



1 **Monitoring Land Subsidence at San Francisco International Airport Using Satellite Radar**  
2 **Interferometry**

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9 **Abstract:**

10 Coastal airports are increasingly vulnerable to infrastructure degradation from land subsidence  
11 exacerbated by sea-level rise (SLR) and extreme weather events. San Francisco International  
12 Airport (SFO), situated on a reclaimed land overlying thick compressible Young Bay Mud,  
13 provides a representative case study for understanding the implications of land subsidence on  
14 infrastructure resilience. This study employs advanced Interferometric Synthetic Aperture Radar  
15 (InSAR) techniques to measure and analyze spatially detailed subsidence at SFO from 2017 to  
16 2024. We integrate the InSAR data with subsurface stratigraphy derived from geotechnical  
17 investigations and historical construction records to identify and quantify patterns and drivers of  
18 subsidence. The results indicate spatially heterogeneous subsidence rates, with rates exceeding  
19  $-10.0 \pm 0.1$  mm/yr, concentrated primarily under the airfield's infrastructure, notably along  
20 Runway 10R/28L. Temporal analyses of deformation time series reveal significant variability and  
21 nonlinear trends, likely due to seasonal groundwater fluctuations, construction activities, and  
22 heterogeneous subsurface stratigraphy. Areas with older hydraulically placed fills demonstrate  
23 higher rates of long-term compaction, emphasizing the critical role of historical construction  
24 practices and sediment properties. This study's findings underscore the urgent need for  
25 comprehensive and continuous ground deformation monitoring at coastal airports. The  
26 implications for infrastructure resilience planning at SFO serve as a valuable model for other  
27 coastal airports facing similar geotechnical and climatic challenges.

28 **Keywords:** Vertical Land Motion, Subsidence, InSAR, Infrastructure Resilience, Sea-Level  
29 Rise, San Francisco International Airport, Coastal Airports.

30



## 31 **1 Introduction**

32 Coastal airports, over a thousand of which are situated within the Low-Elevation Coastal Zone  
33 (LECZ) globally, are increasingly exposed to compound hazards driven by land subsidence, sea-  
34 level rise, and extreme weather events (De Vivo et al., 2022; Griggs, 2020; Yesudian and Dawson,  
35 2021). These processes interact to amplify flood risk, reduce the effectiveness of coastal defenses,  
36 and threaten the long-term operability of critical transport infrastructure. Among these hazards,  
37 land subsidence, represents a subtle yet significant driver of infrastructure vulnerability (Dasho  
38 and Shirzaei, 2025; Nicholls et al., 2021; Shirzaei et al., 2020). Subsidence reduces freeboard for  
39 flood defenses, compromises stormwater management systems, exacerbates relative sea-level rise  
40 (RSLR) exposure, and creates localized hazards such as pavement cracking and ponding, directly  
41 impacting operational safety and maintenance requirements.

42 San Francisco International Airport (SFO) exemplifies the challenges faced by coastal airports  
43 constructed in subsidence-prone regions. The airport was developed primarily through large-scale  
44 land reclamation projects that transformed tidal marshes and mudflats into operational airfield  
45 space. As a result, much of its infrastructure, including runways, taxiways, and terminal facilities,  
46 is founded on thick, highly compressible deposits of Young Bay Mud overlain by hydraulically  
47 placed fill materials (Baldwin et al., 2018; Fugro, 2013).

48 Extensive historical land reclamation, beginning in the early twentieth century and accelerating  
49 after World War II, enabled the expansion of SFO into former tidal marshes, mudflats, and shallow  
50 bay environments (Fugro, 2013). Early construction practices predated the adoption of modern  
51 ground improvement methods such as preloading, surcharging, or deep foundation systems,  
52 leaving large portions of the airfield supported by unconsolidated fill and compressible subsoils.  
53 The resulting heterogeneity in fill thickness, compaction, and consolidation history has led to  
54 spatially variable settlement rates across the airport. Shoreline protection structures, including  
55 levees and revetments, provide the first line of defense against tidal inundation; however, these  
56 aging systems were not originally designed to accommodate accelerated sea-level rise or  
57 continuing subsidence, leading to declining freeboard and increasing flood risk.

58 The impacts of ongoing subsidence at SFO are well-documented (Stock et al., 2019). Persistent  
59 ground deformation has been linked to drainage inefficiencies, localized ponding, and accelerated  
60 pavement deterioration, as surface cracking and uneven settlement challenge airport operations.  
61 Several studies and engineering reports have highlighted the heightened exposure of SFO to high-  
62 tide flooding and storm surge events, especially as effective freeboard margins diminish due to  
63 ongoing settlement and rising sea levels (Johnson et al., 2018; Moffatt & Nichol, 2015). These  
64 historical and contemporary observations underscore the critical need for comprehensive,  
65 continuous ground motion monitoring to inform adaptive infrastructure management and long-  
66 term resilience planning.



67 Satellite-based Interferometric Synthetic Aperture Radar (InSAR) techniques represent a  
68 transformative advance for monitoring Vertical Land Motion (VLM) and ensuring infrastructure  
69 resilience at large, operationally critical sites like SFO (Bianchini Ciampoli et al., 2020; Gagliardi  
70 et al., 2021). Compared to traditional leveling or ground-based surveys, InSAR offers non-  
71 invasive, cost-effective, and millimeter-precision measurement capabilities over extensive areas  
72 without disrupting airport operations (Shirzaei et al., 2020). This technology enables early  
73 detection of localized settlement patterns, quantification of differential motion across complex  
74 facilities, and improved forecasting of areas at risk for surface cracking, drainage failure, or flood  
75 exposure. The innovation of satellite-based monitoring lies not only in its precision and efficiency  
76 but also in its ability to generate actionable data to guide maintenance prioritization, engineering  
77 design adjustments, and climate adaptation strategies.

78 In this study, we integrate InSAR observations to map land subsidence across SFO from 2017 to  
79 2024. The VLM measurements are combined with stratigraphic models derived from geotechnic  
80 investigation and historical construction records to elucidate the underlying geotechnical processes  
81 driving deformation. We quantify the spatial distribution of subsidence, analyze temporal trends  
82 at representative hotspots, investigate the influence of subsurface stratigraphy, and evaluate the  
83 relative contributions of historical land reclamation practices, paleoenvironmental setting, and  
84 operational aircraft loading. The results provide new insights into the mechanisms governing  
85 ongoing ground deformation at SFO and offer a transferable framework for incorporating remote  
86 sensing data into infrastructure resilience planning at coastal airports worldwide.

