Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1462

Dynamic analysis of structures affected by soil cracking due to regional subsidence in abrupt transition zones

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ABSTRACT: Regional subsidence in the lacustrine zone of Mexico City, mainly due to aquifer overexploitation, causes differential settlements, cracking, and severe damage to infrastructure. Abrupt transition zones between soft clays and rigid volcanic deposits are especially critical, concentrating stresses that favor the formation of step-like cracks. This study analyzes an elevated viaduct in such a zone under two conditions: (1) subsidence with ground cracking and (2) combined cracking and seismic loading. A previously calibrated 2D model was used to define crack trajectories, and a 3D slice model evaluated the soil–structure interaction, including pile foundations on basalt or stiff soils, compensated caissons, columns, and an equivalent superstructure beam. The 50-year static projection showed greater slope changes and vertical differentials in pile-supported foundations compared to caissons, with cracks amplifying these effects. Seismic analysis, limited to a longitudinal subduction scenario, produced smaller vertical differentials but revealed bidirectional displacements that may affect joints and continuity in the superstructure. The results underline the combined impact of static and dynamic mechanisms in abrupt transitions and demonstrate the usefulness of numerical modeling to identify critical areas and guide mitigation strategies. Future work will extend the analysis to bidirectional seismic loading and other subsidence-affected sites.

KEYWORDS: regional subsidence; step crack; abrupt transition zone; soil–structure interaction; numerical modeling; elevated viaduct; seismic; subduction earthquake.

1 INTRODUCTION

Regional subsidence in the lacustrine zone of Mexico City has been documented for more than ninety years (Gayol, 1925; Carrillo, 1947), mainly caused by exploitation of aquifers through deep wells. Despite technical and regulatory efforts to mitigate it, this process continues to produce differential settlements, structural distortions, and ground cracking that severely affect urban infrastructure (Auvinet *et al*., 2017).

One of the most critical scenarios occurs in abrupt transition zones between soft lacustrine soils and rigid volcanic materials. The marked contrast in stiffness and compressibility generates concentrations of shear and tensile stresses that favor the formation of step-type cracks (Auvinet *et al*., 2022). These discontinuities have been responsible for significant damage to buildings, roadways, and strategic linear structures such as elevated viaducts and hydraulic networks.

Sánchez *et al*. (2024) proposed a numerical methodology to represent the combined effects of regional subsidence and step-type cracking in abrupt transition zones. Using two-dimensional models calculated with geotechnical, geophysical, and ambient vibration data, they simulated crack trajectories and their evolution over time under static subsidence conditions, identifying critical zones of stress and strain concentration.

This study builds upon the same case study and numerical model developed by Sánchez *et al*. (2024), incorporating the methodological approach of Martínez *et al*. (2021) to assess behavior under seismic loading. Two scenarios are analyzed:

1. regional subsidence with step-type cracking, and
2. combined step-type cracking and representative seismic excitation.

This dual approach enables exploration of the interaction between static and dynamic deformations, providing criteria for design and mitigation of damage in infrastructure located in transition zones affected by active subsidence.

2 SITE DESCRIPTION

2.1 *Location and geological context*

The study site is located in the eastern sector of Mexico City, in the vicinity of the Santa Marta Station of Subway Line A (Figure 1). This area corresponds to an abrupt transition zone between soft lacustrine deposits and shallow volcanic basalt flows.

This lithological contrast produces marked differences in the mechanical properties of the subsoil, favoring stress concentration and the formation of step cracks associated with differential regional subsidence.

