INTEGRATED SUBSURFACE MODELING AND LIQUEFACTION ASSESSMENT OF THE DURRËS COASTAL AREA USING CPTU AND ACTIVE SEISMIC METHODS IN SUPPORT OF CIVIL EMERGENCY PLANNING

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ABSTRACT

This study highlights the critical role of integrated geological-engineering, geotechnical, and geophysical investigations in the reliable assessment of soil liquefaction hazard. Major urban areas in Albania, many of which are located near highly active tectonic structures, have experienced significant seismic activity over the last century, with earthquakes of magnitude ranging from 5.4–6.6. The earthquakes of 21 September 2019 (Mw 5.4) and 26 November 2019 (Mw 6.3) caused severe damage in the city of Durrësi and surrounding areas, with clear manifestations of soil liquefaction observed along the coastal zone during the 26 November event. The primary objective of this research was to develop a detailed integrated subsurface model to evaluate the liquefaction potential of the coastal area of Durrësi, situated within a tectonically active region capable of generating strong earthquakes. The investigation was based on an extensive dataset including 60 geological-engineering boreholes, 71 CPTu tests (Cone Penetration Testing with pore pressure measurements) and 40 MASW surveys (Multichannel Analysis of Surface Waves). The integration of these datasets enabled a robust characterization of the stratigraphy and the key geotechnical and geophysical parameters controlling liquefaction susceptibility. The results allowed for the accurate identification of liquefiable layers and their depth ranges, providing essential input for seismic risk mitigation strategies and supporting the preparation of the Civil Emergency Plan for the city of Durrësi. The proposed integrated methodology represents a valuable framework for sustainable coastal development and for enhancing urban resilience to seismic hazards.

Keywords**:** liquefaction phenomenon, geological-engineering model, geophysical model, civil emergency plan

1. INTRODUCTION

Albania, located in the western Balkan region, is characterized by high seismic hazard due to its complex geodynamic and tectonic setting. From a geological and seismotectonic perspective, the country represents a young and highly active territory, making it particularly vulnerable to earthquake-related hazards, including strong ground motion amplification and soil liquefaction (Skrame, 2023). The regional seismicity pattern is dominated by frequent low-magnitude earthquakes, sporadic moderate events (moment magnitude Mw 5.5–5.9), and rare but potentially destructive strong earthquakes with Mw > 6.5. The seismic activity is mostly concentrated in the upper and middle crust and is directly related to the tectonic deformation occurring along the western margin of the Adriatic indentation (Ormeni *et al*. 2025)

Seismic activity in Albania is mainly concentrated along three major seismogenic belts: (i) the Ionian–Adriatic coastal belt, extending northwest–southeast along the boundary between the European Plate and the Adria microplate; (ii) the Peshkopia–Korça (Drini) belt, trending north–south in the eastern part of the country; and (iii) the Elbasan–Dibër–Tetovo transverse belt, oriented southwest–northeast and intersecting the former two structures (Aliaj *et al*. 2010). Over the last 114 years, at least seventeen significant earthquakes with magnitudes ranging from 5.4 and 6.6 have occurred along these belts, resulting in substantial human casualties and widespread structural damage.

Among these events, the 26 November 2019 earthquake (Mw 6.3) represents one of the most damaging seismic events in Albania’s recent history, causing 51 fatalities and extensive damage in the cities of Durrës, Thumanë, Tirana, Vora, Shijak, and surrounding areas. Field observations and post-earthquake investigations highlighted the significant role of local site effects, including soil amplification and widespread manifestations of soil liquefaction, particularly within the coastal deposits of Durrës (Skrame *et al*. 2020; Ormeni and Ozturk, 2024). These effects substantially influenced the spatial distribution and severity of damage, emphasizing the need for detailed subsurface characterization in seismic-prone urban areas (Mancini *et al*. 2021).

Accurate evaluation of liquefaction susceptibility requires reliable characterization of subsurface stratigraphy and soil dynamic properties. In geotechnical earthquake engineering practice, in-situ testing methods are widely adopted to reduce uncertainty associated with soil behavior under cyclic loading. In this study, Cone Penetration Testing with pore pressure measurements (CPTu) was employed to obtain continuous profiles of cone resistance (qc), sleeve friction (fs), and pore water pressure (u2), while Multichannel Analysis of Surface Waves (MASW) was used to derive shear-wave velocity (Vs) profiles representative of small-strain soil stiffness. The combined interpretation of CPTu and MASW data allowed for a detailed delineation of subsurface stratigraphy and the identification of potentially liquefiable sand and silty sand layers, as well as the assessment of their thickness and lateral continuity.

