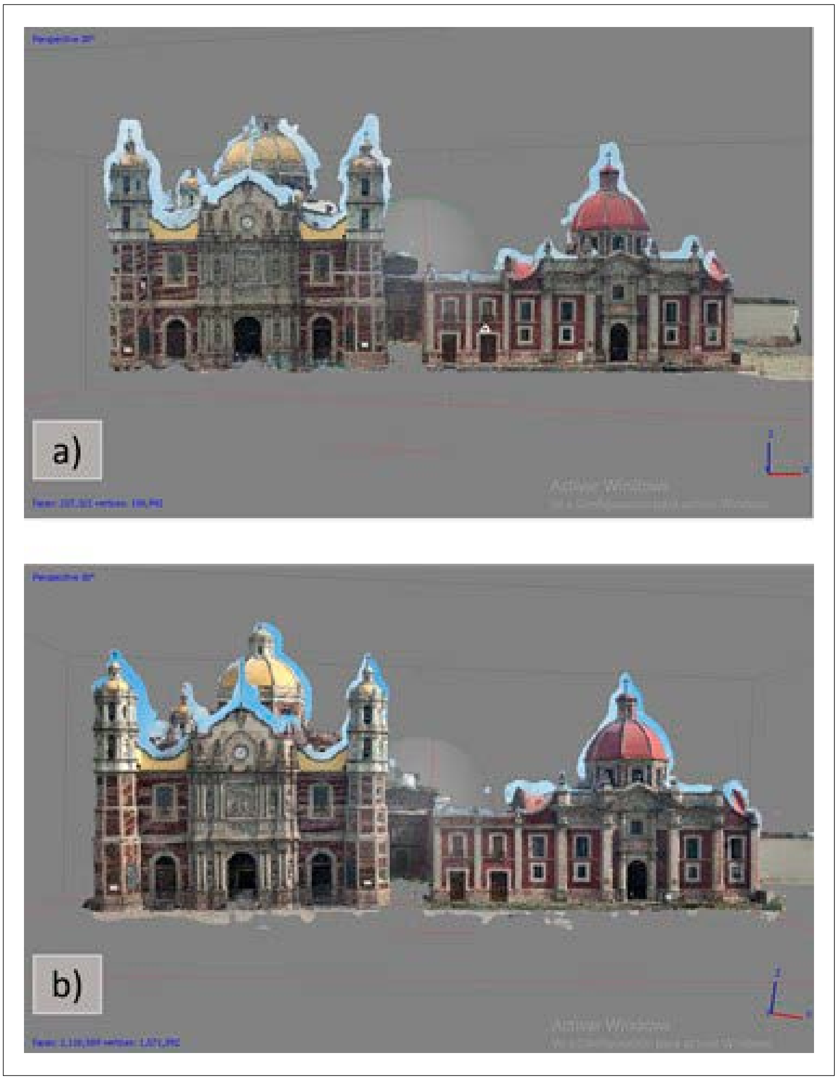

Figure 6. a) Comparison between the existing 3D model (left, PL1) and the new 3D model generated in this study (right, PL2). The central building shows a pronounced tilt in both models.

demonstrate that PL1 serves as a methodological reference, while PL2 highlights the potential for improving 3D reconstructions through optimized workflows. Continuous monitoring of fractures already mapped in the field and modeled here is essential to assess the vulnerability of the OBG structure and to inform potential mitigationmeasures.

## RECOMMENDATIONS

We propose establishing a periodic monitoring program for the OBG and surrounding heritage structures within the Villa de Guadalupe. Annual 3D models would provide a temporal record of deformation and fracture evolution, supporting conservation strategies for all buildings affected by regional subsidence.

### Regional deformation assessment using InSAR data

Regional ground deformation derived from InSAR analysis between March 2024, and January 2025 reveals significant spatial variability in subsidence rates across Mexico City (Figure 13). The highest deformation rates, exceeding 40 cm $yr^{-1}$, are con-

Figure 7. Representation of the property tilt (red line) relative to a vertical reference (blue line). Best 3D models: PL1 (a) and PL2 (b); bottom: actual view of the property (c).