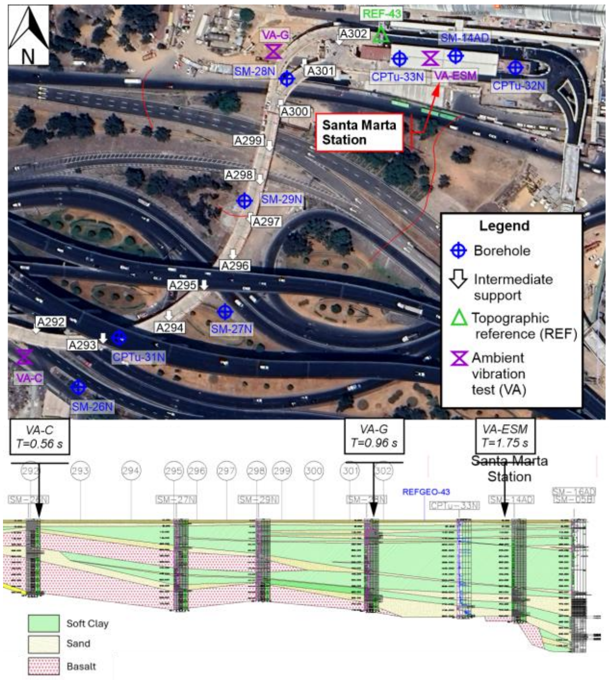


Figure 1. Location of the study site and geotechnical investigations in the abrupt transition zone

Figure 1 shows the location of the geotechnical investigations carried out in the area, which include Standard Penetration Tests (SPT) and piezocone penetration tests (CPTu), as well as ambient vibration (VA) measurements used to estimate the site's fundamental period. The data were complemented with topographic reference points and the location of intermediate supports of the elevated viaduct.

2.2 *Stratigraphy and Geotechnical Parameters*

For the definition of the geotechnical parameters of the numerical model, borehole SM-28N was selected as the reference because it presents the most complete stratigraphic sequence in the study area. This borehole was complemented with information from other nearby profiles (SM-29N and SM-14AD) to identify lateral variations and establish correlations that would allow an adequate representation of the subsoil conditions in the abrupt transition zone (Figure 2).

The strategy consisted of developing a reduced stratigraphic model from the combined information, maintaining the equivalent thickness and total potential for regional subsidence. This simplified model allowed the number of layers with differentiated properties to be reduced without losing geotechnical representativeness or the capacity to reproduce the site's dynamic response.

Index properties (water content, unit weight) and mechanical properties (undrained cohesion, friction angle, elastic modulus) were determined from laboratory tests and empirical correlations based on water content, following the methodology documented in Sánchez (2025).

The initial dynamic characterization was defined by adjusting shear wave velocities (V_s) for each layer so that the calculated site fundamental period matched the values obtained from ambient vibration measurements. The calculation followed the standard "Norma Técnica Complementaria para Diseño por Sismo de la Ciudad de México (NTC-DS, 2023)", using thicknesses and velocities associated with the boreholes closest to the measurement stations.

Table 1 summarizes the representative geotechnical parameters used in the numerical model, integrating index, mechanical, and dynamic properties for each layer of the reduced profile.

