

A synthetic stratigraphic parameter to quantify the liquefaction susceptibility of layered soil deposits

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ABSTRACT: Earthquake-induced soil liquefaction can cause significant damage to the built environment, making the assessment of liquefaction susceptibility critical for estimating potential impacts. Traditionally, simplified analyses have been used to evaluate liquefaction susceptibility, but these methods often overlook key factors, such as cross layer interactions that directly modify both response of individual layers and overall response of the deposit; water flow between adjacent layers and morphological effects, which refer to structural characteristics of deposits that inhibit water flow and diffusion effects. This research focuses the attention on the last aspect. Over 100 CPT (Cone Penetration Test) datasets from Sakarya (1999 Kocaeli earthquake, Turkey) were analyzed, revealing notable differences between sites where liquefaction occurred and those where it did not. These differences are primarily linked to the deposit characteristics, such as the thickness and vertical continuity of liquefiable layers. Based on experimental data, a new synthetic parameter (SLEI, *Soil Liquefaction Evidence Index*) to quantify the liquefaction vulnerability has been introduced. SLEI incorporates the thickness of liquefiable layers, the presence of a non-liquefiable crust, and the number of liquefiable layers up to a depth of 15 meters.

KEYWORDS: Soil liquefaction, stratigraphy effect, liquefaction evidence

1 INTRODUCTION

Soil liquefaction during earthquakes is a highly dynamic process involving rapid development of excess pore water pressures (EPWP), reduction of soil stiffness and strength, and diffusion of EPWPs through water flow. The liquefaction process is characterized by strong cross-layer interactions throughout the depth of liquefying deposits. Effects of such interactions are evident in shake table tests, centrifuge experiments, and dynamic analyses of liquefiable deposits. For example, when first triggering of liquefaction occurs in a rigorous non-linear dynamic analysis accounting for EPWPs, the response of the whole deposit is severely impacted by the softening of the liquefied soil (e.g., Cubrinovski et al., 2019). Comprehensive studies of numerous liquefaction case histories from the 2010-2011 Canterbury (New Zealand) earthquakes have demonstrated that dynamic interactions play important role in the evolution of the liquefaction response and even govern the severity of liquefaction manifestation at the ground surface (Cubrinovski et al., 2019). However, despite the intent to capture the overall performance of the deposit at a given site, in the simplified liquefaction evaluation procedures each layer is considered in isolation, and a factor of safety against liquefaction triggering, maximum shear and volumetric strains are estimated separately, and independently, for each layer.

Based on comprehensive series of seismic effective stress analyses and interpretation of liquefaction case histories, Cubrinovski and Ntritsos (2023) classified dynamic interactions within the deposit and their effects into three categories:

(1) *Dynamic response effects*, which refer to cross-layer interactions that directly modify both response of individual layers and overall response of the deposit. For example, once liquefaction is triggered in a loose sand layer during shaking, significant reduction in the seismic demand (amplitude of cyclic shear stresses) will occur in subsequent shaking due to softening of liquefied soils, which in turn will substantially

affect the evolution of the response throughout the depth of the deposit.

(2) *Diffusion effects*, refer to diffusion of EPWPs through water flow. Typical diffusion effects include fluidization of previously liquefied layer, thickening of liquefied zone, and seepage-induced liquefaction in near-surface soils due to dissipation of EPWPs, upward water flow and inflow of water from underlying soils.

(3) *Morphological effects*, which refer to structural characteristics of deposits that inhibit water flow and diffusion effects. Typical morphological factors include presence of non-liquefiable crust, multiple non-liquefiable layers that isolate liquefiable soils and prevent formation of thick liquefied zones, and partial saturation of near-surface soils. In particular, Cubrinovski and Ntritsos (2023) showed that at a fixed thickness of sandy layer in the first 10 m from ground surface, profiles with vertically continuous liquefiable deposits (Fig. 1) exhibit larger damages on surface compared to profiles with interbedded liquefiable deposits (Fig. 1). For vertically continuous deposits, onset of liquefaction in the shallow critical layer (zone) occurs in the early stages of the liquefaction response which sets the conditions for severe liquefaction response and extreme liquefaction manifestation at the ground surface. Conversely, in interbedded deposits, typically deep liquefaction is first triggered, which delays the onset of liquefaction in the shallow critical layer to the late phase of the liquefaction response. This reduces the overall liquefaction response and substantially mitigates liquefaction manifestation of interbedded deposits, the effects of which are especially significant as these deposits have multiple layers of low liquefaction resistance throughout depth.

This work focuses on the morphological effects of liquefaction by analyzing soil stratigraphy of Sakarya region (Turkey), which was heavily affected by extensive liquefaction phenomena during the 1999 Kocaeli earthquake.