## 87 **2 Material and Method**

### 88 **2.1 InSAR Analysis**

89 We measured ground deformation at SFO using multitemporal InSAR analysis from Sentinel-1  
90 A/B satellites. The dataset comprises 184 ascending orbit images acquired from February 24, 2017,  
91 to May 12, 2024, and 229 descending orbit images acquired from November 13, 2015, to April 23,  
92 2024. From these images, we generated 780 interferograms for ascending mode (heading angle =  
93  $-13.28^\circ$ ) and 973 interferograms for descending mode (heading angle =  $193.29^\circ$ ). Maximum  
94 temporal and perpendicular baselines for the dataset were 600 days and 35 m, respectively.

95 To ensure appropriate spatial resolution, we applied multi-looking factors of 6 (range) by 1  
96 (azimuth), resulting in a pixel size of approximately  $15 \times 15$  meters. Sets of interferometric triplets,  
97 consisting of interferograms with diverse temporal baselines, were created using Delaunay  
98 Triangulation and dyadic down-sampling methods to minimize phase closure errors (Lee and  
99 Shirzaei, 2023). Topographic and flat-earth effects were corrected using the 30-meter resolution  
100 Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (Farr et al., 2007) and precise  
101 satellite orbital information (Franceschetti and Lanari, 1999). Absolute phase changes were  
102 estimated by applying a two-dimensional minimum cost-flow algorithm (Mario Costantini, 1998)  
103 to a sparse set of high-quality pixels (Costantini and Rosen, 1999). Line-of-sight (LOS)



104 displacement time series were computed by integrating unwrapped phase values of the  
105 interferograms through a reweighted least-squares approach (Shirzaei, 2013). Atmospheric delays  
106 were identified and mitigated using two-dimensional smoothing splines (Lee and Shirzaei, 2023)  
107 and wavelet-based filters (Shirzaei and Bürgmann, 2012). Mean LOS displacement rates were  
108 derived from the slopes of best-fitting lines applied to each pixel's displacement time series. Final  
109 displacement LOS velocities and standard deviations for both ascending and descending datasets  
110 are shown in Fig. S1 – S2 of Supporting Information. The standard deviation is derived from the  
111 regression uncertainty of the velocity estimate.

112 The observed LOS displacement velocities represent combined horizontal (east-west, north-south)  
113 and vertical (uplift-subsidence) components. Given the polar orbit of Sentinel-1 satellites, only  
114 east-west and vertical displacement components could be reliably quantified, thus we assumed  
115 negligible north-south motion. Consequently, we combined ascending and descending LOS  
116 displacement velocities using co-located pixels to derive accurate, east-west (E) and vertical (U)  
117 velocity maps, following the methodology outlined in (Miller and Shirzaei, 2019). The model to  
118 combine ascending and descending LOS displacement velocities is represented by Equation 1.

$$119 \quad \begin{bmatrix} ASC_{LOS} \\ DES_{LOS} \end{bmatrix} = \begin{bmatrix} v_E^{ASC} & v_U^{ASC} \\ v_E^{DES} & v_U^{DES} \end{bmatrix} \begin{bmatrix} E \\ U \end{bmatrix} \quad (1)$$

120 where,  $ASC_{LOS}$  and  $DES_{LOS}$  are the ascending and descending Sentinel-1 LOS displacement  
121 velocities, respectively.  $v$  is the unit vector projecting the displacement onto the LOS (Hanssen,  
122 2001), which are functions of the incidence and heading angles. The final solution to Equation 1  
123 is given by Equation 2:

$$124 \quad X = A^{-1}L \quad (2)$$

125 where,

$$126 \quad X = \begin{bmatrix} E \\ U \end{bmatrix}, A = \begin{bmatrix} v_E^{ASC} & v_U^{ASC} \\ v_E^{DES} & v_U^{DES} \end{bmatrix}, L = \begin{bmatrix} ASC_{LOS} \\ DES_{LOS} \end{bmatrix}$$

127 The East-west velocity as well as its standard deviation is presented in Fig. S3. Also, the  $1\sigma$   
128 standard deviation of the VLM is shown in Fig. S4.

129 The VLM measurement was tie to the IGS14 reference frame using the nearest GNSS station  
130 (HSIB) from data provided by the Nevada Geodetic Laboratory.

## 131 2.2 Statistical Analysis



132 We applied the Geographical Detectors (GD) statistical analysis to measure the driving influence  
133 of construction year, paleoenvironment and touchdown zone on VLM along the four runways in  
134 SFO. The analysis is a spatial statistical technique designed to analyze spatial stratified  
135 heterogeneity and identify driving factors behind observed geographical patterns. The method  
136 operates on the principle that if an independent variable (X) significantly influences a dependent  
137 variable (Y), their spatial distributions should exhibit similarity (Chen et al., 2020; Zhang et al.,  
138 2022)

139 Factor Detector, a component of GD, quantifies the explanatory power of independent variables  
140 using the q-statistic:

142 
$$q = 1 - \frac{SSW}{SST}$$

141 where:

- 143 •  $SSW = \sum_{h=1}^L N_h \sigma_h^2$  (Within sum of squares)  
144 •  $SST = N \sigma^2$  (Total sum of squares)  
145 •  $L$  = number of strata,  $N_h$  = units in stratum  $h$ ,  $\sigma_h^2$  = stratum variance

### 146 **2.3 Ancillary Data**

147 The construction year, paleoenvironment and stratigraphy datasets were extracted from (Fugro,  
148 2013). Reclaimed land area filled in the year 1973 and 1974 were combined and presented as filled  
149 in the year 1974.

150 The stratigraphy dataset reveals multiply subsurface layers which consist of artificial fill, young  
151 bay mud, alluvium, and old bay mud. The artificial fill unit comprises very loose to medium-dense,  
152 poorly graded sand interspersed with silt, clay, and gravel (Baldwin et al., 2018; Fugro, 2013).  
153 Beneath the fill, the young bay mud forms a laterally extensive, highly compressible unit  
154 composed of unconsolidated organic-rich clay to silty clay, with thicknesses ranging between 20  
155 to 70 feet across the airport (Baldwin et al., 2018; Fugro, 2013).