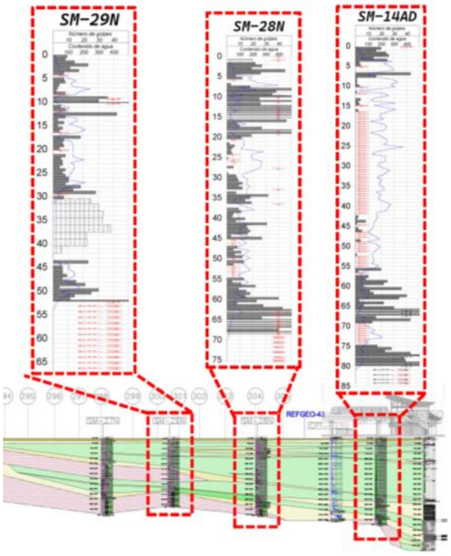


Figure 2. Stratigraphic model for the abrupt transition zone

Table 1. Representative geotechnical parameters used in the numerical model

Layer	Description	ω_{corr} %	γ kN/m^3	E' kN/m^2	c_u kN/m^2	ϕ'	Cc	Cs	e	G_{max} kN/m^2	$\gamma_{0.7}$
UG01	Sand lens	37	16.6	25000	100	25	-	-	0.3	552,905	-
UG02	Soft clay	185	12.8	-	25	35	2.96	0.296	5.6	30,286	0.0001
UG03	Soft clay	70	14.7	-	48	37	1.12	0.112	1.8	32,843	0.0002
UG04	Sand lens	44	16.1	11500	200	25	-	-	1.2	459,939	-
UG05	Soft clay	115	14	-	51	35	1.84	0.184	3.1	37,634	0.0001
UG06	Soft clay	227	12.3	-	55	35	3.632	0.3632	6.0	51,769	0.0002
UG07	Soft clay	151	13.2	-	57	35	2.416	0.2416	4.0	53,589	0.0001
UG08	Sand lens	88	14.1	15000	250	31	-	-	2.1	806,878	-
UG09	Soft clay	111	13.9	-	60	37	1.936	0.1936	3.4	906,830	0.00003
UG10	Soft clay	90	13.6	-	70	37	1.6	0.16	3.6	116,323	0.00006
UG11	Soft clay	100	13.2	-	75	38	2.432	0.2432	4.0	138,175	0.00002
UG12	Sand lens	57	15.3	15000	300	30	-	-	1.3	968,048	-
UG13	Sand lens	29	17.4	15000	400	29	-	-	0.7	999,722	-
UG14	Basalt	0	22	250000	2,000	45	-	-	0.0	1,435,270	-

2.3 *Dynamic Soil Characterization*

Shear wave velocities (V_s) were defined from the results of in situ geophysical surveys using SPAC and MASW methods, which allowed characterization of the stratigraphic profile down to the rigid basement. The obtained values were assigned to each layer of the reduced geotechnical model and complemented with piezocone penetration resistance (q_c) results from CPTu tests.

The estimation of V_s from q_c was performed using the correlation proposed by Ovando and Romo (1991) for the clays of Mexico City. This combination of results provided a velocity profile consistent with the geotechnical and dynamic conditions of the site.

3 CRACKING MECHANISM

3.1 *Methodology for crack analysis due to subsidence*

The mechanism of formation and propagation of step-type cracks in the abrupt transition zone was evaluated following the criterion proposed by Auvinet *et al.* (2021), which makes it possible to determine crack trajectories from the distribution of angular deformations, shear stresses, and plastic points generated by regional subsidence. This approach, originally developed for the southeastern area of Mexico City, considers the interaction between highly compressible soils and rigid materials, as well as the location of stress concentration zones that precede the appearance of surface discontinuities.

Based on this methodology, a two-dimensional (2D) numerical model of the study site was constructed (Figure 3), without including the projected foundation, in order to isolate the deformation pattern induced solely by regional subsidence. The model adopted the HS Small constitutive behavior for the soft layers and the Mohr–Coulomb (MC) model for the rigid soils, using as input the mechanical and index parameters presented in Table 1.

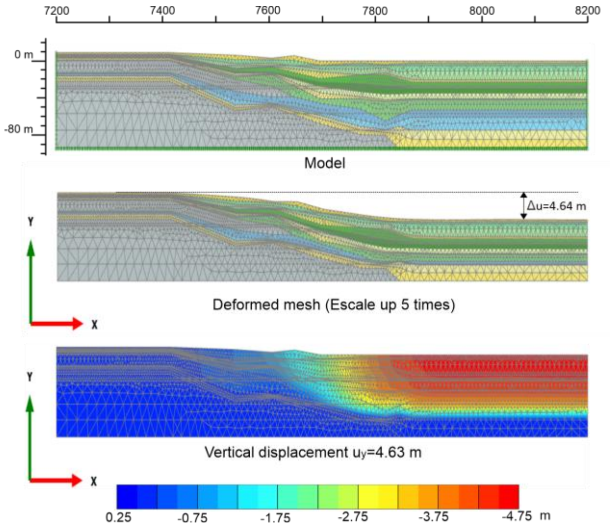


Figure 3. Longitudinal model without crack trajectories

The calibration was carried out based on historical measurements of surface deformation at the site, adjusting the model until reproducing the expected displacement over a 50-year period. Once the deformed condition was defined, interfaces were incorporated along the cracking trajectories verified in the field and determined according to the criterion of Auvinet *et al.* (2021).

