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Cyclic response of Adıyaman- Gölbaşı fine-grained soils shaken by 2023 Kahramanmaraş earthquakes

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ABSTRACT: This study investigates the cyclic response of fine-grained soils retrieved from the Gölbaşı district of Adıyaman, Türkiye. Field reconnaissance studies documented widespread damage to residential structures and infrastructure mostly due to liquefaction-induced excessive settlements, bearing capacity losses and lateral spreading in Gölbaşı after the February 6, 2023, Pazarcık and Ekinözü, Kahramanmaraş-Türkiye earthquakes of moment magnitude (M_w) 7.8 and 7.6, respectively. Comprehensive site investigation studies performed after the earthquake revealed that most of the sites with pronounced damage were underlain by soft, medium to high-plasticity clays below shallow groundwater depths. Site investigation studies include the execution of in-situ tests including but not limited to Standard Penetration Test (SPT), Cone Penetration Test (CPT), Shear wave velocity (V_s), and disturbed and undisturbed soil sampling. The soil specimens were characterized through index tests confirming their medium to high plasticity consistencies. Additionally, oedometer tests were performed, and consistent with their young age, they were mostly classified as normally-consolidated to slightly overconsolidated with over consolidation ratio typically, of less than 1.3. Constant-volume monotonic and cyclic direct simple shear (CDSS) tests were performed at vertical effective stresses of 100 kPa, selected to assure a normal consolidated response. Test results revealed that consistent with their soft nature, significant cyclic softening response was observed at cyclic loading scenarios representative of Kahramanmaraş earthquakes` shaking levels in Gölbaşı. Despite their high plasticity, significant cyclic excess pore pressures, exceeding r_u values of 0.65, were recorded. These findings help to understand the underlying mechanisms of foundation failures reported in the district and demonstrate the importance of site-specific evaluations for seismic soil liquefaction assessments.

KEYWORDS: Cyclic loading, Dynamic soil behaviour, Fine grained soil, Liquefaction, Simple shear.

1 INTRODUCTION

On February 6, 2023, Turkiye and Syria experienced an unusual "double shock" earthquake sequence (7.8M_w Pazarcık and 7.6M_w Ekinözü), occurring nine hours apart and marking the most damaging events in the history of the countries. The events resulted in extensive damage across central and south-eastern Turkiye and northern Syria, causing over 55,000 fatalities and rendering more than 650,000 residential units uninhabitable (Çakır & Çetin, 2024; Çetin et al. 2023; Çetin et al. 2024; Çetin et al. 2025a; Lubkowski & Hiçyılmaz, 2024; METU EERC, 2023; Wang et al. 2023).

Unreinforced brick masonry and low-rise concrete frame structures exhibited widespread collapse, with Nurdağı (18.9%) and Kahramanmaraş (17.4%) experiencing high damage rates (Wang et al. 2023) while up to 80% of buildings collapsed in some districts (Moug et al. 2023). Significant geohazards, including widespread seismic soil liquefaction, confirmed by soil ejecta, foundation failures, excessive settlements and lateral spreading in Gölbaşı-Adıyaman and İskenderun-Hatay, were documented. Over 3,000 landslides were mapped and considerable infrastructure damage affecting bridges, ports, and a railway tunnel were reported (Çakır & Çetin, 2024; Çetin et al. 2024; Çetin et al. 2025a; METU EERC, 2023; Moug et al. 2023).

Gölbaşı-Adıyaman region offered a unique opportunity to examine the effects of local soil conditions on damage to residential structures and infrastructure under strong shaking. Extensive seismic soil liquefaction was observed in Gölbaşı, especially in its northern regions, where thick, loose alluvial sediments are prevalent by the lake. This manifested in widespread ejecta, foundation failures, excessive settlement and tilting of structures, railway misalignments, and pavement cracking. Laboratory tests frequently classified the ejecta as low plasticity clays (CL), with many grain size distribution curves falling outside traditional liquefaction susceptibility limits due to their higher plasticity indices (Çetin et al. 2025b). The liquefaction initiation of these medium to high plasticity clayey soils highlighted the significance of understanding the importance of local soil conditions. Damage to residential buildings and infrastructure, due to excessive settlements, lateral spreading and bearing capacity failures, was directly associated with seismic soil liquefaction. These observations underscore the vital need for robust geotechnical investigations and appropriate foundation designs (Çetin et al. 2024; Çetin et al. 2025a; Çetin et al. 2025b).