156 The old bay mud, comprising dense to very dense sand and silty sand and stiff to very stiff clay, is  
157 generally more consolidated than the overlying young bay mud (Baldwin et al., 2018; Fugro,  
158 2013). Interspersed within the older bay mud sequences are discrete coarse-grained lenses,  
159 primarily composed of sand and gravel. Overlying the old bay mud and interbedded with both bay  
160 mud units is the Holocene alluvium, consisting of interlayered sand, silt, and clay (Baldwin et al.,  
161 2018; Fugro, 2013). At greater depth, the Pleistocene alluvium forms the basal unit, consisting of  
162 moderately dense clay, silt, and sand with gravel (Fugro, 2013). This relatively competent stratum  
163 marks the approximate boundary below which significant deformation is not expected and thus  
164 defines the effective mechanical basement of the profile.

165

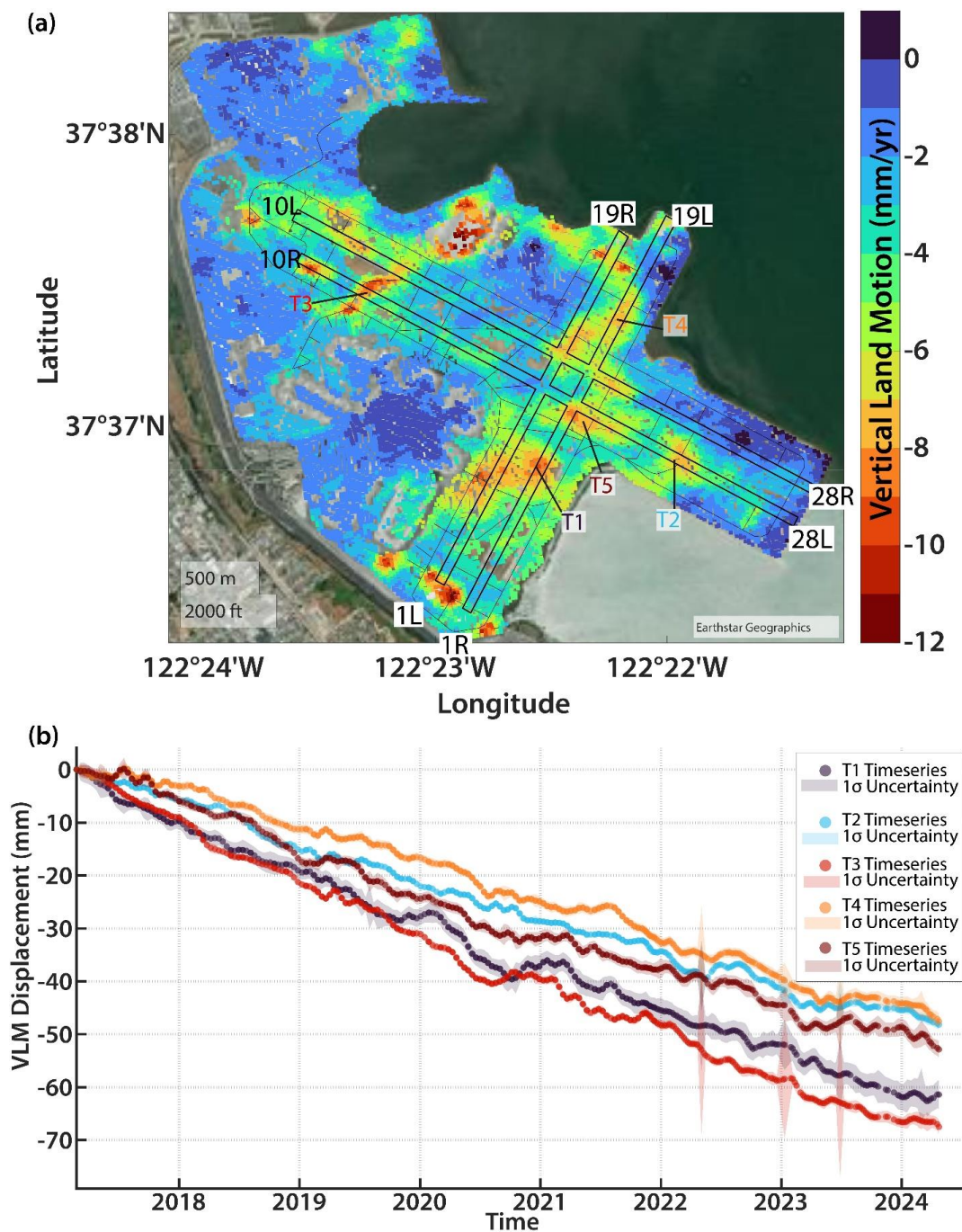


166

## 167 **3 Results**

### 168 **3.1 Spatially dense distribution of VLM at SFO**

169 Figure 1a presents the spatial distribution of VLM across SFO, with runway alignments overlaid  
170 for reference. The VLM estimates are referenced to the International GNSS Service (IGS14)  
171 terrestrial reference frame and span the period from 2017 to 2024. VLM rates exceeding  $-7$  mm/yr  
172 are observed indicating intense ground deformation, consistent with previous findings showing  
173 similar subsidence rates in portions of the San Francisco Bay Area (Blackwell et al., 2020; Dasho  
174 and Shirzaei, 2025; Govorcin et al., 2025). The figure reveals a striking spatial correlation between  
175 subsidence rates and the airfield's infrastructure layout. The runway system is delineated by the  
176 subsidence pattern, with the highest rates of VLM concentrated directly beneath and adjacent to  
177 the runways. The most pronounced deformation is observed along the Runway 10R/28L,  
178 particularly near its 10R end, where the subsidence rate reaches  $-7.8 \pm 0.1$  mm/yr. Runway  
179 10L/28R exhibits a median subsidence of approximately  $-5.5 \pm 0.1$  mm/yr, with maximum rates  
180 concentrated in the central section intersecting the crosswind runways. The 1L/19R and 1R/19L  
181 runways, display spatially variable subsidence ranging from  $-2.0$  to  $-7.0 \pm 0.1$  mm/yr, with the  
182 pronounced deformation again occurring at intersections with the other runways. The central  
183 intersection zone, where all four runways converge, shows marked differential motion, with  
184 localized deformation gradients reaching up to 5 mm/yr over short distances. These sharp spatial  
185 variations likely reflect heterogeneous subgrade conditions and non-uniform loading across the  
186 pavement structure. In contrast, areas exhibiting minimal deformation, including zones of slight  
187 uplift, are predominantly located in the northwest and southwest sectors of the airport, which  
188 correspond to built-up zones such as terminal complexes and administrative buildings, potentially  
189 built on piles extending beyond the soft subsurface sediments to the bedrock.