To estimate the maximum possible step height, both post-seismic records near the study area and the projection of regional subsidence were considered. The objective was to represent discontinuity conditions with a vertical step of up to 1.0 m per crack. For this purpose, each interface was assigned a material with specific properties, documented in Table 2 (Sánchez, 2025).

Table 2. Properties assigned to crack interfaces (contact material) used to simulate vertical step offsets up to 1.0 m at 50 years

Crack	E kN/m^2	c kN/m^2	ν
1	96	100	0.3
2	100	50	0.3
3	220	100	0.3

This procedure made it possible to robustly define the cracking trajectories in the 2D model and to verify the mechanical parameters assigned to the discontinuities (Figure 4).

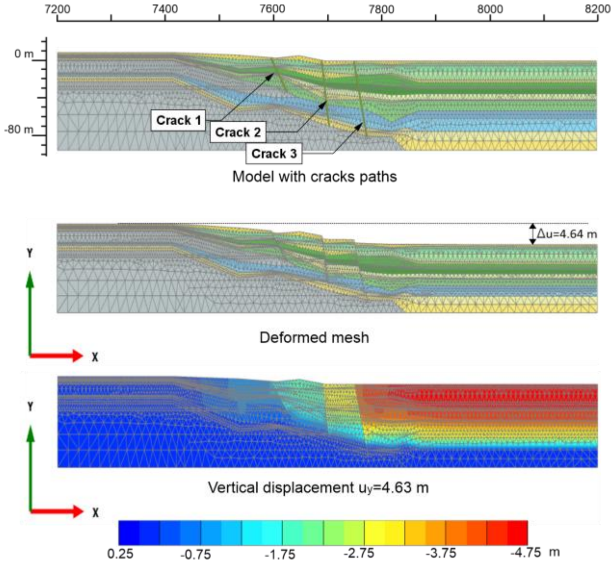


Figure 4. Longitudinal model with crack trajectories

3.2 *Results of the three-dimensional model under cracking effects*

To evaluate the performance of the projected foundation against the combined effects of regional subsidence and ground cracking, a three-dimensional (3D) numerical model was developed in a longitudinal slice configuration, representing the axis of symmetry along the viaduct alignment (Figure 5). The model incorporated the stratigraphy defined in the geotechnical characterization (Section 2.2), including abrupt transitions between soft clays and rigid materials, and considered the crack trajectories previously determined using the Auvinet *et al.* (2021) criterion.

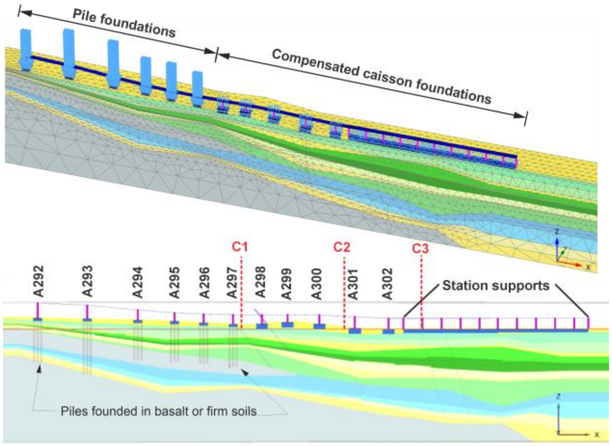
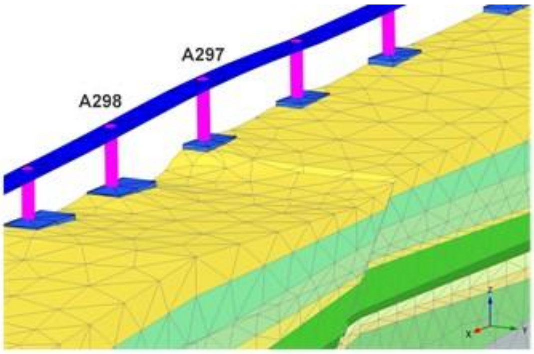