Following the foundation failures observed in Adapazarı–Sakarya after the 1999 Kocaeli earthquake (7.5M_w), Seed et al. (2003) and Bray et al. (2004) suggested that the Plasticity Index (PI) is a more reliable indicator of the liquefaction susceptibility of fine-grained soils than clay-size content and advocated discontinuing the traditional "Chinese Criteria." Subsequently, Boulanger and Idriss (2004, 2006) refined the classification by distinguishing between liquefaction (sand-like behavior) and cyclic failure (clay-like behavior). In their framework, the term liquefaction is reserved for soils whose cyclic resistance can be readily assessed using penetration test data (Boulanger and Idriss, 2008). They recommended PI < 7 for sand-like (liquefiable) soils and PI ≥ 7 for clay-like soils (susceptible to cyclic failure), noting the transition between CL and ML classifications. Like Seed et al. (2003) and Bray et al. (2004) they strongly advocated abandoning the "Chinese Criteria".

Stuedlein et al. (2023) demonstrated that single-amplitude shear strains, more than 5%, are required to observe the ultimate hysteretic behavior (i.e., sand-like vs. clay-like), which can be critical for long duration earthquakes. Their hysteretic metrics, such as maximum excess pore pressure ratio, minimum tangent shear modulus, objectively classify the behavior. What may be classified as clay-like soils can transition to sand-like behavior at larger strains and higher pore pressures after sufficient loading cycles.

This study investigates the cyclic response of Gölbaşı clays. The manuscript presents a brief summary of site investigation studies and focuses on the geotechnical characteristics of retrieved undisturbed soil samples, and the results of cyclic direct simple shear (DSS) tests performed on them.

2 SUBSURFACE CHARACTERISTICS OF GÖLBAŞI

Çetin et al. (2025b) summarized the findings of pre-earthquakes site investigation studies by Akıl et al. (2006). The studies involved the drilling of 21 boreholes with depths ranging from 15 to 19 m, and the collection of 174 disturbed (SPT) and 18 intact soil samples. The investigation revealed that the subsurface stratigraphy in Gölbaşı is predominantly composed of fine-grained, soft clays of low to high plasticity. They were classified as CL and CH type soils, whereas less frequent coarse-grained soils were as clayey sands (SC).

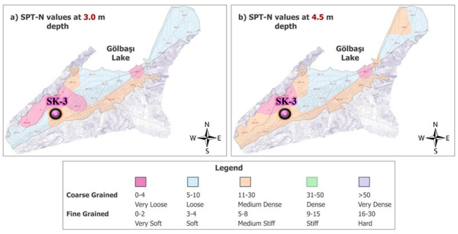

Figure 1. Standard Penetration Test (SPT) N_{60} values at 3.0 m and 4.5 m depths in Gölbaşı, (Adapted from Çetin et al. 2025b).

As illustrated in Figure 1, SPT-N_{60} values in the northern areas of the district were generally low—typically ranging from 5 to 8 blows/30 cm suggesting low shear resistances for soils at depths 3.0 to 4.5m. In contrast, the southern areas exhibited comparatively higher SPT-N_{60} values, ranging from 11 to 30 blows. Groundwater levels were observed at or near the surface adjacent to Gölbaşı Lake and generally within 2 to 4 meters below ground surface in the southern zones. The combination of low shear strength and shallow groundwater in the northern part of the district correlates strongly with the more severe structural damage and poor performance of buildings and foundations observed in this region (Figure 2).

3 RETRIEVED INTACT SAMPLE CHARACTERISTICS

Through an extensive field investigation conducted by Geodestek Ltd. several intact samples were recovered from the Gölbaşı district. To evaluate the cyclic performance of Gölbaşı clays, particularly in terms of normalizing cyclic shear stress (representing seismic demand) against undrained shear strength (representing capacity), a sample from borehole SK-3 (37°46'35.07"N, 37°37'20.92"E) at a depth of 2.5–3.0 m was selected. This location lies within a zone of moderate to severe building damage, as shown in Figure 2.