190

191 **Figure 1.** (a) VLM at SFO derived from Sentinel-1 InSAR observations spanning 2017–2024. The  
192 color scale represents vertical velocity in mm/year, with positive values indicating uplift and



193 negative values indicating subsidence. Major runways (10L/28R, 10R/28L, 1L/19R, and 1R/19L)  
194 are overlaid for reference. Subsidence hotspots are labelled T1, T2, T3, T4 and T5. (b) VLM time  
195 series from 2017 to 2024 at the labelled subsidence hotspots. The chart illustrates vertical  
196 displacement in millimeters (mm) derived from InSAR observations at all five locations referenced  
197 to the first observation epoch in the IGS14 terrestrial reference frame. Each colored line represents  
198 an individual hotspot time series, with associated  $1\sigma$  uncertainty shaded. Background satellite  
199 imagery © Esri, Earthstar Geographics.

200

### 201 **3.2 VLM time series at subsidence hotspots**

202 Figure 1b illustrates VLM time series derived from five representative subsidence hotspots within  
203 SFO, based on multi-temporal InSAR analysis. The displacement is referenced to the first  
204 observation epoch in the IGS14 terrestrial reference frame and spans the period from early 2017  
205 to 2024. Vertical deformation is expressed in millimeters (mm), and the  $1\sigma$  uncertainty envelopes  
206 are shown as shaded regions around each time series.

207 Each trajectory reflects localized ground motion behavior, with sub-linear subsidence rates ranging  
208 from  $-5.4$  mm/year to  $-8.2$  mm/year. While all five sites exhibit long-term downward trends  
209 indicative of sustained ground compaction, they also reveal pronounced temporal variability  
210 superimposed on the linear trajectories. This includes short-term accelerations, periods of relative  
211 stability, and intermittent uplift, likely governed by seasonal fluctuations in groundwater levels,  
212 hydromechanical responses of fill material, or episodic anthropogenic activity.

213 T3 (red dashed line) demonstrates the most rapid and persistent subsidence, with a linear velocity  
214 of  $-9.1 \pm 0.1$  mm/year. The nearly monotonic pattern, with limited seasonal modulation, suggests  
215 dominance of long-term consolidation processes, potentially associated with thick layers of  
216 hydraulically placed fill over compressible Bay Mud. T1 and T5 display similar subsidence rates  
217 of  $-8.4 \pm 0.1$  mm/year and  $-6.9 \pm 0.1$  mm/year, respectively. These sites exhibit moderate seasonal  
218 variability, potentially driven by cyclic groundwater recharge and discharge, or surface loading  
219 effects associated with adjacent infrastructure. T2 and T4 show comparatively slower subsidence  
220 rates of  $-6.5 \pm 0.04$  mm/year and  $-6.4 \pm 0.04$  mm/year, respectively. Both time series present  
221 evidence of episodic accelerations and decelerations in deformation, which may reflect  
222 interactions between hydroclimatic factors, construction activity, and spatially variable  
223 geotechnical properties of the subsurface.

224 The persistence of predominantly linear subsidence across all sites supports the hypothesis of  
225 ongoing secondary consolidation within the underlying unconsolidated deposits. However, the  
226 intermittent non-linearities, particularly the brief reversals or plateaus observed in early 2021,

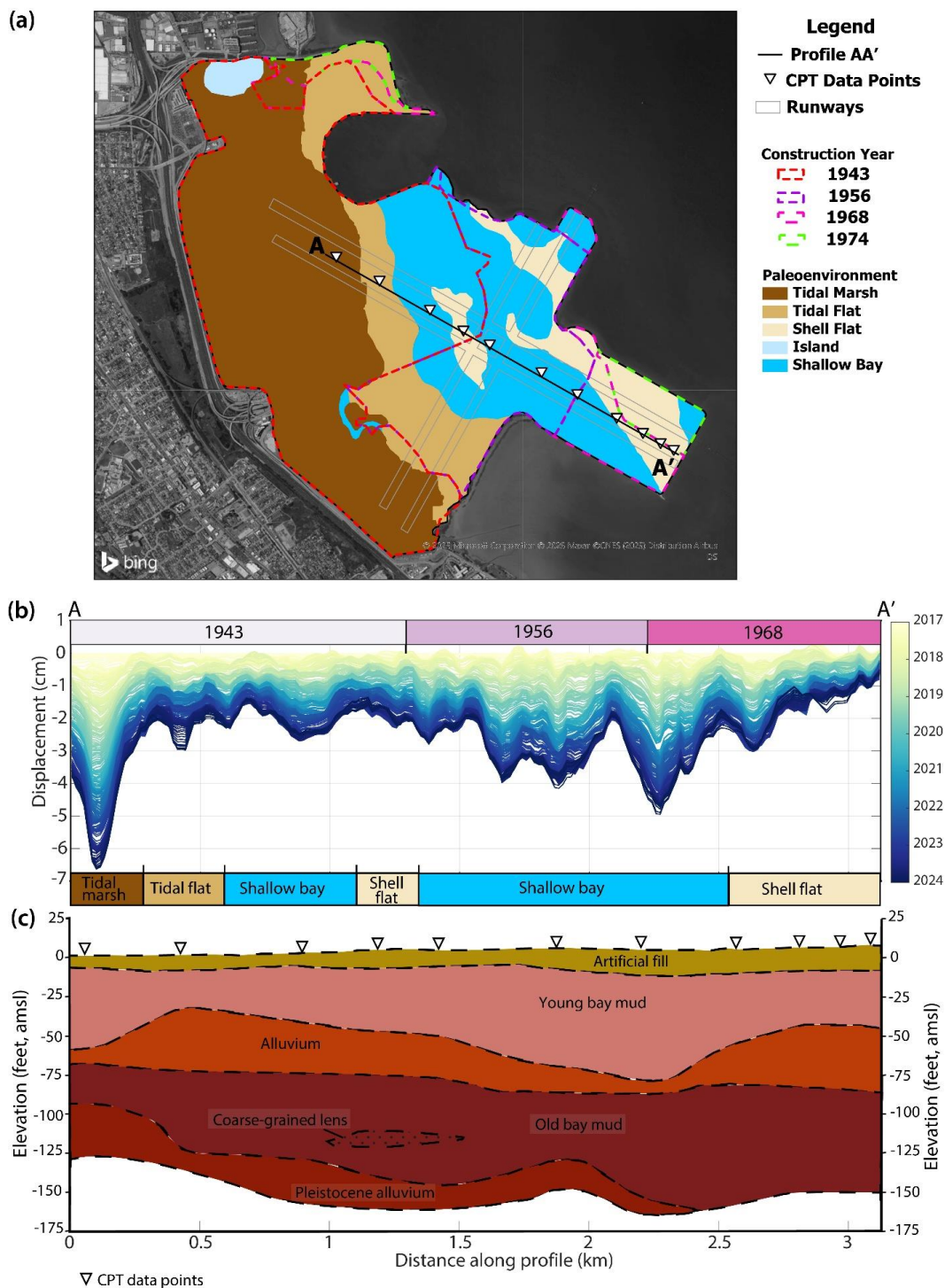


227 highlight the influence of transient deformation mechanisms. These may include regional seismic  
228 activity, rapid changes in hydraulic head or load changes.

