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Liquefaction risk assessment of airport infrastructure using geological data and remote sensing techniques

Évaluation des risques de liquéfaction des infrastructures aéroportuaires à l'aide de données géologiques et de techniques de télédétection

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ABSTRACT: Airport infrastructure plays a crucial role in regional and national economies, as well as during emergencies such as after major earthquakes. However, its functionality remains vulnerable to disruption caused by secondary earthquake effects, such as soil liquefaction. Hence, assess the risk posed to airport facilities by these phenomena becomes paramount for ensuring airport resilience and preparedness in the face of seismic events. This study, introduces a practical and rapid assessment tool for the risk analysis of airport infrastructure located in liquefaction-prone areas. Focusing on the Nestos delta in Greece, where the Kavala International Airport (KVA) is placed, a new methodology is proposed, which combines geological and remote sensing data to assess and map liquefaction susceptibility at local scale. The results reveal that a significant section of KVA's runway and taxiways are located on highly susceptible soils of abandoned meanders. Using FEMA's HAZUS methodology the study quantifies the impacts of liquefaction for a given seismic scenario. The analysis estimates a 49% probability of liquefaction for the highly susceptible class, with ground settlements predicted to reach 30cm. The results of the liquefaction hazard analysis are used for the risk assessment of the airport infrastructure, estimating a total direct loss of €22,2 million. The analysis is validated using datasets from three international airports that sustained extensive seismic damage in the past. This research serves toward safeguarding airport infrastructure in liquefaction-prone regions.

RÉSUMÉ: Les infrastructures aéroportuaires jouent un rôle crucial dans les économies régionales et nationales, ainsi que lors de situations d'urgence comme après des tremblements de terre majeurs. Cependant, sa fonctionnalité reste vulnérable aux perturbations causées par les effets secondaires des tremblements de terre, tels que la liquéfaction du sol. Par conséquent, évaluer le risque que ces phénomènes font peser sur les installations aéroportuaires devient primordial pour garantir la résilience et la préparation des aéroports face aux événements sismiques. Cette étude présente un outil d'évaluation pratique et rapide pour l'analyse des risques des infrastructures aéroportuaires situées dans des zones sujettes à la liquéfaction. En se concentrant sur le delta du Nestos en Grèce, où se trouve l'aéroport international de Kavala (KVA), une nouvelle méthodologie est proposée, qui combine des données géologiques et de télédétection pour évaluer et cartographier la susceptibilité à la liquéfaction à l'échelle locale. Les résultats révèlent qu'une partie importante de la piste et des voies de circulation du KVA est située sur des sols très sensibles de méandres abandonnés. À l'aide de la méthodologie HAZUS de la FEMA, l'étude quantifie les impacts de la liquéfaction pour un scénario sismique donné. L'analyse estime une probabilité de liquéfaction de 49 % pour la classe très sensible, avec des tassements au sol qui devraient atteindre 30 cm. Les résultats de l'analyse du risque de liquéfaction sont utilisés pour l'évaluation des risques de l'infrastructure aéroportuaire, estimant une perte directe totale de €22,2 millions. L'analyse est validée à l'aide d'ensembles de données provenant de trois aéroports internationaux qui ont subi d'importants dommages sismiques dans le passé. Cette recherche sert à sauvegarder les infrastructures aéroportuaires dans les régions sujettes à la liquéfaction.

Keywords: Liquefaction; airports; runways; risk analysis; remote sensing.

1 INTRODUCTION

Earthquakes pose a significant threat to vital infrastructure and communities, as they can induce damage due to ground shaking and ground failure. A common form of failure is soil liquefaction, a phenomenon in which granular material transforms from a solid state into a liquefied state, as a result of decreased effective strength and increased pore pressure during seismic shaking (Youd, 1973). Generally, liquefaction occurs in fluvial and coastal regions and filled land areas, that contain shallow layers of low density, saturated and granular sediments (Youd and Hoose, 1978; Holzer, 1998; Tinsley et al., 1985). Ground settlement and cracking, lateral spreading and foundation failure caused by soil liquefaction have led to extensive damage to transport infrastructure and other lifelines in the past.