Figure 5. Three-dimensional slice model with foundation elements in the study area

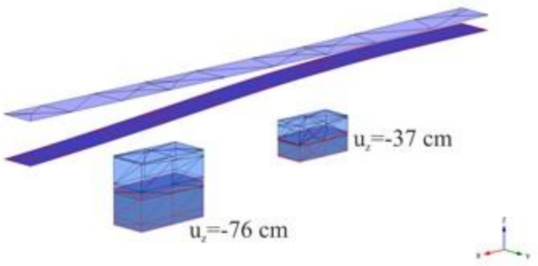
The modeled structure explicitly included the projected foundation elements: piles founded in basalt or stiff soils, columns, compensated box foundations, and an equivalent beam representing the superstructure at the surface. The behavior of soft soils was represented with the HS Small constitutive model, while stiffer materials were modeled using Mohr–Coulomb.

The simulation considered a 50-year projection horizon, corresponding to the estimated service life before a major intervention. Under this scenario, the effects of consolidation induced by regional subsidence were reproduced, along with the redistribution of deformations associated with the presence of step-type cracks.

The results indicate that the 3D model not only identifies progressive changes in slope and differential deformations between adjacent elements, but also quantifies the expected vertical step offset at each crack location. Vertical deformations reach values of up to 1.0 m within the projected period, concentrating at the locations of cracks C1, C2, and C3 (Figures 6 to 8). These discontinuities generate significant differential effects, such as the opening of cold joints in concrete elements, tilting, and differential settlements between supports.