### 229 **3.3 Cross-sectional Analysis of Vertical Displacement and Subsurface Stratigraphy at SFO**

230 Figure 2 presents an integrated cross-sectional view of vertical ground displacement and  
231 subsurface stratigraphy along a 3.2-km transect (A–A') across SFO. The figure is divided into three  
232 panels: Panel A illustrates the extent of reclaimed land at SFO by construction year (1943, 1956,  
233 1968, and 1974) and its paleoenvironmental settings, including tidal marsh, tidal flat, shell flat,  
234 island, and shallow bay. It also shows the geotechnic data points and the cross-sectional profile  
235 AA'. Panel B illustrates cumulative vertical displacement from 2017 to 2024, while the lower panel  
236 depicts a detailed subsurface geologic cross-section, revealing the vertical and lateral  
237 heterogeneity of subsurface materials. The displacement is expressed in centimeters and  
238 temporally color-coded, showing a pattern of progressive subsidence with subtle annual  
239 fluctuations likely driven by seasonal groundwater dynamics. Several pronounced subsidence  
240 troughs are observed at approximately 0.2 km, 1.7 km, and 2.3 km along the profile, indicating  
241 localized zones of enhanced consolidation. Historical shoreline boundaries from 1943, 1956, and  
242 1968 are superimposed, corresponding to key phases of land reclamation and providing essential  
243 context for anthropogenic modifications of the landscape. The paleoenvironmental zones, tidal  
244 marsh, tidal flat, shallow bay, and shell flat, further highlight the site's transitional coastal origin,  
245 characterized by soft, water-saturated sediments that now underlie engineered fill.

246 The lower panel presents a high-resolution geologic cross-section delineating five primary  
247 stratigraphic units: artificial fill, young bay mud, Holocene alluvium, old bay mud, and Pleistocene  
248 alluvium. This profile reflects a complex Quaternary depositional history characterized by  
249 alternating layers of highly compressible fine-grained sediments and more competent granular  
250 materials, including discrete coarse-grained lenses. The heterogeneous subsurface architecture  
251 exerts a primary control on the spatial variability of differential subsidence observed along the 3.2  
252 km transect. Variations in the thickness of the young bay mud, ranging from approximately 5 to  
253 70 feet (1.5 to 21 meters), are particularly influential, with the most pronounced subsidence  
254 occurring between 0–0.5 km and 1.5–2.5 km, where these deposits are thickest. In contrast, zones  
255 of relative surface stability or slight uplift align with areas underlain by shallower alluvium  
256 materials. Although a strong spatial correlation exists between the young bay mud thickness and  
257 the vertical deformation, the location of the maximum deformation (0.2 km along profile) does not  
258 coincide with the greatest thickness of young bay mud, suggesting additional controls such as  
259 paleoenvironmental conditions, the chronology of land reclamation, and the method of fill  
260 emplacement. The artificial fill layer, which is generally thicker over in later reclamation years  
261 and thinner in earlier years, reflects varying reclamation strategies employed over time. These  
262 differences in fill placement, along with associated variations in preloading, drainage conditions,  
263 and consolidation behavior, likely contribute to the non-uniform deformation response.





265 **Figure 2.** Cross-sectional subsidence and stratigraphy along a 3.2 km transect (A–A') at SFO.  
266 **Panel A** illustrates the extent of reclaimed land at SFO by completed construction year (1943,  
267 1956, 1968, and 1974) and its paleoenvironmental settings including tidal marsh, tidal flat, shell  
268 flat, island, and shallow bay (modified from (Fugro, 2013)). **Panel B** depicts cumulative vertical  
269 displacement along transect AA' from 2017 to 2024, revealing differential subsidence patterns  
270 associated with construction history and underlying paleoenvironmental conditions. **Panel C**  
271 presents the subsurface stratigraphy derived from the geotechnic investigation (modified from  
272 (Fugro, 2013)), highlighting distinct geological layers such as artificial fill, Young Bay Mud,  
273 alluvium, Old Bay Mud with coarse-grained lenses, and Pleistocene alluvium. This integrated  
274 profile emphasizes the relationship between historical reclamation practices, subsurface geology,  
275 and observed vertical land motion. Background satellite imagery © Microsoft Corporation,  
276 provided via Bing Maps; imagery content © 2025 Maxar, © CNES, Distribution Airbus.