Airports are one of the most critical infrastructure, especially in the aftermath of devastating natural disasters, as they play a pivotal role in emergency response and recovery efforts. Previous seismic events in Niigata (Japan) in 1964, Loma Prieta (USA) in 1989, Nisqually (USA) in 2001, Tohoku in 2011 and the most recent one in Turkey-Syria in 2023 revealed the vulnerability of airports to both ground shaking and secondary earthquake effects like soil liquefaction. These factors can lead to damage and disrupt the normal operation of the airport. In particular, runways, taxiways, and ramp areas are susceptible to sinking or shifting, similarly to roadways, leading to substantial discontinuities or pavement cracking. Moreover, air traffic control, navigation, piping and fuel storage facilities, may incur damage from ground deformation or differential settlement. Given that most of the airport infrastructure has low tolerance to deformations, such damage can impede the transport of people and supplies, and result to destructive effects on the regional economy (Grogan and Vallerga, 2000). Therefore, it is crucial to have a comprehensive understanding of liquefaction mechanisms and their impact on airport environments, for ensuring that efficient mitigation measures are taken.

This paper introduces a practical and rapid tool for facilitating the risk analysis of airport infrastructure located in liquefaction prone areas. A new methodology is proposed for local-scale liquefaction assessement and mapping, which combines geological data and remote sensing techniques. This is applied on the Nestos delta in Greece, where the Kavala International Airport (KVA) is located. The results are utilised to estimate the permanent ground displacement (PGD), such as vertical displacements and lateral spreadings, due to liquefaction. Subsequently, PGD is used as the intensity measure for the risk analysis of the infrastructure. The liquefaction susceptibility and vulnerability assessment are validated using datasets from Oakland, King County (USA) and Hatay (Turkey) international airports.

2 METHODOLOGY

Considering the significant influence of depositional processes on the susceptibility of sediments to liquefaction, we have developed a methodology that enables the identification of surface geological units prone to liquefaction. This method involves creating a geomorphologically oriented map by integrating geological and remote sensing data, as outlined in the study by Taftsoglou et al. (2022). This procedure includes four phases (Figure 1).

In phase 1 geological and historical maps of the area, orthophotos and satellite images are collected in order to examine the geological formations and the geomorphological evolution of the plain. By combining these layers of information with the local topography (DEM) the mapping of geomorphological features is conducted in phase 2. Geomorphological formations, such as abandoned stream/meanders, point bars, oxbow lakes, dunes and lagoons are detected and traced during this step and a new geomorphological map is compiled. In phase 3 the classification of surficial geological units susceptible to liquefaction is performed. In particular, data provided by the geological maps and the new geomorphological map are used to define the age (<500yr, Holocene, Pleistocene) and the depositional environment of the geological units. Subsequently, the criteria by Youd and Perkins (1978) are applied to classify the geological units according to their susceptibility to liquefaction. In phase 4, a liquefaction susceptibility map is compiled, including four classes (Low, Moderate, High and Very High), where coastal and fluvial deposits are classified as high to very high susceptible units.

2.1 Liquefaction Susceptibility of KVA

KVA is located in the west side of Nestos delta plain in Thrace, Greece. The location of the airport along with the deposition of recent Holocene sediments and the presence of high potential onshore and offshore active faults capable to trigger large earthquakes in the area, were the motivational factors for this application.

By employing the proposed methodology, we noted a deficiency in the geological maps (HSGME) with regard to accurately representing Pleistocene and Holocene deposits. Using historical orthophoto maps dated before 1945 and Declassified Satellite images (KH-4) from 1960 and 1968 we were able to examine the geomorphological evolution of the plain and enrich the original classification of geological formations, mainly with the addition of fluvial and coastal deposits, such as abandoned river channels, oxbow lakes, point bars, dunes and deltaic deposits.