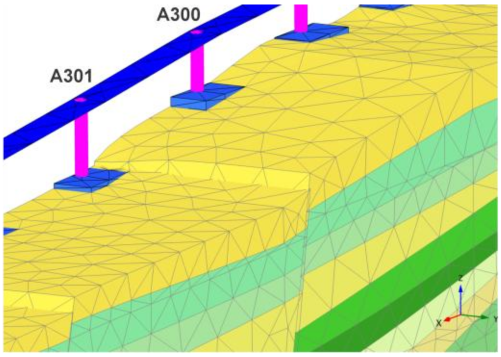


Deformed mesh of caissons, deformations scaled by a factor of 5

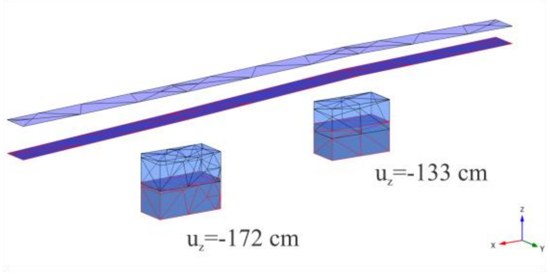


Deformed mesh of the ground with crack 1, deformations scaled by a factor of 5

Figure 6. 3D model results for crack C1

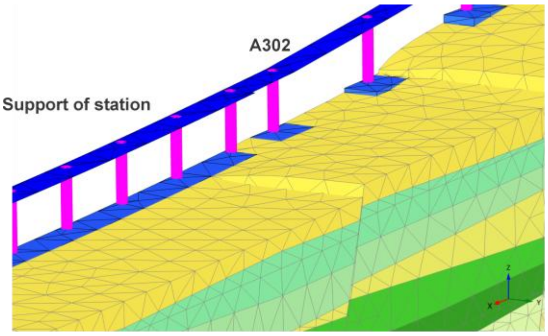


Deformed mesh of caissons, deformations scaled by a factor of 5

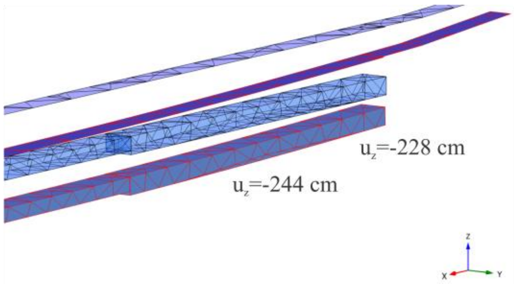


Deformed mesh of the ground with crack 2, deformations scaled by a factor of 2.5

Figure 7. 3D model results for crack C2



Deformed mesh of caissons, deformations scaled by a factor of 5



Deformed mesh of the ground with crack 3, deformations scaled by a factor of 2.5

Figure 8. 3D model results for crack C3

The spatial distribution of the offsets matches the alignment of the geotechnical transition zone and the trace of cracks observed in the field, supporting the validity of the calibrated model. Additionally, the detailed analysis of the deformed mesh (with scale factors applied for visualization) shows how the cracks disrupt the continuity of both the ground and the structure, conditioning their long-term performance.

4 SEISMIC ANALYSIS

4.1 *Seismic environment and adjustment of dynamic parameter*

For the definition of the design earthquake, the results obtained from the SASID program were used. This program is the official tool for obtaining design spectra in accordance with the standard “Norma Técnica Complementaria para Diseño por Sismo de la Ciudad de México (NTC-DS, 2023)”.

The uniform hazard spectrum (UHS) and the elastic response spectrum for a return period of 250 years were determined, considering the coordinates of the Santa Marta station as the analysis point. Figure 9 shows the UHS together with the response spectra associated with subduction and intermediate-depth events.

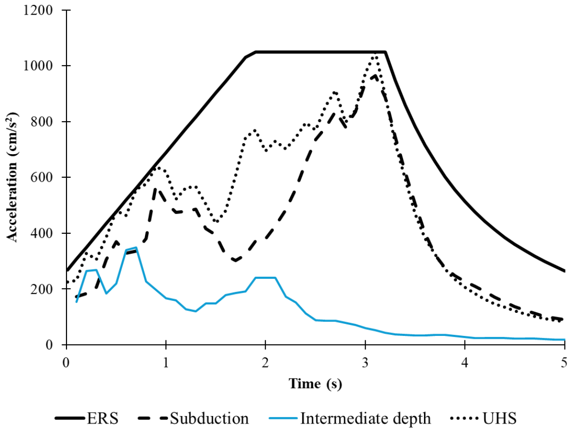


Figure 9. Uniform hazard spectrum obtained from SASID

In addition, SASID was used to generate synthetic accelerograms for each seismic scenario, representative of excitation from the rock basement (Figure 10).

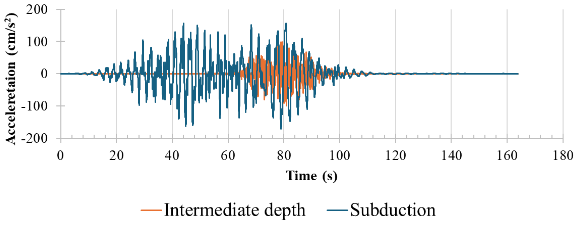


Figure 10. Synthetic acceleration time histories for intermediate-depth and subduction earthquakes in the study area

The soil's dynamic properties were initially defined based on shear wave velocity (V_s) values derived from geophysical exploration, which were correlated with cone penetration test (CPTu) tip resistance values using the correlation proposed by Ovando and Romo (1991). From the Vs values, the maximum shear modulus (G_{max}) was calculated, adjusting the thicknesses and stiffnesses of each layer so that the site's fundamental period matched the one obtained from ambient vibration measurements.

Calibration of the stiffness and degradation parameters ($\gamma_{0.7}$) for the HS Small model was performed through analyses in the DeepSoil program, reproducing the response of the synthetic subduction and intermediate-depth earthquakes generated in SASID.

In the numerical model, free-field boundary conditions were adopted to allow the propagation of seismic waves without spurious reflections at the lateral boundaries, ensuring the representativeness of the response in the central domain.

The base of the model was considered as a compliant base, enabling the introduction of acceleration or equivalent displacement records from the rock basement and avoiding the over-amplifications that would occur with fixed-base conditions.