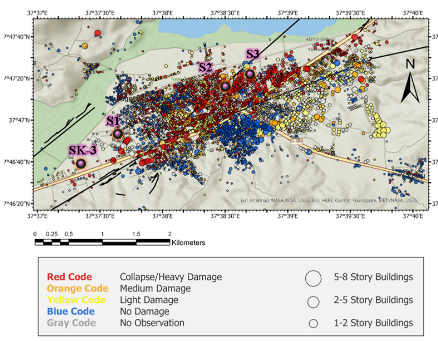

Figure 2. Map of Gölbaşı showing reported damage levels indicating the locations of borehole SK-3 and other samples referenced in this study (Adapted from Çetin et al., 2025b).

Within the scope of this manuscript, site investigation findings at SK-3, which is a site where liquefaction induced bearing capacity failure was reported, are to be discussed for illustrating the notable response of Gölbaşı fine grained soils. Table 1 provides the characteristics of the intact soil samples retrieved at 3.0 m depth. In the same table, the characteristics of soil ejecta samples S1, S2 and S3 are also comparatively presented. It is worth noting that ejecta S1 is retrieved from a site by immediate vicinity of SK-3 (Çetin et al., 2025b). This comparisons may provide a better understanding of the clayey soil's spatial distribution in the Gölbaşı area (locations shown in Figure 2), The sample from 3.0 m depth is classified as high plasticity clay (CH), and is classified to exhibit clay-like behavior or as none liquefiable, following the criteria proposed by Boulanger and Idriss (2006), Bray and Sancio (2006), and Stuedlein et al. (2023).

Table 1. S1, S2, S3 and SK3-3.0m samples soil classification (USCS) and characteristics.

Sample ID		SK3-3.0m	S1	S2	S3	
Specific Gravity	G_s	2.65	-	-	-	-
4.75mm Retained	-	1.1	0.0	0.0	0.0	%
Fines Content (0.075 mm)	*FC*	67.7	49.5	99.0	58.4	%
Clay Content	*CC*	35.9	-	-	-	%
Liquid Limit	*LL*	56	37	54	42	-
Plastic Limit	*PL*	24	17	20	19	-
Plasticity Index	*PI*	32	20	34	23	-
USCS Classification	-	CH	SC	CH	CL	-

Following extraction from the thin-walled Shelby tube, a one-dimensional consolidation (oedometer) test was performed to evaluate both the stress history and the quality of sampling and specimen extraction methods. The results are shown in Figure 3.

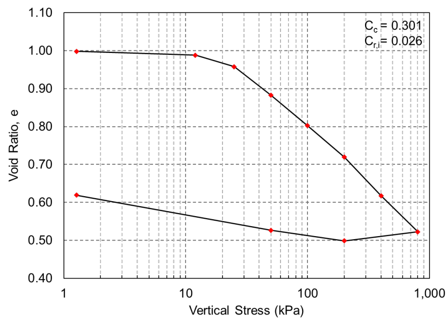

Figure 3. One-dimensional consolidation (oedometer) test results for the intact SK3-3.0 m specimen.

The specimen quality was assessed using the ratio of the initial recompression index to the compression index ($C_{r,i}/C_c$), as recommended by DeJong et al. (2018). Specimens with compression ratios below 0.15 are of high quality. The SK3-3.0 m intact specimen yielded a $C_{r,i}/C_c$ ratio of 0.09, indicating minimal disturbance and excellent sample integrity. The pre-consolidation vertical effective stress was estimated as ~ 40 kPa using the Casagrande method. This aligns well with the estimated in-situ vertical effective stress (σ'_{vo}) of ~37 kPa at the sampling depth of 2.75 m, confirming its normally consolidated (NC) nature.

4 CONSTANT VOLUME, MONOTONIC DIRECT SIMPLE SHEAR TEST

A GeoAnts/Geodestek multi-directional cyclic direct simple shear (CDSS) apparatus was used for testing purposes. The device accommodates specimens with a diameter of 50 mm and a height of 20 mm, consistent with ASTM D4318 and D6528 standards. It can apply uni- or multi-directional monotonic and cyclic loading within the horizontal plane. The system is also equipped with a three-dimensional load cell mounted directly above the top cap to minimize compliance effects, as shown in Figure 4.

A constant-volume monotonic shear test was conducted to determine the undrained shear strength ($s_{u,DSS}$) of the sample. The test was performed after K_o-consolidating the sample at a vertical effective stress (σ'_{vc}) of 100 kPa at a shear strain rate of 0.5 mm/min.