The integration of CPTu-derived geotechnical parameters with Vs-based dynamic soil properties provides a robust framework for liquefaction hazard assessment and site response analysis. The methodological approach presented in this study contributes to improving seismic microzonation practices and supports risk-informed urban planning and engineering design. The outcomes are particularly relevant for coastal cities characterized by young, saturated deposits and high seismic exposure, offering practical implications for the development of earthquake-resilient infrastructure and mitigation strategies.

2. DATASET, SURVEYING AND MODELLING METHODOLOGIES

A three-step procedure was adopted to develop the integrated subsoil model for the coastal area of Durrësi, Albania. Each step is detailed below.

The first step involved the construction of an engineering–geological model at the municipal scale, primarily based on the interpretation and correlation of existing borehole data and geophysical investigations (Konomi, 1980). Geological formations were interpreted in terms of lithofacies according to their sedimentological characteristics and subsequently characterized by their main physical and mechanical properties. This process allowed the definition of a representative lithotype scheme suitable for engineering and seismic applications (Skrame *et al*. 2023).

The second step focused on data acquisition and analysis. In addition to the collection and review of results from previous studies, several new investigations were conducted. These included detailed geological, hydrogeological, and geomorphological surveys at a scale of 1:5000, aimed at updating and refining the geological map of the city. To improve the assessment of local seismic hazard and to characterize the dynamic properties of the identified lithotypes, a series of active seismic surveys was performed. A total of 40 MASW (Multichannel Analysis of Surface Waves) surveys were carried out to derive shear-wave velocity (Vs) profiles, generally reaching a maximum investigation depth of approximately 30 m. The MASW surveys were conducted using a 24-channel seismograph equipped with 4.5 Hz vertical geophones (figure 1). A receiver spacing of 2 m was selected following a preliminary evaluation of subsurface conditions, and a 10 kg sledgehammer was used as the seismic energy source. In parallel, 71 Cone Penetration Tests with pore pressure measurements (CPTu) were performed using a 20-ton piezocone penetrometer (Figure 1). Data acquisition was carried out using dedicated CPTu software. The CPTu system consisted of a hydraulic pushing and leveling unit, 1 m-long segmented rods, piezocone sensors, and a data acquisition unit mounted on the rig. The piezocone was equipped to continuously measure penetration depth, cone resistance, sleeve friction, pore water pressure, and inclination at 1 cm intervals. The cone had a projected area of 10 cm^2, and the system was capable of reaching a maximum depth of 40 m at a constant penetration rate of 2 cm/s (Figure 1).

The third step involved numerical modeling and data interpretation. To define the spatial distribution of the sedimentary infill, an integrated subsoil model was developed by combining geological, geotechnical, and geophysical datasets. The resulting model was subsequently validated and refined using geotechnical information obtained from 60 boreholes, thereby ensuring consistency between stratigraphic interpretation and measured soil properties.

Fig. 1: Geotechnical and Geophysical onsite measurements,

3. RESULTS AND DISCUSSIONS

The city of Durrës has long been exposed to significant seismic hazard and has suffered severe damage from a series of destructive earthquakes. Based on historical seismicity and the regional geological–tectonic framework, Durrësi is located close to the frontal zone of the Albanian Orogen, where compressional tectonic mechanisms dominate. These tectonic processes have generated numerous strong earthquakes with magnitudes exceeding 5.0 and macroseismic intensities reaching IX on the MSK-64 scale (Ormeni and Ozturk 2024). During the period from September 2019 to January 2020 alone, eight earthquakes with magnitudes greater than 5.0 were recorded. The most destructive event occurred on 26 November 2019 (Mw 6.4, I_0 = IX MSK-64), resulting in 51 fatalities and extensive damage to thousands of buildings in the cities of Durrës, Tirana, Kavaja, Shijak, Thumanë, and surrounding areas (Skrame *et al*. 2020).