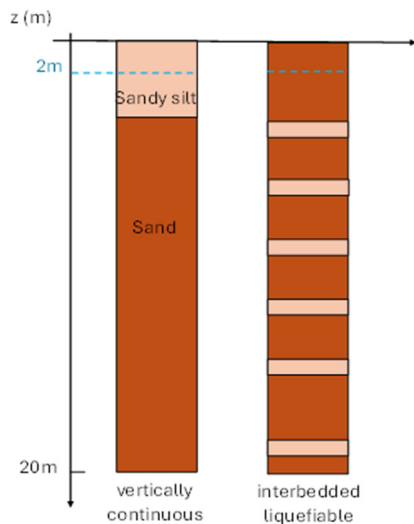


Figure 1. Example of vertically continuous and interbedded soil deposits.

2 CASE STUDY: SAKARYA (TURKEY)

2.1 1999 Kocaeli earthquake

Turkey experienced a major earthquake on 17 August 1999 (M_w 7.4), which ruptured a 140-km segment of the North Anatolian fault, extending from Izmit Bay on the west to Melen Lake on the east in the eastern Marmara region. A second major earthquake on 12 November 1999 (M_w 7.1) ruptured another 30 km of the fault further east, from Melen Lake near Duzce to Kaynasli. Sakarya, located approximately 40 km east of the epicenter of the 1999 Kocaeli Earthquake (M_w 7.4), was among the most severely affected areas. The peak horizontal ground acceleration was recorded as 0.41g at the Sakarya station SKR5401. In the city center (is called Adapazari), shallow (<6 m) loose alluvial soil layers were subjected to cyclic stress ratios (CSR) ranging between 0.3 and 0.5 (Bray et al., 2004). Earthquake-induced damage was caused not only by inertial effects but also by liquefaction phenomena. Damage due to soil liquefaction was widespread in some areas and less severe in others. The non-uniform distribution of damage clearly indicates the influence of local site effects associated with alluvial basins (Bakir et al., 2002). For this reason, the area has attracted significant interest from researchers and has been extensively investigated through both laboratory and in-situ tests (Bray et al., 2004; Bol et al., 2010; Arel, 2012).

2.2 Soil characterization of Sakarya region

Figure 2a shows the investigated area in the Sakarya region, while Figure 2b provides a detailed view of 133 Cone Penetration Tests (CPT), 44 Standard Penetration Test (SPT), 8 SASW and 8 down hole (DH) conducted in the same region (Bray et al., 2003) and reported as yellow, green and red dots. It should be noted that the study area is divided into three zones: A, B, and C.

Zone A showed no evidence of liquefaction, while zone B exhibited only limited cases. In contrast, liquefaction was widespread in zone C (close to Sakarya river). All available CPTs were analyzed, revealing three distinct soil profiles, each characteristic of a zone. The simplified profiles are shown in Figure 3, reporting the kind of soil through the Unified Soil Classification System. Cold colors have been used to identify non liquefiable layers, while warm colors have been used for liquefiable soils.



(a)



(b)

Figure 2. Investigated area of Sakarya region (a) and performed CPTs and SPTs indicated with yellow, green and red dots (b)

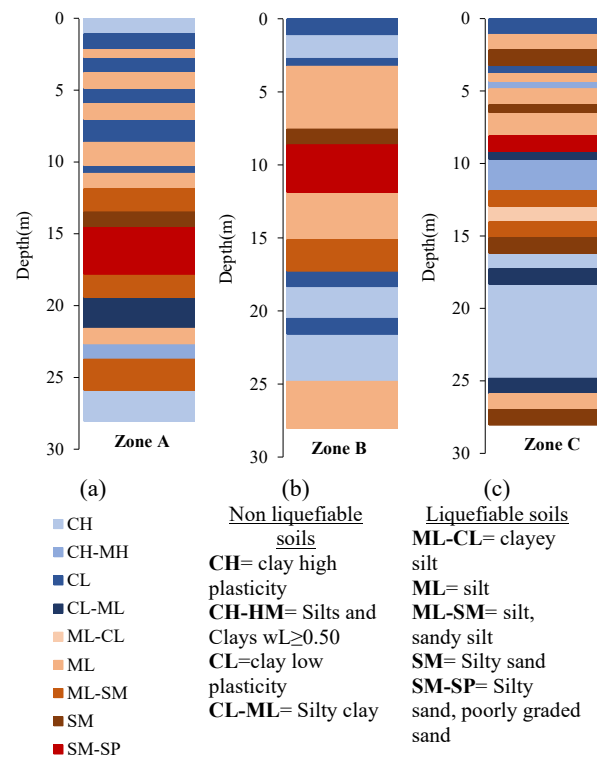


Figure 3. Simplified soil profiles of zone A, B and C of Sakarya region.