Figure 4. GeoAnts multi-directional cyclic direct simple shear (CDSS) apparatus.

Figure 5 presents the results of the monotonic DSS test normalized using (σ'_{vo}); the specimen exhibited normally consolidated (NC) behavior, characterized by a nearly perfectly plastic and contractive response, and exhibited $s_{u,DSS}$ = 40 kPa. This monotonic test serves as a reference for selecting appropriate cyclic shear stress amplitudes in subsequent CDSS testing. Given that clayey soils—particularly those exhibiting clay-like behavior—may respond as either normally consolidated or over-consolidated under the same σ'_{vc}, depending on their stress history, this preliminary assessment aids in better anticipating the specimen's cyclic response.

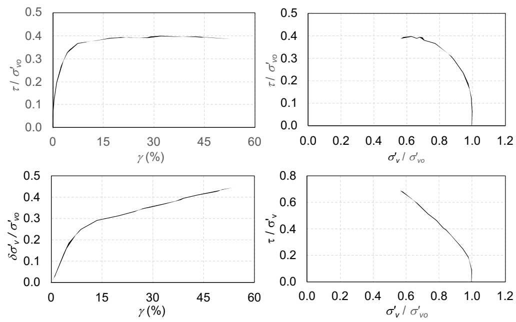

Figure 5. Monotonic direct simple shear (DSS) test results for the intact SK3-3.0 m specimen.

5 SEISMIC DEMAND IN ADIYAMAN, GÖLBAŞI

Consistent with the findings of Çetin et al. (2025b), the peak ground acceleration (PGA) at a typical soil site in Gölbaşı during Pazarcik event is estimated as 0.5*g*. Consistent with this value, to simulate seismic demands at depths of 3 to 6 m, cyclic shear stresses (τ_{cyc}) were estimated as to vary in the range of 17.5 to 35 kPa.

The duration of seismic loading in Gölbaşı was represented by number of equivalent shear stress cycles (N_{eq}). N_{eq} values were evaluated to vary in the range of 30 to 40 cycles, as discussed in Elsaid and Çetin (2024). As previously outlined in Section 2, the clayey soils at shallow depths in Gölbaşı exhibit an average standard penetration test (SPT) blow count (N_{60}) of 5–8 in the northern areas, roughly corresponding to an undrained shear strength (s_u) of 25–40 kPa (Stroud, 1974), whereas this value increases to the range of 55 to 150 kPa in the southern areas. As a result, the seismic demand in the northern and southern parts of Gölbaşı can be typically expressed by the ratio of $\tau_{cyc}/s_{u,\ DSS}$ = 0.70 - 0.88 and 0.20-0.30, respectively during the 2023 Kahramanmaraş event.

6 CONSTANT VOLUME, CYCLIC DIRECT SIMPLE SHEAR TEST

Constant-volume, stress-controlled cyclic direct simple shear (DSS) tests were conducted on normally consolidated (MC-NC; $\sigma'_{p,\ exceeded}$) intact specimens under σ'_{vc} of 100 kPa. The testing program involved applying cyclic shear stresses at varying levels (*CSR* = 0.2-0.4, $\tau_{cyc}/s_{u,DSS}$ = 0.6-0.9) with a loading frequency of 0.1 Hz to evaluate the cyclic behavior of Gölbaşı clay deposits. It is important to note that although the applied cyclic shear stress levels reached up to 90% of reported monotonic shear strength ($s_{u,\ DSS}$), the corresponding *CSR* values still remained below the estimated seismic demand of the earthquake. Cyclic DSS test results are illustrated in Figure 6.