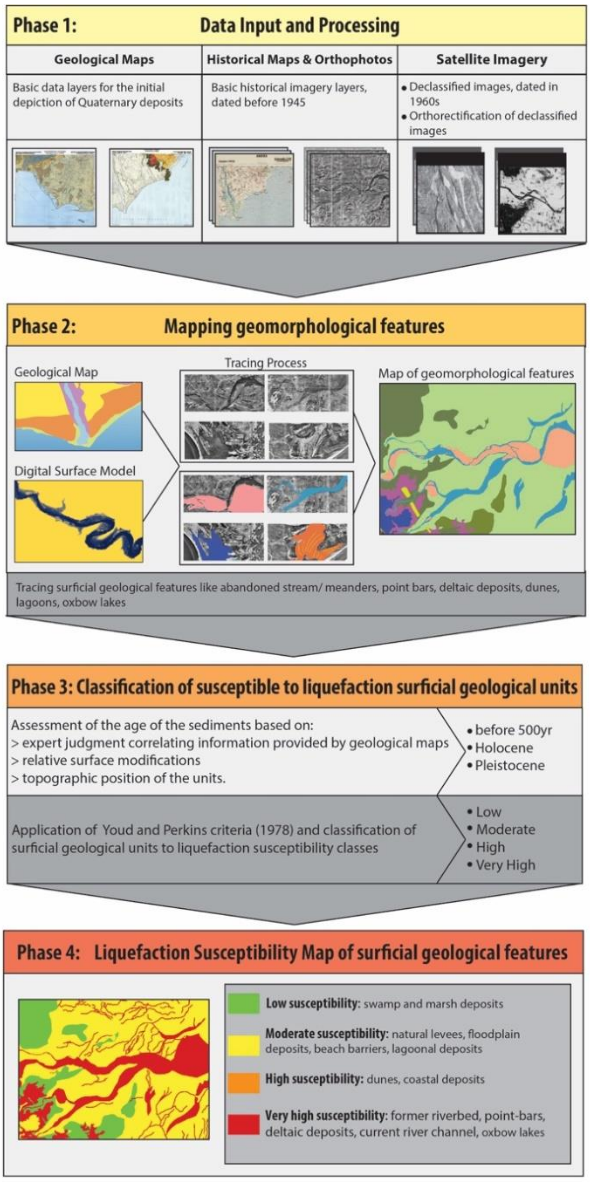

Figure 1. Methodology for assessing liquefaction susceptibility (Taftsoglou et al. 2022).

Another important observation was the extensive river network in the west side of Nestos plain, where old estuaries of Nestos river were formed. The airport was built during 1980s in this area, where land reclamation and modifications had already been occurred. Focusing on this location, the new geomorphological map reveals that a significant part of the airport's facilities and runway were built on an abandoned river branch of old estuaries and deltaic deposits (Figure 2). After the application of Youd and Perkins criteria, it was clear that part of the runway, taxiways and apron are located on a very high susceptible zone.