It can be observed that the stratigraphic profiles for the three zones differ significantly. In zone A, the first 12 m show an alternation of liquefiable and non-liquefiable layers, similar to the interbedded deposits illustrated in Figure 1. In zone B, a shallow non-liquefiable crust is present within the first 3 m, underlain by a continuous liquefiable layer extending down to approximately 16 m. Finally, in zone C, the crust is about 1 m

thick, and the soil remains liquefiable down to 10 m, with minor interlayers occurring at depths of 3 and 4 m below ground surface. Since zone C is the most affected by evidence of liquefaction, this suggests that the presence of interbedded layers (zone A) and a 3 m-thick crust (zone B) may mitigate liquefaction manifestations, as also indicated by Cubrinovski et al. (2019). To further investigate the site response during the 1999 Kocaeli earthquake, 1D non-linear dynamic analyses were performed for the three zones.

2.3 1D non-linear dynamic analyses

1D non-linear dynamic analyses have been performed on three zones of Sakarya by using DEEPSOIL v.7 code (Hashash et al., 2020). DEEPSOIL code allows to perform effective stress analyses according to a loosely coupled approach. It offers a range of simplified pore water pressure models. Among these, energy-based excess pore water pressure models were considered, since they result both simple and effective for estimating earthquake-induced pore pressures. Effective stress analysis using DEEPSOIL was conducted with the pore pressure generation model proposed by Berrill & Davis (1985):

$$r_u = \alpha \cdot W_s^\beta \quad (1)$$

where W_s represents the energy dissipated per unit volume of the soil normalized to the initial mean effective stress, and α and β are parameters to be calibrated through cyclic laboratory tests. However, Mele et al., (2023) proposed a straightforward calibration method using in-situ CPT or SPT test results. So, the results of CPT tests have been used to calibrate α and β of eq. (1). As reported by Bray et al., (2004) bedrock is supposed at 200m. It has been modelled as an elastic half-space ($V_s=900$ m/s). The soil stratigraphy between 28 m and 200 m depth was assumed to be the same for all three zones and corresponds to that reported by Bray et al. (2004) (Fig. 4). The average ground water table is considered at 1.5 m from ground surface in zones A and B and 1 m in zone C (Yoshida et al., 2001; Bray et al., 2003).

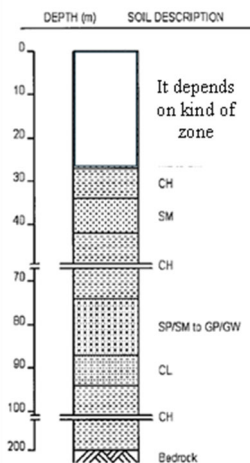


Figure 4. Generalized soil conditions of Sakarya basin (modified after Bray et al., 2004).

The shear wave velocity (V_s) profiles for the three zones were derived from downhole (DH) tests, while the profile from 28 m to 200 m depth was adopted from Bray et al. (2004). For modeling the non-linear and dissipative behavior of soils, G/G_{max} and Damping with shear strain curves from Darendeli (2001) have been adopted. Strong motion recorded at Sakarya station during the 17 August 1999 has been considered as input motion at the base of model (Fig. 5).

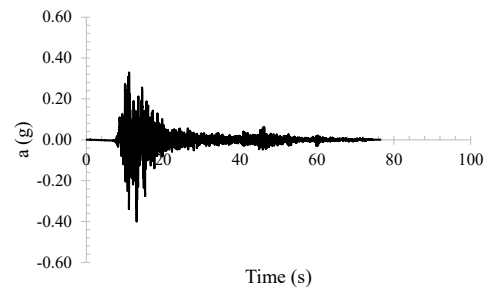


Figure 5. Strong motion recorded at the Sakarya permanent station (SKR5401) during the 17 August 1999 earthquake.

The results of analyses in terms of pore water pressure ($u_0+\Delta u$) profiles have been plotted together with total stress in Figure 6 for each zone until 15 m from ground surface. The results show that in all liquefiable layers ($I_c \leq 2.6$) pore pressures reach total stress, indicating the attainment of liquefaction ($\sigma' \approx 0$).

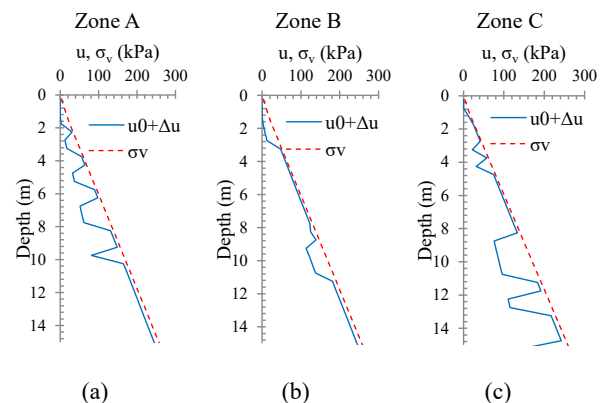


Figure 6. Results of 1D non-linear analyses in terms of pore pressure profile for three studied areas.