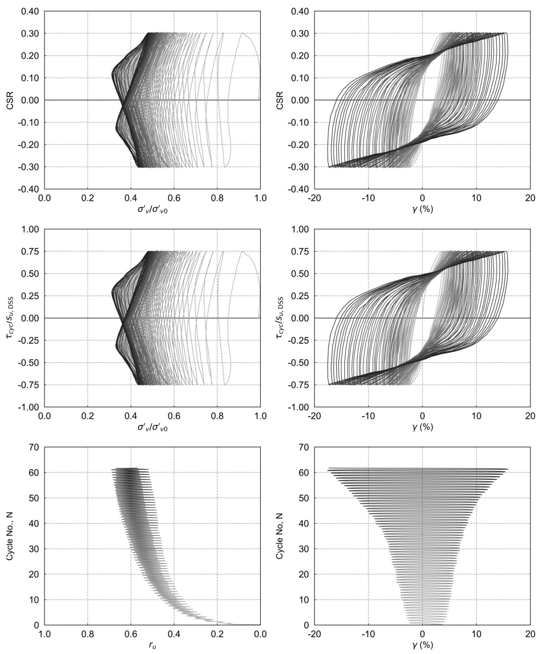

Figure 6. Cyclic direct simple shear (DSS) test results for SK3-3.0 m intact specimen under constant-volume conditions.

Figure 6 illustrates the cyclic response of the intact SK3-3.0 m specimen subjected to a normalized cyclic shear stress of $\tau_{cyc}/s_{u,DSS}$ = 0.75 and a corresponding *CSR* of 0.30. The specimen exhibited a notable cyclic softening response. Specifically, after *N* = 30 to 40 cycles, the effective vertical stress (σ'_v) had decreased by more than 60% (i.e., excess pore pressure ratio r_u > 0.60). Concurrently, the cyclic shear strain exceeded a double amplitude γ_{DA} levels of 15%.

Figure 7 presents the applied $\tau_{cyc}/s_{u,DSS}$ plotted versus *N* to a specified double-amplitude shear strain, γ_{DA}, overlain with the estimated number of equivalent earthquake-induced cycles and the anticipated cyclic shear stress level. The experimental results align well with field observations of lateral spreading, ground settlement, and structural damage reported in the northern part of Gölbaşı. Notably, these findings support the interpretation that earthquake-induced damage correlates strongly with variations in undrained shear strength across the region.

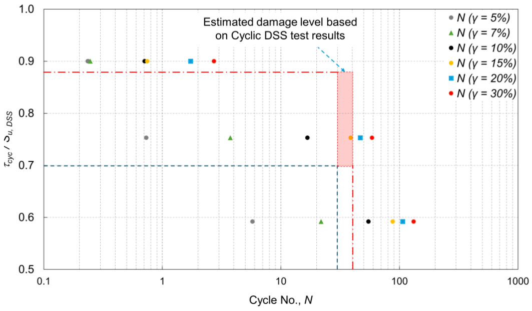

Figure 7. Cyclic stress ratio (*CSR*) and normalized cyclic shear stress ($\tau_{cyc}/s_{u,DSS}$) vs cycle number (*N*) corresponds to various double strain levels.

In particular, the southern portion of Gölbaşı—characterized by higher SPT-N values (ranging from 11 to 30, approximately 2–3.5 times greater than those in the north)—exhibited less structural damage. This contrast underscores the importance of shear strength in controlling cyclic response and damage potential in fine-grained soils. Although the estimated *CSR* values are similar across the region due to comparable levels of effective confining stress, the resulting damage was not. This highlights a key distinction: for clay-like soils, seismic demand (*CSR*) alone is insufficient to predict damage potential. Instead, it is the variation in seismic capacity—reflected in undrained shear strength—that governs the observed performance. In simpler terms, the seismic loading exhibited greater spatial uniformity than the resistance and the most severe damage was concentrated in areas with lower shear strength.

7 CONCLUSION

This study examined the cyclic response of fine-grained soils from the Gölbaşı region of Adıyaman, Türkiye, following the February 6, 2023, Kahramanmaraş earthquakes. Field reconnaissance revealed severe structural damage associated with shallow groundwater, low shear strength, and evidence of liquefaction and cyclic softening, particularly in the northern districts. To investigate these conditions, an intact high-plasticity-clay specimen was retrieved and tested using one-dimensional consolidation, monotonic, and cyclic direct simple shear (DSS) methods.

Despite its high plasticity, the specimen exhibited significant cyclic softening and loss of effective stress under cyclic stress ratios (*CSR* = 0.2–0.4 and $\tau_{cyc}/s_{u,DSS}$ = 0.6-0.9), indicating cyclic failure within 30–40 cycles. Although seismic demand (*CSR*) may be relatively uniform across the region, observed damage correlated strongly with variations in undrained shear strength. These findings emphasize the importance of assessing both seismic demand and soil resistance in evaluating liquefaction potential, especially for fine-grained, clay-like soils.

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