Durrësi is located along the Adriatic coast in central Albania, within the lowland of the Periadriatic Depression. Aliaj *et al.* (2010) stated that this depression corresponds to a wide, actively subsiding foredeep basin developed at the outer front of the west-verging Albanides orogenic belt, comprising the Ionian and Kruja zones with a predominant N–S structural trend. The foredeep basin is filled with more than 2 km of marine to continental deposits, which have been affected by syn-sedimentary tectonic activity since the Pliocene. Compressive tectonics have significantly shaped the local geomorphology, leading to the formation of the Durrës Hill, which consists of Messinian to Lower Pliocene shallow-marine sandstones, conglomerates, and clays with gypsum. These formations are unconformably overlain by Quaternary deposits composed of alluvial, lagoonal–marshy, and marine sediments, characterized by alternating layers of silts, peats, clays, sands, and gravels.

CPTu test data were used to define soil profiles, soil behavior types, and geotechnical parameters for the various subsurface layers at each investigation point. Based on mechanical characteristics such as strength, stiffness, and compressibility, as well as soil behavior type classification (SBTn), distinct soil layers were identified and characterized at each CPTu location. The interpretation of static cone penetration test results allowed for a detailed classification of subsurface strata and the derivation of their physical and mechanical parameters. The complete set of geotechnical parameters is summarized in representative stratigraphic columns, as shown in Figure 2 (Skrame *et al.* 2025).

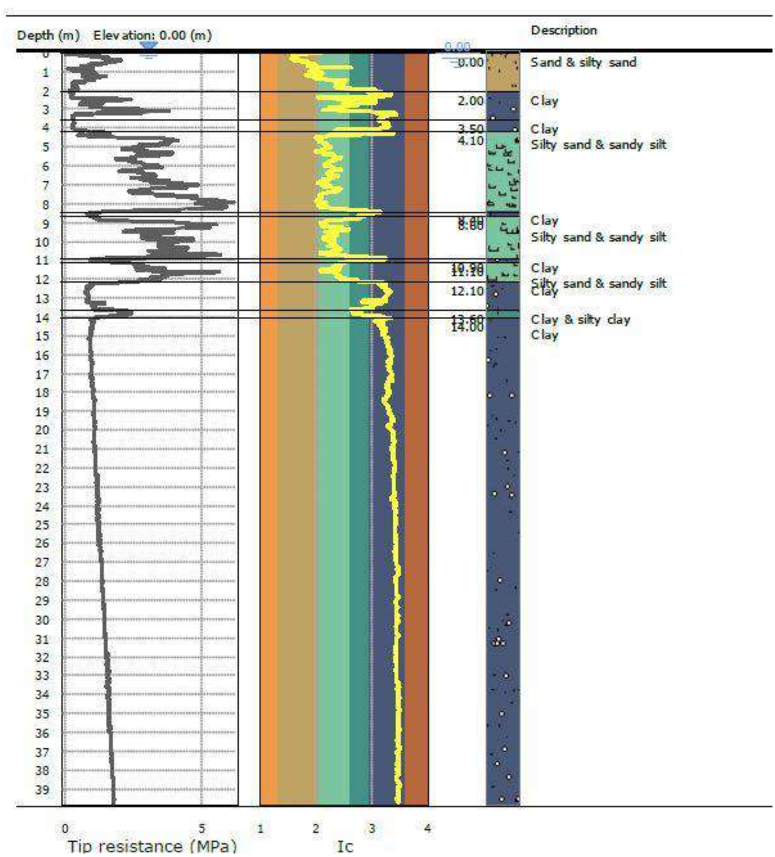

Fig. 2: Stratigraphic column type of the Durres coastal area (Skrame *et al*. 2025).

Liquefaction analyses were performed using the Robertson and Wride (1998) method. Calculations were conducted using specialized computational software. Safety factor profiles, determined in accordance with the NCEER-97-0022 procedure, indicate that liquefaction is expected to occur within the investigated area. Safety factor values lower than 1.0 (FS < 1.0) identify soil layers susceptible to liquefaction. As shown in Figure 3, liquefaction is expected primarily in near-surface layers, extending to depths of approximately 20 m. The liquefaction potential was quantified using the Liquefaction Potential Index (LPI), which ranges from 0 to 20. Values between 0 and 5 indicate low liquefaction potential, values between 5 and 15 indicate high potential, and values greater than 15 indicate very high or certain liquefaction occurrence. For the analysis, a design earthquake with moment magnitude Mw = 6.6 and a peak ground acceleration a_{max} = 0.26 g was adopted, representing the maximum horizontal acceleration expected at the seismic bedrock based on available literature data for the study area.