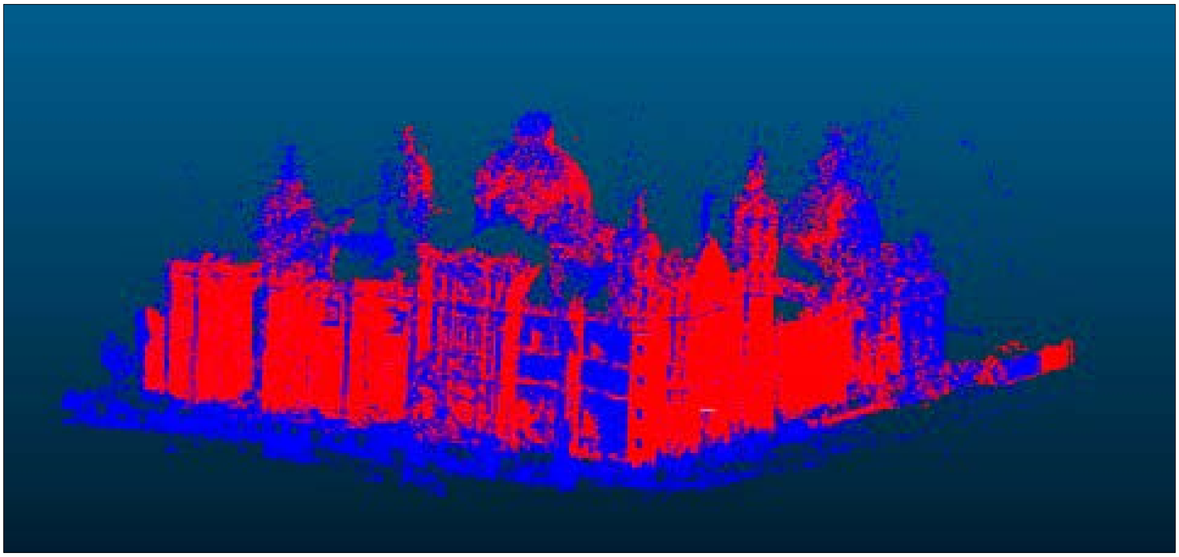

Figure 8. Comparison of dense point clouds from model PL1 (red) and model PL2 (blue) obtained in this study.