The synthetic earthquakes were applied at the base as displacement records, optimized to reduce computation time using the Arias intensity method, retaining only the interval containing between 5% and 95% of the cumulative energy of the record.

Before performing the coupled soil–structure and cracking analysis, the dynamic response of the stratigraphic profile was verified in a 2D model without interfaces or cracks. The comparison of the resulting spectra with those from SASID (Figure 11) confirmed that the model adequately reproduces the fundamental periods and expected amplification, validating its use for the coupled analysis phase.

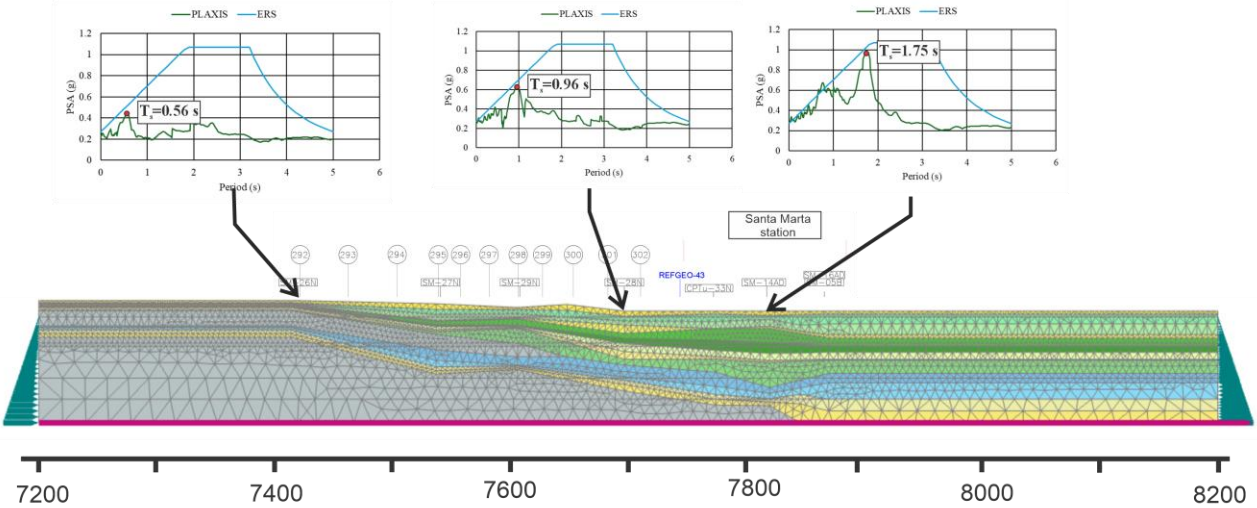


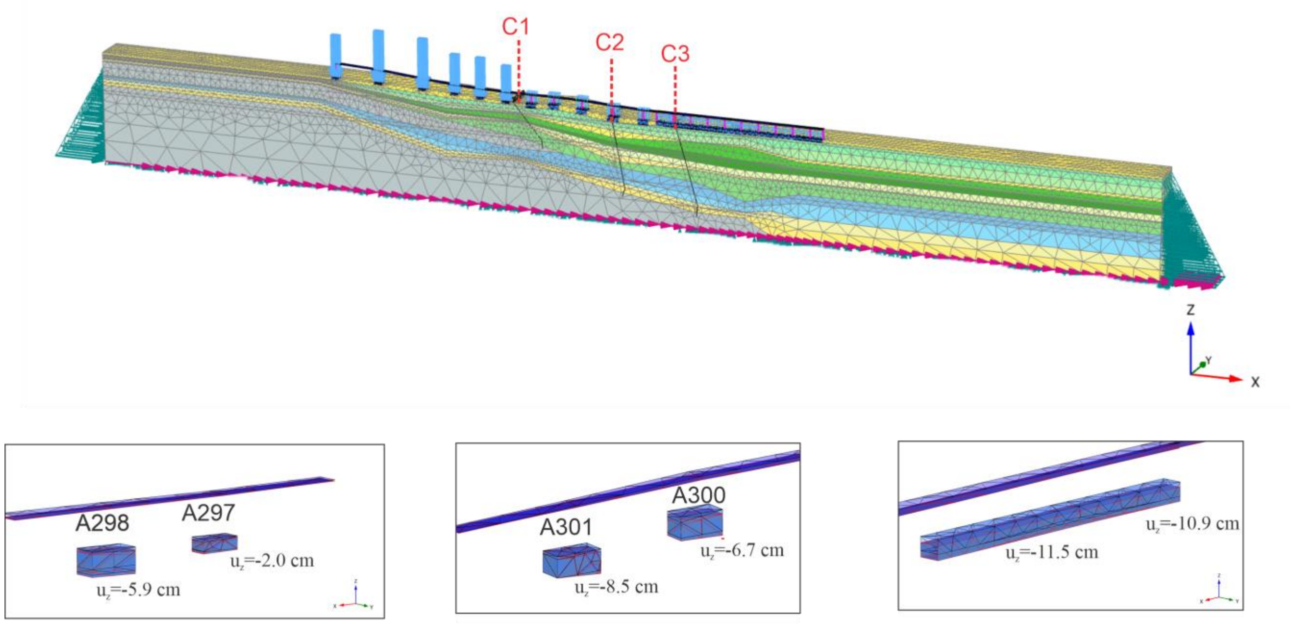
Figure 11. Verification of the dynamic response of the stratigraphic profile

4.2 *Numerical model with seismic conditions of the elevated viaduct*

The three-dimensional model considered the stratigraphy defined in the geotechnical characterization and the structural configuration of the elevated viaduct, including foundations with piles and compensated caissons, columns, and an equivalent beam representing the superstructure. The dynamic soil properties were defined according to the previous calibration carried out with the HS Small model.

The seismic excitation was applied at the base as displacements compatible with the synthetic subduction accelerogram obtained from SASID, considering only the longitudinal direction. Figure 12 presents the global response of the viaduct in terms of maximum displacements, highlighting the influence of local ground conditions on the dynamic behavior of the structure.

Although the vertical differentials are smaller than those produced by regional subsidence, displacements in both directions were identified, which could compromise the performance of the joints in the superstructure. These results are preliminary and are part of an ongoing research effort that will incorporate the bidirectional effect of the earthquake to further evaluate the behavior in the abrupt transition zone.



Zone of crack 1 Zone of crack 2 Zone of crack 3