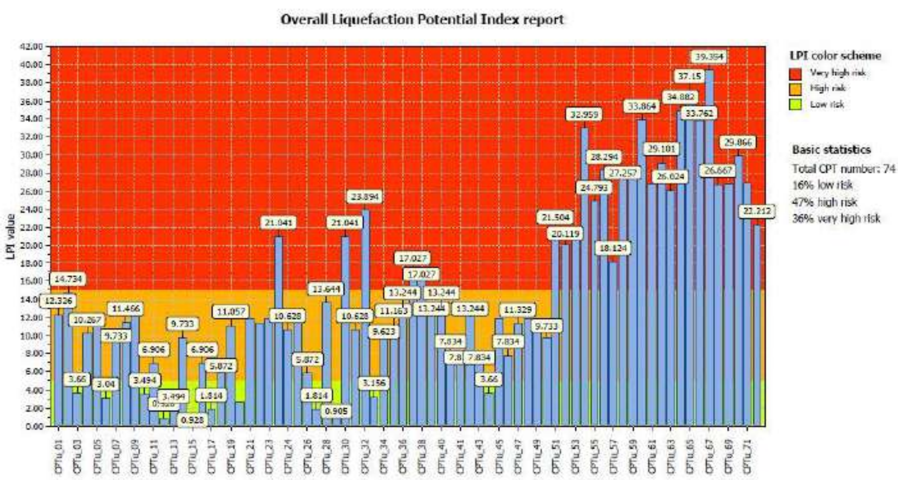

Fig. 3: Shows the presence of the Liquefaction phenomena in all the CPTu tests. Liquefaction Potential Index (LPI) shows always values above 15 for all the methodologies.

4. CONCLUSIONS

This study demonstrates that the development of an integrated subsoil model based on the combined application of Cone Penetration Testing with pore pressure measurements (CPTu) and Multichannel Analysis of Surface Waves (MASW) constitutes a reliable and effective approach for characterizing complex coastal deposits. The implementation of this methodology in the coastal area of Durrësi, Albania, enabled detailed reconstruction of subsurface stratigraphy and the identification of the thickness and spatial distribution of sand, silt, clay, and peat layers.

The integration of CPTu-derived geotechnical parameters with shear-wave velocity (Vs) profiles obtained from MASW significantly reduced uncertainties in the estimation of soil physical, mechanical, and dynamic properties. These results provided a robust basis for evaluating liquefaction susceptibility and identifying depth intervals with a high potential for liquefaction under strong seismic loading.

The results here reported confirm that the combined CPTu–MASW approach offers substantial advantages over conventional investigation techniques, particularly in urban coastal areas characterized by young, saturated sediments and high seismic exposure. The proposed integrated methodology provides essential input for liquefaction hazard assessment, seismic microzonation, and risk-informed urban planning. Furthermore, it represents a valuable tool for the design of earthquake-resilient infrastructure and the development of effective mitigation strategies.

Declarations

Data accessibility (websites, platforms): None

Declaration of AI use: There has been no use of AI when writing the actual paper.

Author Contributions

KS – Conceptualization, compilation and preparation of the manuscript. Geotechnical and geophysical investigations. Geotechnical modeling. Geophysical modelling. Writing the original draft preparation, and writing – review & editing. **RrO** - Existing Data collection. Preparation of the earthquake catalog. Tectonic interpretation; Writing the original draft preparation, and writing – review and editing.

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Table 1 provides the expected average maximum acceleration on bedrock (PGA) for return periods of seismic action of 50, 100, 200, 500 and 1000 years.

Table 1. Expected average maximum accelerations on bedrock PGA

Return period in **years**	50	100	200	500	1000
Acceleration in **g**	0.114	0.153	0.201	0.283	0.335

4. SEISMO GEOLOGICAL INVESTIGATIONS

The geophysical investigations within the framework of this work were conducted with the purpose of determining the parameters of the lithological environments of the investigated location, which have local influence on the changes of regional seismic force.

Fig.3: Investigated location

The geophysical investigations conducted in this study aimed to dertermine the lithological parameters of the site, which exert a local influence on variations in regional seismic forces results of the