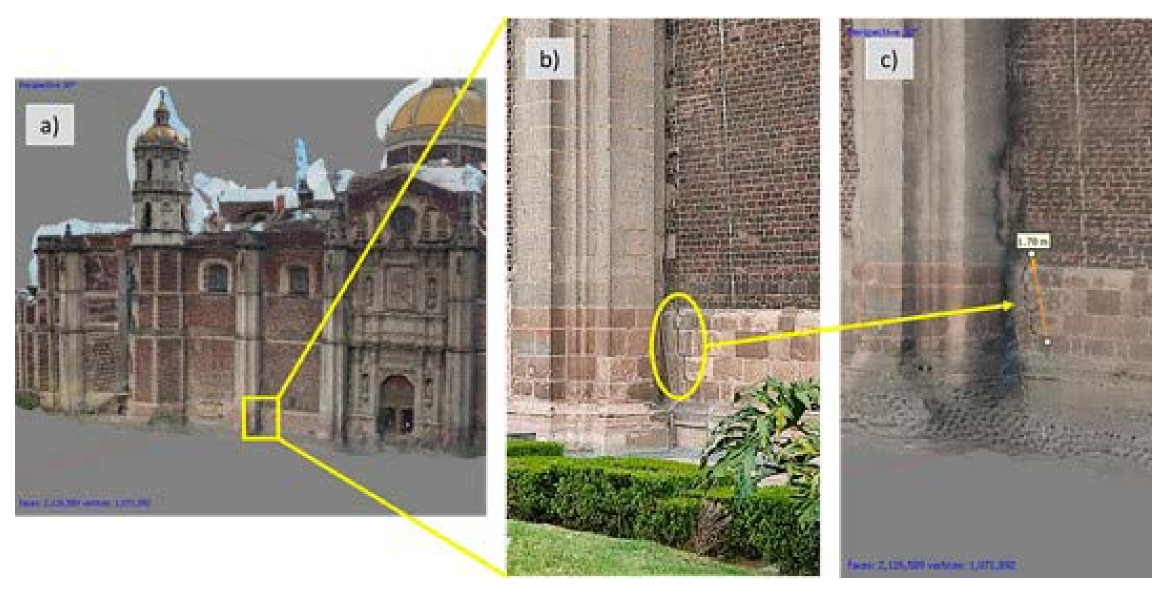

Figure 9. Newly identified fracture detected in PL2. a) Overall view of the PL2 3D model showing the fracture location; b) Field photograph of the fracture; c) Detailed view of the fracture in the PL2 model with approximate measurement.

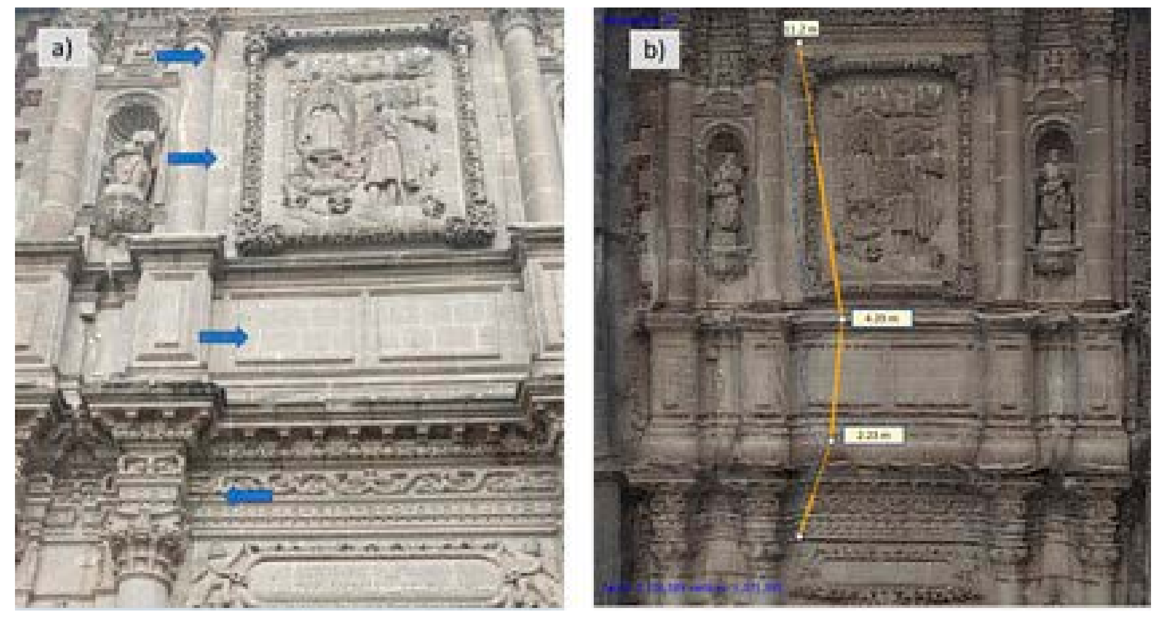

Figure 10. Fracture at the western transept access. a) Field photograph taken during data acquisition; b) Fracture location and measurement in the PL2 model.