3 EFFECT OF SOIL STRATIGRAPHY IN LIQUEFACTION MANIFESTATIONS

The results shown in Figure 6 indicate that sandy soils and non-plastic silty soils liquefy in each of the examined areas. Therefore, as also reported by Cubrinovski et al. (2019), the different effects observed at the ground surface could be attributed to the soil stratigraphy.

It is expected that the parameters controlling liquefaction manifestations are related to:

- overall thickness of liquefiable layers ($H_{liq} = \sum H(r_u \geq 0.90)$);
- thickness of shallow crust (H_{cru});
- number of liquefiable layers within 15 m (n_{liq}) which accounts for the continuity or discontinuity of the layers.

These parameters are summarized for each zone in Table 1. Interestingly, zones A and C have the same H_{liq} (9.50 m) and n_{liq} (4) nevertheless, zone C exhibits more extensive evidence of liquefaction. This may be due to the thinner crust H_{cru} , which is only 0.75 m thick in zone C compared to 1.75 m in zone A. On the other hand, zone B, which shows moderate evidence of liquefaction, has the greatest H_{liq} (12.50 m) compared to the other zones; however, its H_{cru} is the thickest, reaching 2.75 m.

Table 1. Parameters ruling liquefaction evidence

Parameter	Zone A	Zone B	Zone C
H_{liq} (m)	9.50	12.50	9.50
H_{cru} (m)	1.75	2.75	0.75
n_{liq}	4	2	4

Therefore, it seems that the extent of liquefaction manifestations could be estimated using a synthetic parameter that takes into account all the three mentioned parameters: H_{liq} , H_{cru} and n_{liq} . To this aim, a simple parameter named *Soil Liquefaction Evidence Index* (SLEI) is proposed:

$$SLEI = \frac{H_{liq}}{H_{cru} \cdot n_{liq}} \quad (2)$$

A higher SLEI indicates a greater extent of liquefaction manifestations at the ground surface.

3.1 SLEI in Christchurch stratigraphy profiles

In order to assess the effectiveness of the SLEI in predicting liquefaction manifestations, the index was also calculated for 6 available soil profiles located in Christchurch (New Zealand), already studied in Cubrinovski and Ntritsos (2023).

For comparison purposes between the two case studies of Sakarya and Christchurch, a qualitative scale was defined to represent the observed level of liquefaction manifestations: a value of 1 was assigned to sites with no evidence of liquefaction, 1.5 to sites with moderate evidence, and 2 to sites with extensive evidence. These values were plotted on the Y-axis, while the calculated SLEI values were plotted on the X-axis in Figure 7. As expected, the results show that also for Christchurch, a higher SLEI indicates a greater extent of liquefaction manifestations at the ground surface. Even though only two case studies were examined, some indicative ranges of liquefaction manifestation levels can be proposed based on the SLEI values. For $SLEI < 1.5$, no liquefaction manifestations are likely to be observed; for $1.5 \leq SLEI < 2.5$, moderate liquefaction evidence can be expected; and for $SLEI \geq 2.5$, extensive liquefaction evidence is likely to occur.

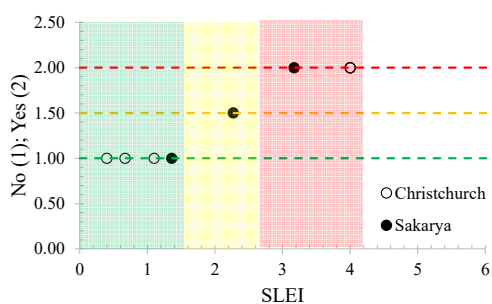


Figure 7. SLEI and liquefaction evidence

4 FINAL REMARKS

This study highlights the significant role of soil stratigraphy in controlling the surface manifestations of liquefaction and, as a consequence, the effect on the built environment. By introducing the Soil Liquefaction Evidence Index (SLEI), which combines the total thickness of liquefiable layers, the thickness of the non-liquefiable crust, and the number of interbedded layers, a simple yet practical tool has been proposed to estimate the expected severity of liquefaction

phenomena. Preliminary validation using two case studies (Sakarya and Christchurch) suggests that the SLEI can provide useful insight into the system effect and site-specific response. Although the proposed thresholds are indicative and based on a limited dataset, they offer a starting point for future research aimed at improving the prediction of liquefaction manifestations in similar geological contexts.

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