Figure 12. Response of the elevated viaduct under longitudinal-direction subduction seismic excitation

5 CONCLUSIONS

This research analyzed the combined effects of regional subsidence, step-like ground cracking, and seismic loading on an elevated viaduct located in an abrupt transition zone between lacustrine soils and rigid volcanic deposits in the eastern sector of Mexico City.

The results of the static numerical simulations showed that, over a 50-year projection horizon, the presence of ground cracks significantly increases vertical differentials and induces changes in slope between adjacent supports. In pile foundations bearing on basalt or stiff soils, the magnitude of these changes is more pronounced when compared to compensated caissons, which tend to follow the regional subsidence pattern.

Under the simulated seismic scenario, limited to a subduction earthquake in the longitudinal direction, the vertical differentials were smaller than those generated by subsidence. However, bidirectional displacements were observed, which could affect the performance of expansion joints and the continuity of the superstructure. Additionally, the results highlight the contrasting response of pile-supported foundations, which tend to amplify differential movements due to their higher stiffness, compared with compensated caissons that more closely follow the regional subsidence pattern.

This study confirms that the interaction between static deformation mechanisms and dynamic loads can critically influence the structural performance of infrastructure located in active subsidence zones with abrupt geotechnical transitions. The proposed modeling approach allows for identifying critical points, estimating the evolution of differential movements, and supporting the design of mitigation strategies.

This research will continue to develop for this case study and others, aiming to assess the structural performance under both subsidence and seismic conditions, and to propose specific design and intervention criteria for critical infrastructure in similar environments.

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