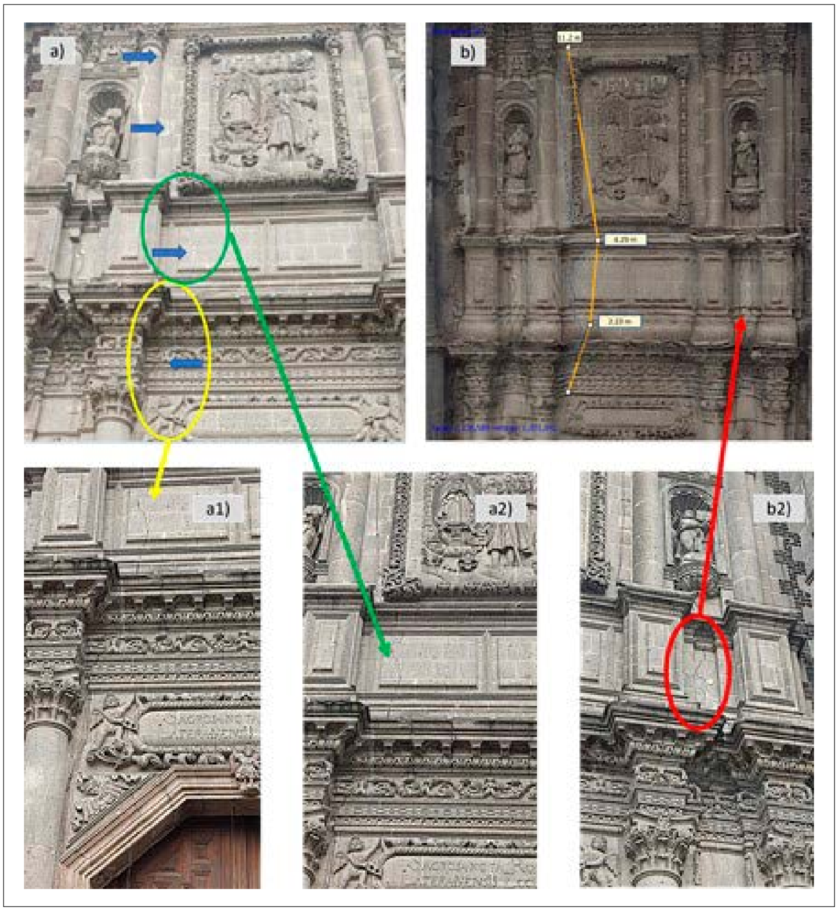

Figure 11. Fracture at the western transept access with zoomed views of the cracks. a1–a2) Detailed visualization of the fracture in different regions for better assessment. b1) A fracture identified in the field that is not represented in the PL2 model.

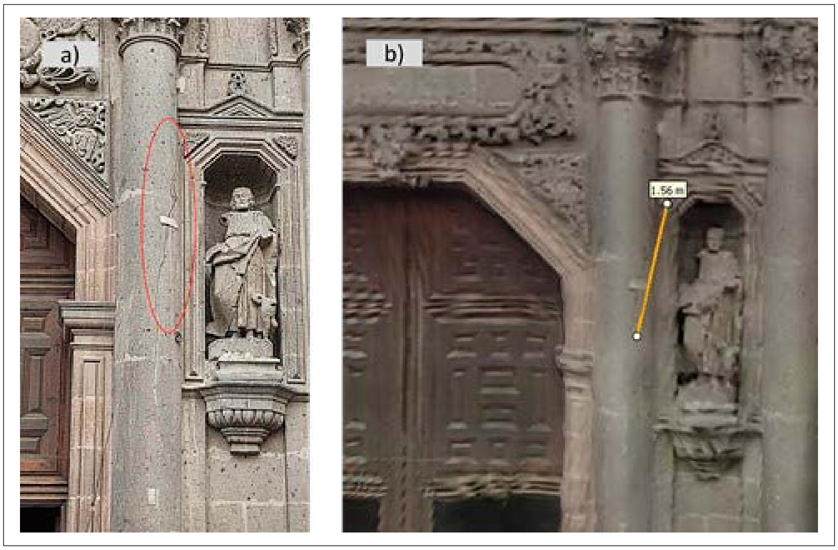

Figure 12. Fracture on a load-bearing column at the western transept access. a) Field photograph taken during the survey; b) Images and measurements extracted from the PL2 model.

Figure 13. Fracture between the Old Basilica of Guadalupe and the adjacent museum at the rear of the property. a) Field photograph showing the fracture; b) Image extracted from the 3D model.

centrated in the southeastern sectors of the basin, whereas the northern areas exhibit moderate to low subsidence values. The OBG is located within a transition zone between stable volcanic deposits and highly compressible lacustrine sediments. Although the OBG area shows moderate deformation rates compared to the city's periphery, the average displacement reaches approximately 1 cm/month, which is substantial when accumulated over long time periods. These results justify the need for high-resolution, close-range photogrammetric surveys to monitor structural deformation and evaluate the impact of continuous subsidence on heritage conservation.