277

### 278 **3.4 Other Possible Land Subsidence Drivers at SFO**

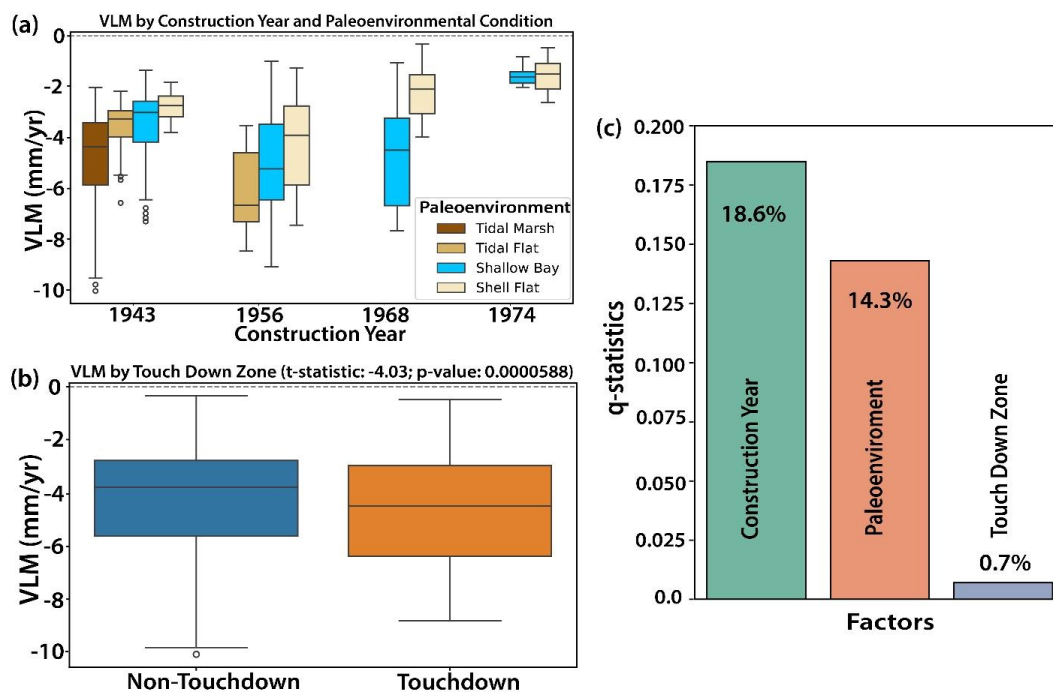
279 Analysis of VLM across all four runways at SFO reveals that deformation rates vary systematically  
280 with both construction history and paleoenvironmental conditions (Fig. 3a). Sites constructed  
281 during earlier reclamation phases (1943, 1956, and 1968) exhibit significantly greater subsidence  
282 rates, with vertical displacements reaching up to  $-6$  to  $-9$  mm/year. In contrast, areas constructed  
283 in 1974 show minimal deformation, suggesting that improvements in ground preparation and fill  
284 compaction practices reduced subsequent settlement. The underlying paleoenvironment also plays  
285 a critical role: regions built over Tidal Marsh and Shallow Bay deposits experience greater  
286 settlement, reflecting the compressibility of underlying soft clays and silts, whereas areas over  
287 Shell Flat and Tidal Flat environments exhibit reduced settlement associated with firmer, less  
288 compressible soils.

289 Comparison of VLM between touchdown and non-touchdown zones across all four runways (Fig.  
290 3b) indicates a statistically significant difference ( $t$ -statistic =  $-4.03$ ,  $p$ -value  $\approx 0.00005$ ). However,  
291 the magnitude of this difference is modest when compared to the more pronounced impacts of  
292 construction history and paleoenvironmental conditions. Additionally, the observed touchdown  
293 zones may not uniformly experience consistent aircraft landing loads, potentially further reducing  
294 the detected effect. Consequently, while repetitive aircraft loading does contribute to localized  
295 differential settlement, it remains a secondary factor relative to broader geotechnical and historical  
296 influences.

297 The results of the geographical (factor) detector analysis (Fig. 3c) quantitatively reinforce these  
298 observations. Among the three variables considered, construction year explains the largest share  
299 of VLM variance (18.6%), highlighting the long-term influence of historical fill practices.  
300 Paleoenvironment accounts for 14.3% of the variance, affirming the strong control exerted by



301 natural geological conditions. Touchdown zone effects account for only 0.7% of the variance,  
 302 underscoring that operational loading, while statistically detectable, plays a comparatively minor  
 303 role in driving settlement along runways. In total, construction year, paleoenvironment and  
 304 touchdown zone account for less than 35% of the variance in the VLM dataset along runways.



305

306 **Figure 3. Influence of construction history, paleoenvironmental setting, and infrastructure**  
 307 **usage on VLM along runways at SFO.** (a) Boxplots of VLM rates (mm/year) grouped by  
 308 construction year (1943, 1956, 1968, and 1974) and paleoenvironmental condition (Tidal Marsh,  
 309 Tidal Flat, Shallow Bay, Shell Flat). Results show that earlier construction phases and specific  
 310 paleoenvironmental settings (e.g., Tidal Marsh) are associated with higher subsidence rates, while  
 311 later construction (1974) exhibits relatively stable conditions. (b) Comparison of VLM between  
 312 touchdown zones (areas subjected to frequent aircraft landing impacts) and non-touchdown areas.  
 313 Touchdown zones show statistically higher subsidence rates, as indicated by a significant t-test  
 314 result (t-statistic = -4.03, p-value < 0.0001). (c) Bar plot of q-statistics from a geographical  
 315 detector analysis, quantifying the variance in VLM explained by each factor. Construction year  
 316 accounts for 18.6% of the variance, paleoenvironmental condition for 14.3%, and touchdown zone  
 317 presence for 0.7%, highlighting construction history as the dominant driver of observed VLM  
 318 patterns.