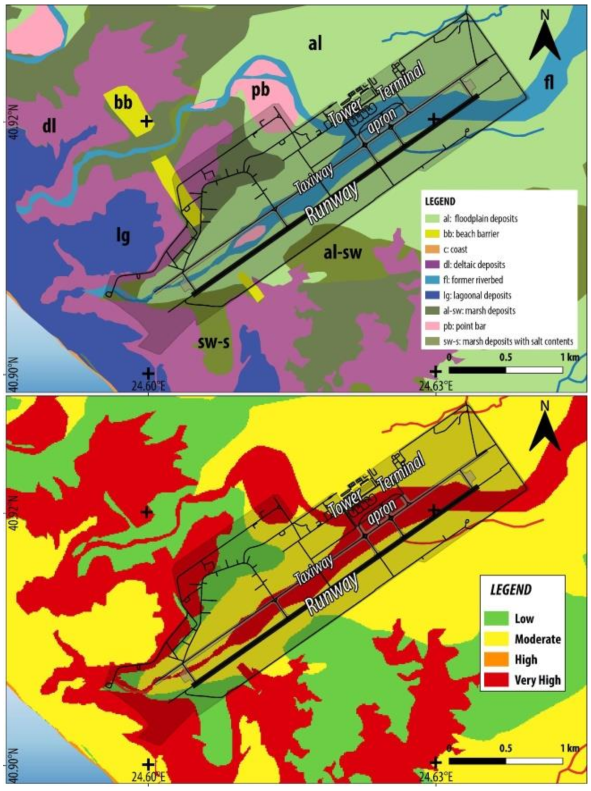

Figure 2. New geomorphological map and liquefaction susceptibility map of KVA.

2.2 Risk Analysis of KVA airport

The HAZUS (FEMA, 2022) methodology was adopted to evaluate the probability of liquefaction and the PGD based on the results described in section 2.1 and a representative seismic scenario based on SHARE and GreDaaS databases of seismogenic sources (Caputo et al, 2012; Giardini et al, 2013). An event of Mw 6.3 in the closest seismogenic source of Kavala-Xanthi-Komotini fault was selected and the ground motion map (PGA) was produced using REDAS software (Papatheodorou et al., 2023). Subsequently, the probability of liquefaction was assessed for each susceptibility category, taking also into account the amplitude of the ground shaking at the airport location (PGA=0.36g) and a groundwater depth of less than 6m. In particular, the probabilities for high and very high susceptibility classes were estimated to be 30 % and 49%, respectively (Figure 3).

The PGD in terms of ground settlements were evaluated following the criteria outlined by Tokimatsu and Seed (1987), while the lack of extended waterways in the vicinity of the infrastructure limited the expectations of lateral spreading phenomena. It is projected that areas classified as highly susceptible will experience ground settlement up to 15.2 cm, while those categorised as very highly susceptible can reach 30.4 cm of settlement.

The vulnerability of the runway (3,000x45m), taxiways (4,000x35m) and apron (96,000m^2) is assessed based on the fragility functions that are included in HAZUS methodology (Figure 4). The probabilities of exceeding slight/moderate, extensive, and complete damage level were assessed for PGD values of 5.08 cm and 30.4 cm, as the runway, taxiways and apron are located on the moderate and very high susceptibility classes. Based on the probabilities of exceeding each damage state and a repair ratio of 0.1 for slight/moderate, 0.4 for extensive, and 0.8 for complete damage, average loss ratios of 0.125 and 0.590 were calculated for the two PGD values (Argyroudis, 2022). The reconstruction cost was considered equal to 180€/m^2 for the runway and 160€/m^2 for the taxiway and apron (Markovich, 2011). By multiplying the construction cost, average loss ratio and the corresponding area, the direct losses were estimated (Table 1). The total loss for this seismic scenario is assessed equal to €22,2 m. Yet, this is a conservative estimation assuming that liquefaction affects the entire runway, taxiway and apron. In reality, it is expected that ground failure due to liquefaction will likely be more localised, resulting in damage to a portion of these infrastructure.

Table 1. Estimation of direct losses for KVA.

Header	PGD (cm)	Area (m^2)	Loss ratio	Loss (million €)
Runway	5.08	122,247	0.125	2,8
	30.4	12,753	0.590	1,4
Taxiway	5.08	45,513	0.125	0,9
	30.4	99,489	0.590	9,3
Apron	5.08	17,605	0.125	0,4
	30.4	78,468	0.590	7,4

3 VALIDATION DATASETS

The liquefaction susceptibility assessment and risk analysis for the KVA airport are validated in the case studies of Oakland (OAK), Hatay (HTY) and King County (BFI) international airports, where the most extended liquefaction-related damages occurred to the runways areas. The estimated probabilities of liquefaction and PGD according to HAZUS-FEMA methodology, are consistent with the liquefaction occurrences after the earthquakes of Loma Prietta (1989), Turkey-Syria (2023) and Nisqually (2001) in the three airport locations (Table 2).