## DISCUSSION

This study demonstrates the potential of close-range photogrammetry based on smartphone imagery combined with Structure-from-Motion (SfM) techniques to monitor fracture evolution and structural deformation in heritage buildings affected by subsidence. By comparing two photogrammetric surveys—PL1 (2022) and PL2 (2023)—we show that optimizing acquisition parameters, including image density, overlap, and camera angles, significantly improves the fidelity of 3D reconstructions. The enhanced PL2 model enabled a more detailed detection of fracture propagation, structural tilt, and differential settlement in the Old Basilica of Guadalupe (OBG), offering a replicable workflow for monitoring heritage structures exposed to similar geohazard conditions.

At the regional scale, the InSAR-derived deformation map provides insights into spatial patterns of subsidence across Mexico City between March 2024 and January 2025 (Figure 13). The highest deformation rates, exceeding 40 cm $yr^{-1}$, are concentrated in the southeastern sectors of the basin, while the northern areas exhibit moderate to low subsidence. The OBG is located within a transition zone between stable volcanic deposits and highly compressible lacustrine sediments. Although this area shows average displacements of approximately 1 cm/month, the continuous ground motion poses a long-term risk to the structural stability of the OBG. These regional-scale findings justify the need for high-resolution, close-range photogrammetric surveys to monitor localized damage and assess the cumulative impact of ground deformation on heritage structures.

Our findings align with previous studies validating the application of photogrammetry in heritage conservation. Moyano et al. (2020) demonstrated that close-range photogrammetry achieves accuracy comparable to terrestrial laser scanning (TLS) in point density and mesh quality, supporting its use for structural monitoring. Similarly, De Fino et al. (2023) highlighted the increasing adoption of low-cost photogrammetry for architectural documentation, particularly in scenarios where deploying drones or specialized equipment is restricted. The improved PL2 model confirms these findings by achieving a tenfold increase in mesh detail—from 207,322 to 2,126,589 faces—resulting in enhanced fracture mapping and tilt analysis even under limited site accessibility. Recent studies emphasize the growing role of smartphone-based photogrammetry in high-accuracy heritage monitoring. Asadpour et al. (2021) reported deviations below 1% when comparing smartphone-derived models to reference measurements, demonstrating the suitability of mobile devices for fine-scale documentation. In the Mexican context, Vidal-García (2025) compared smartphone-based photogrammetry and LiDAR point clouds for deformation monitoring in subsidence-prone urban environments, confirming that optimized workflows can reliably capture small-scale displacements. These results reinforce the applicability of accessible, low-cost methodologies for documenting fragile heritage sites.

This approach gains further relevance in Mexico City, one of the most subsidence-affected megacities worldwide, with localized deformation rates exceeding 40 cm/year (López-Quiroz et al., 2009; Solano-Rojas et al., 2020). Monitoring heritage structures such as the OBG under these extreme conditions provides a unique opportunity to validate scalable and transferable 3D workflows. Our results align with CENAPRED (2017), which emphasizes the need for improved monitoring strategies in high-risk areas affected by fractures and differential settlement. By providing high-resolution temporal datasets, this methodology enables evidence-based conservation while contributing to integrated urban risk management frameworks.

Globally, the integration of 3D technologies into heritage conservation is reshaping monitoring practices. Yu et al. (2025) reviewed digital heritage risk management strategies and highlighted the increasing role of photogrammetry, LiDAR, and UAV-based surveys for preserving built heritage under environmental stressors. Similarly, Gado (2024) demonstrated that combining drone-based photogrammetry with TLS enhances both efficiency and model accuracy, an approach relevant for urban heritage contexts. Li (2024) further proposed single-drone workflows to democratize public engagement in heritage monitoring, showing how lightweight, cost-effective solutions are gaining ground. These global findings validate the significance of methodologies like ours and support their integration into heritage conservation policies.