319

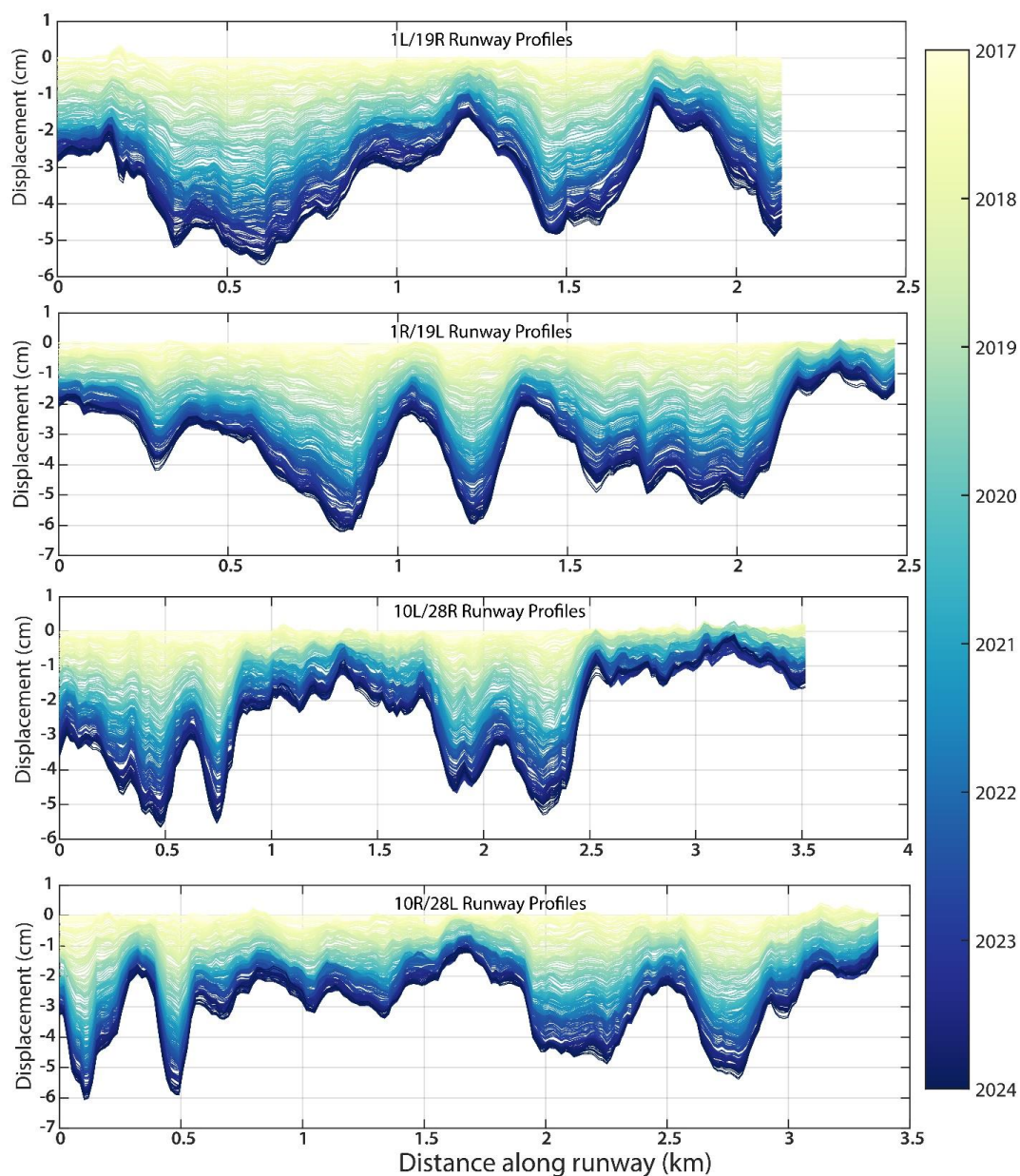


### 320 **3.5 Runway Displacement Profiles**

321 Figure 4 illustrates the progressive vertical displacement along the four runways (1L/19R, 1R/19L,  
322 10L/28R, and 10R/28L) at SFO between 2017 and 2024. Several important patterns emerge across  
323 all runways, displacement profiles generally deepen year after year, as indicated by the gradual  
324 shift from lighter (2017) to darker (2024) colors. This reflects a clear temporal trend of ongoing  
325 vertical settlement, with cumulative displacements reaching several centimeters over the  
326 observation period. Rather than uniform displacement along each runway, multiple localized  
327 subsidence "troughs" appear, especially pronounced at specific distances. These troughs likely  
328 correspond to underlying variations in subsurface composition, such as differences between fill,  
329 soft bay mud, or paleoenvironment, and varying mechanical properties along the runways.

330 Runways 10L/28R and 10R/28L (the east-west runways) exhibit larger and more complex patterns  
331 of subsidence compared to 1L/19R and 1R/19L. These differences may reflect heavier aircraft  
332 traffic (including frequent landings of larger jets) and greater cumulative stresses. Particularly  
333 along 10R/28L, deeper subsidence troughs are visible near the touchdown zones (2–3 km), where  
334 repeated mechanical loading likely exacerbates consolidation of underlying materials.

335 The narrowing vertical separation between successive annual deformation profiles toward the end  
336 of the observation period (2022–2024) indicates a deceleration of subsidence in several sections  
337 of the runways. Given the historical sequence of land reclamation and the underlying geotechnical  
338 context at SFO, this trend is most consistent with secondary consolidation (creep) and reduction  
339 in soil permeability, both time-dependent processes that produce diminishing settlement rates once  
340 excess pore pressures have fully dissipated (Jian et al., 2012; Kooi and Erkens, 2020; Liu et al.,  
341 2020; Wang et al., 2021). Nonetheless, the localized differential settlement along the runways  
342 presents potential hazards, including pavement cracking, surface irregularities, and compromised  
343 operational safety margins. If these patterns continue, maintenance interventions (e.g., resurfacing,  
344 subsurface ground improvement) will be necessary to preserve safe operating conditions and limit  
345 disruptions.



346

347 **Figure 4. Time-evolving surface displacement profiles along major runways at San Francisco**  
348 **International Airport (SFO).** Each subplot shows sequential displacement profiles along the  
349 length of four primary runways, 1L/19R, 1R/19L, 10L/28R, and 10R/28L, from 2017 to 2024. The  
350 y-axis indicates cumulative vertical displacement in centimeters, while the x-axis represents  
351 distance along each runway (in kilometers). Line color transitions from light yellow (earlier years)



352 to dark blue (later years) according to the color scale bar, capturing progressive subsidence patterns  
353 over time. Distinct subsidence troughs, spatially localized along runway segments, are evident,  
354 indicating differential settlement likely associated with variations in underlying fill materials,  
355 usage intensity, and construction history.

356

#### 357 **4 Discussion**

358 This study presents a detailed assessment of VLM spatiotemporal distribution and drivers across  
359 SFO based on spatially continuous InSAR observations and integrated geotechnical data. The  
360 analysis reveals that subsidence patterns are controlled by a complex interplay of historical land  
361 reclamation practices, paleoenvironmental setting, subsurface stratigraphy, and, to a lesser extent,  
362 operational aircraft loading. The spatial variability in subsidence rates at SFO closely aligns with  
363 the thickness of the underlying Young Bay Mud deposits, while fill emplacement techniques,  
364 natural paleoenvironmental settings and construction chronology may have secondary influence.  
365 This observation has significant implications for infrastructure performance, operational safety,  
366 and long-term resilience in a changing coastal environment.