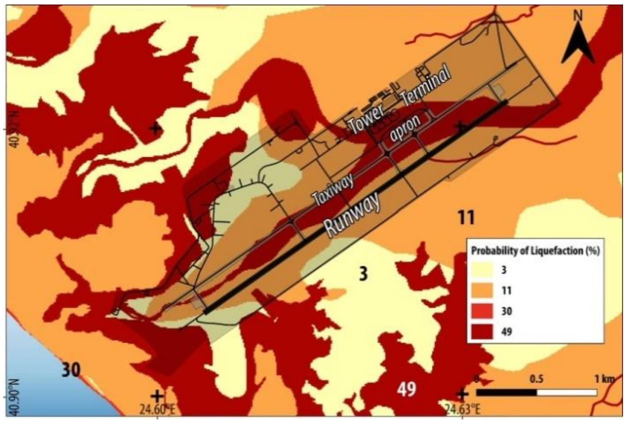

Figure 3. Probability of liquefaction in KVA area.

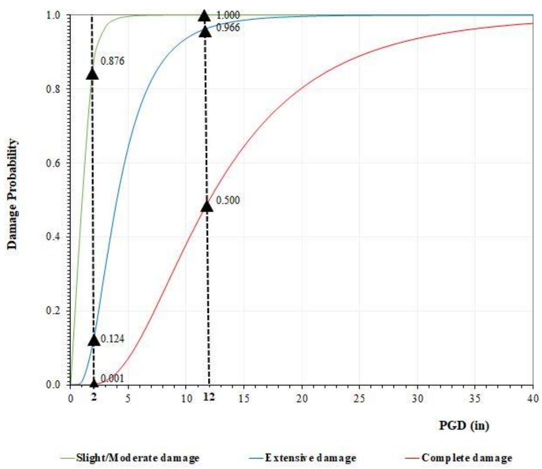

Figure 4. Fragility curves for the runway, taxiways and apron as a function of PGD (FEMA, 2022).

OAK is located on the eastern shore of the San Francisco Bay in western Alameda County. On the northeastern field is located the original part of the airport, built on a tidal marshland with deltaic and stream deposits of San Leandro Creek and fine-grained marsh sediments. The southwestern younger section was constructed on fill over tidal flats and shallow bay areas (Lajoie and Helley, 1975; Witter et al., 2006). During the 1989 Loma Prieta earthquake the extensive liquefaction induced damage resulted in property loss of at least $99 million (Holzer, 1998). According to the FEMA methodology, OAK predominantly falls within the very high susceptibility class, with a probability of 22.3% for liquefaction occurrences, corresponding to PGD of 30.4 cm (Table 2). Validation confirms the consistency between these estimations and the observed damage. Particularly, 900 m of the north-western runway was damaged by sand boils, together with cracking and buckling of the pavement and lateral spreading, while in the adjacent taxiway pavement cracks of 30 cm width and 15 cm vertical displacement were detected. Moreover, the west part of the runway shifted around 0.6 m to the south.

Liquefaction also occurred at the main terminal buildings and taxiways at the south end with pavement settlements up to 8 cm (Holzer, 1998; Seed et al. 1991).

HTY is located in the western part of Amik plain; on the formerly Amik Lake. During the 2023 earthquake doublet of Mw 7.7 and Mw 7.6 on East Anatolian Fault Zone (EAF) extensive liquefaction was observed over the former Amik lake floor, striking also HTY. In particular, the eastern part of the airport was affected by liquefaction shaking deformation phenomena (ground oscillation-lateral spreading) and or possibly triggered shallow slip of pre-existing neotectonic fault traces (Taftsoglou et al., 2023). Ground cracks and soil craters were detected on the runway and its closer area leading to closure of the airport for six days. In contrast to the east side, ground cracks of significant length in the western part of the airport were observed, related to surface fault ruptures of an unknown EAF segment, which cross Amik plain through this area. The results of FEMA's are consistent with the observed damages in this area, with almost all airport infrastructure classified to as highly susceptible to liquefaction, with probability of 98% and PGD of 15.2 cm (Figure 5).