Despite its advantages, smartphone-based photogrammetry presents limitations. Several fractures documented during field inspections were only partially reconstructed or absent in PL2, primarily due to uneven image coverage, restricted acquisition angles, and challenging lighting conditions. Additionally, while photogrammetry offers sufficient precision for structural deformation analysis, it cannot yet replace high-precision tools such as TLS, InSAR, or geodetic benchmarks where millimetric monitoring is required. Therefore, we advocate its complementary role within integrated multi-sensor frameworks, especially when combined with UAV photogrammetry and ground-based LiDAR for complete documentation. Overall, this study contributes to the growing body of literature demonstrating that smartphone-based photogrammetry is an accessible, scalable, and replicable monitoring tool for heritage structures affected by geohazards. By enabling periodic 3D surveys, it supports long-term deformation mapping and contributes to evidence-based conservation strategies. In regions like Mexico City, where rapid ground subsidence and structural instability pose escalating threats to heritage, integrating low-cost 3D workflows into urban resilience planning becomes not only valuable but essential.

## CONCLUSIONS

This study demonstrates the effectiveness of close-range photogrammetry using smartphone imagery combined with Structure-from-Motion (SfM) techniques for monitoring structural deformation and fracture evolution in heritage buildings affected by subsidence. Two photogrammetric surveys were conducted in the Old Basilica of Guadalupe (OBG), an emblematic Baroque-style religious building constructed between 1695 and 1709, located in northern Mexico City. The OBG is situated on highly compressible lacustrine sediments within one of the most subsidence-affected areas of the city, where continuous ground settlement has caused structural tilting, wall fractures, and foundation damage. By comparing the two surveys—PL1 (2022) and PL2 (2023)—we show that optimizing image acquisition strategies, including camera angles, overlap, and image density, significantly improves the accuracy and visual fidelity of 3D reconstructions. The PL2 model achieved a tenfold increase in mesh detail compared to PL1, enabling enhanced detection of fracture propagation, tilt, and differential settlement in the OBG.

Beyond its technical contribution, this methodology offers a replicable and cost-effective workflow for monitoring heritage structures in urban environments exposed to geohazards. Mexico City, one of the most subsidence-affected megacities globally, represents an extreme testing ground where heritage assets face accelerated deterioration due to ground settlement. In this context, smartphone-based photogrammetry provides a non-invasive and accessible tool that complements traditional high-precision techniques, supporting evidence-based conservation strategies and long-term monitoring frameworks. Smartphone photogrammetry offers advantages in restricted-access environments where UAV deployment or TLS surveys are impractical. However, high-precision techniques such as TLS or InSAR remain necessary for millimetric monitoring. Integrating these datasets into multi-temporal 3D frameworks can significantly improve conservation planning and predictive models for geohazard impacts.

However, certain limitations remain. Despite these improvements, the expected horizontal positional accuracy is approximately 2.5–3 cm, which may explain why some field-mapped fractures were not reconstructed. Some fractures documented during field inspections were only partially reconstructed or absent in the PL2 model, mainly due to restricted access, uneven image coverage, and challenging lighting conditions. While smartphone-based photogrammetry provides sufficient accuracy for identifying structural deformation, it cannot fully replace advanced surveying techniques such as terrestrial laser scanning (TLS), InSAR, or geodetic benchmarks, especially when millimetric precision is required. Future work should focus on integrating multi-sensor data, combining smartphone-based photogrammetry with UAV surveys, TLS, and InSAR measurements to improve reconstruction accuracy and enable multi-temporal deformation analysis. Establishing periodic 3D monitoring protocols for heritage buildings like the OBG would generate high-resolution datasets essential for understanding deformation trends, assessing geohazard-related risks, and informing conservation policies.

Overall, this study contributes to the growing body of research demonstrating that smartphone-based photogrammetry is a scalable, replicable, and accessible approach for documenting and monitoring heritage structures affected by ground subsidence. By enabling periodic, high-resolution 3D reconstructions, it supports evidence-based heritage conservation, urban risk management, and global discussions on the role of digital technologies in preserving cultural heritage under environmental pressures.

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