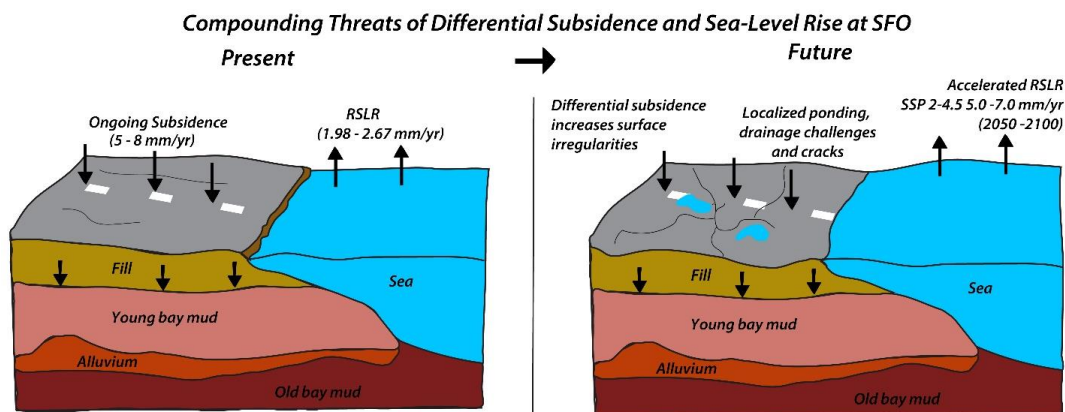
367 Spatially heterogeneous subsidence generates differential vertical displacement across pavement  
368 structures, imposing bending stresses that rigid concrete pavements are particularly ill-suited to  
369 accommodate. Where displacement gradients approach several millimeters per year across  
370 distances of tens to hundreds of meters, as observed at runway intersections and subsidence troughs  
371 at SFO, these stresses promote fatigue cracking, joint faulting, and slab rocking in rigid pavements,  
372 and rutting and longitudinal cracking in flexible systems (Fig. 5) (Cigna et al., 2012; Dasho and  
373 Shirzaei, 2025; Ohenhen et al., 2024). Localized surface depressions formed by differential  
374 settlement create persistent ponding zones that reduce skid resistance, accelerate subgrade  
375 saturation, and impair stormwater drainage efficiency (Dasho and Shirzaei, 2025). Cumulatively,  
376 these deformation-induced defects reduce pavement service life, escalate maintenance  
377 expenditure, and introduce operational safety risks for aircraft during ground movement phases  
378 where surface continuity tolerances are tightly regulated by aviation authorities.

379 Beyond localized pavement distress, subsidence fundamentally alters SFO's exposure to coastal  
380 flooding by amplifying effective RSLR at the airfield surface. The subsidence rates of -5 to -8  
381 mm/yr documented here add directly to projected regional SLR of 0.19 m by 2100 under SSP 2-  
382 4.5 (Garner et al., 2021). Expressed cumulatively, subsidence alone, projected linearly and  
383 therefore likely representing an upper bound given the deceleration observed in recent years, could  
384 lower airfield surface elevations by 0.38–0.60 m by 2100, a magnitude larger than the projected  
385 regional SLR under low-to-intermediate emissions scenarios over the same period. This  
386 compounding effect accelerates the timeline to critical thresholds, including recurrent tidal  
387 inundation under fair-weather conditions, progressive loss of freeboard in shoreline protection



388 structures, increased storm surge penetration, and declining surface elevation relative to fixed  
389 stormwater drainage infrastructure. Runways 10R/28L and 10L/28R, underlain by the thickest  
390 compressible deposits, face the earliest onset of these compounding hazards.

391 Given these converging challenges, adaptive maintenance and resilience planning at SFO must  
392 integrate both differential subsidence and RSLR projections into engineering design standards,  
393 risk assessment frameworks, and long-term capital improvement plans. Potential strategies include  
394 continuous monitoring of ground deformation using multi-sensor InSAR; targeted ground  
395 improvement (e.g., deep soil mixing, stone columns) beneath critical infrastructure to arrest or  
396 slow secondary consolidation; strengthening flood defenses; upgrading stormwater management  
397 systems to accommodate accelerated relative sea-level rise; and integrating flexible pavement  
398 designs that can tolerate differential movement. Ultimately, effective resilience strategies will  
399 require a combined approach addressing both the geotechnical realities of ongoing land  
400 deformation and the climate-driven threats of sea-level rise. SFO's experience can serve as a  
401 critical case study for other major airports and coastal infrastructure hubs worldwide that are  
402 increasingly challenged by the intersection of anthropogenic subsidence and extreme weather  
403 event.



404

405 **Figure 5. Structural and Hydrological Impacts of Progressive Subsidence at SFO:**  
406 Illustration showing how ongoing land subsidence SFO could cause surface cracking, runway  
407 deformation, water ponding and elevation loss, which compromise shoreline protection and  
408 increase exposure to coastal flooding under rising sea level.

409

#### 410 **Conclusion**

411 This study provides a spatially dense assessment of VLM across SFO, revealing that ongoing  
412 ground deformation is predominantly governed by the complex interplay between historical land



413 reclamation practices, underlying subsurface stratigraphy, and, to a lesser extent, operational  
414 aircraft loading. Subsidence is most pronounced where thick, compressible Young Bay Mud  
415 deposits underlie hydraulically placed fill, with localized rates exceeding  $-10$  mm/year.

416 Temporal analysis indicates a general deceleration of subsidence in recent years, nevertheless,  
417 localized differential settlement persists, posing operational risks such as pavement distress,  
418 surface ponding, and reduced structural serviceability. These effects, compounded by subsidence-  
419 driven amplification of relative sea-level rise rates, threaten to accelerate the loss of functional  
420 freeboard for SFO's coastal protection systems and increase the likelihood of tidal and storm-  
421 induced flooding.

422 Given these challenges, continuous deformation monitoring, integration of ground improvement  
423 technologies, elevation enhancement of critical infrastructure, and updated drainage designs must  
424 be incorporated into SFO's long-term resilience planning. More broadly, the insights gained from  
425 SFO underscore the urgent need for integrated geotechnical and climate adaptation strategies at  
426 coastal airports worldwide, where the intersection of anthropogenic subsidence and climate change  
427 represents an emerging threat to critical transportation infrastructure.

#### 428 **Code and Dataset Availability**

429 The Sentinel-1 dataset used in this study can be accessed through the Alaska Satellite Facility at  
430 <https://asf.alaska.edu/>. The GNSS dataset can be accessed through Nevada Geodetic Laboratory at  
431 <https://geodesy.unr.edu/>. The WabInSAR software used for InSAR processing can be accessed via  
432 <https://www.eoivt.com/software>. The VLM dataset (Dasho and Shirzaei, 2026) referenced in this  
433 manuscript are publicly available via the Virginia Tech Data Repository at  
434 <https://doi.org/10.7294/31974768>.

#### 435 **Author contribution**

436 OD and MS designed the experiments and OD carried them out. OD prepared the manuscript.  
437 MS revised and edited the manuscript.

#### 438 **Competing interests**

439 The authors declare that they have no conflict of interest.

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