The last case study is the BFI airport. After the 2001 earthquake of Mw6.8 in Nisqually valley, extensive liquefaction was observed at BFI (Nisqually Earthquake Clearinghouse Group, 2001; Bray and others, 2001), which is predominantly situated within an area highly susceptible to liquefaction, with a substantial portion of its runway built upon deposits from abandoned meanders that exhibit an extremely high susceptibility to these phenomena. The extensive liquefaction primarily affected the eastern runway, leading to the formation of ejecta-covered zones extending approximately 90 m in length. Ground surface settlements of up to 20 cm were occurred in this area. While a few isolated sand boils were observed along the western runway, a significant sinkhole measuring 1.2 m in width and 1.8 m in depth was reported at the northern end of the western runway. These phenomena were attributed to apparent ground oscillations, which resulted in the development of cracks in the pavement joints along both runways. Along the west edge of the western runway, a longitudinal crack measuring roughly 3 km in length and ranging from 1.2-2.5 cm in width was noted. Interestingly, the distribution of sand boils and pavement cracking appeared to align with the path of an ancient meander of the Duwamish River. As per HAZUS, the probability values for areas categorized as highly susceptible and very highly susceptible are 7.5% and 16.6% respectively, with estimated PGD of 15.2 cm and 30.4 cm. The observed damaged areas align closely with these estimations, indicating the accuracy in identifying the affected zones.

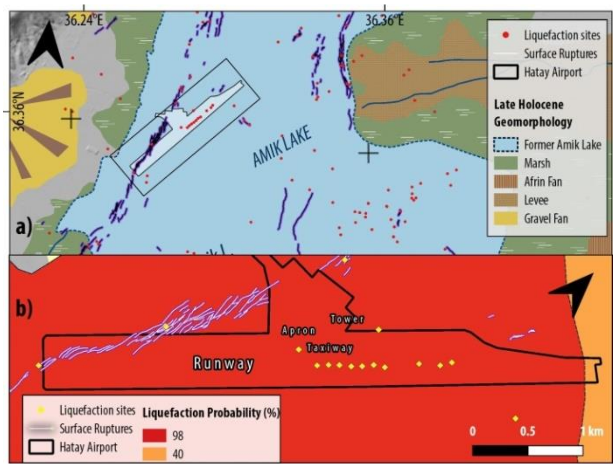

Figure 5. Liquefaction manifestations at HTY, after the 2023 earthquake doublet.

Table 2. Estimation of liquefaction probability (%) and PGD (cm) according to FEMA (2022) for different susceptibility classes (SC).

Airport	KVA	OAK	BFI	HTY	
PGA (g)	0.36	0.20	0.18	0.80	
Mw	6.3	6.9	6.8	7.7	
SC		**Probability (%)**			**PGD (cm)**
VH	49	22.3	16.6	100	30.4
H	29	11	7.5	98	15.2
M	11	3	1.6	41	5.1
L	3	0	0	15.5	2.5

4 CONCLUSIONS

This paper presents an efficient and rapid evaluation tool for assessing the risk of airport infrastructure located in liquefaction-prone areas, using geological and remote sensing data. The methodology is applied to the area where the Kavala International Airport (KVA) in Greece is built to produce a liquefaction susceptibility map. Subsequently, the probability of liquefaction and ground settlements are estimated for a representative seismic event. The direct losses for the runway, taxiways and apron are estimated to €22,2m. However, in reality, the ground failure caused by liquefaction is expected to be more localized, leading to damage in specific sections of this infrastructure and consequently resulting in reduced losses. The methodology is validated using three cases study airports which sustained damage due to liquefaction. The results show a good agreement between the observed and estimated damaged areas confirming the accuracy of the proposed approach in identifying the susceptibility of areas prone to liquefaction. This research can inform decision making for mitigating risks due to liquefaction hazard in airports, and hence allow for continuous or very quick return to operations following seismic events.

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