March 2024, Vol:2, Issue:1

International Journal of New Findings in Engineering, Science and Technology

journal homepage: *https://ijonfest.gedik.edu.tr/*

The Liquefaction Behavior of Leachate-Contaminated of Sand under Cyclic Loads

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Abstract

Uncontrolled solid waste affects the stress-strain behavior of the sand as well as causes an environmental problem. In this research, the effect of leachate on the dynamic behavior of sand has been studied and the results were compared with clean sand with different saturation degrees. The modified split molds at 50 mm diameter and 100 mm height were used to prepare the leachate-contaminated sand. Both contaminated and clean sand samples were prepared by dry pluviation method. After preparation, the sand samples in the modified mold were put in the leachate wastewater to keep for different cure times. Then they were installed on the dynamic triaxial test system at 0.1 Hz and the same cyclic stress ratio. During the saturation process to prevent the structure of contaminated sands from being disturbed, samples were not passed through CO_2 and distilled water. Stress-controlled cyclic tests were conducted at on both clean and contaminated sand consolidated at 100 kPa isotropically. After consolidation phase the measured B values varied between 0.45-0.93. Results show that leachate-contaminated sands are more liquefiable depending on cure time at the same saturation value and saturated clean sand samples and partially saturated leachate-contaminated sand samples show similar liquefaction behavior under the same cyclic ratio.

Keywords: Leachate; Critical Deformation Level; Contaminated Sand; Dynamic Behavior; Curing Time.

1. INTRODUCTION

The storage of solid waste is one of the important environmental problems. According to 2022 data, 14.1% of the domestic solid waste collected in Turkey is currently stored as unsanitary disposal by municipalities, and this amount is approximately 4.27 million tons/year [1]. The wrong storage of urban waste effects soil layers, ground and underground water. In sanitary landfill sites, the waste water leachate contamination affects the engineering properties of soil layers underlying solid waste landfill. Leachates disrupt the properties of soil within the chemical content. In practice, impermeable clay barriers have been used to minimize the infiltration of leachates in sanitary landfills. For this reason, clay soil contamination with leachate has been studied by many researchers. Tuncan et al.,1988 conducted a series of laboratory tests on clay soils mixed and cured with leachate to study the unconfined compressive strength, stress-strain relationship, and permeability [2].

The unconfined compression strength increased with increasing leachate wastewater ratio for short curing periods and decreased with longer curing periods. Roque and Didier, 2006 studied the effect of demineralized water and acid leachate on the hydraulic conductivity of fine-grained soils. Hydraulic conductivity increased due to the

https://doi.org/10.61150/ijonfest.2024020104

chemical reactions of the acidic leachate [3]. Another hydraulic conductivity characteristics of soils including fines have been studied by Nayak et al. (2007) Contaminated specimens were prepared by mixing soil with leachate in the amounts of 5%, 10% and 20% by weight. The results indicated a small reduction in maximum dry density and an increase in hydraulic conductivity [4]. Brandl, 1992 treated silty clays with different chemicals to determine the effect of chemicals on the plasticity index. The results indicated that the plasticity index decreased as hydraulic conductivity increased [5]. Although there are many studies conducted with clays contaminated with waste-water leachate, there is a lack of research on how leachate affects the dynamic properties of sands. The effect of sand exposed to different pollutants on the dynamic behavior has been studied by many researchers. Naeini and Shojaedin (2014) used Firoozkuh sand containing 4%, 8%, and 12% crude oil by weight leaked from oil pipelines and tanks and revealed that contamination levels up to 8% increased liquefaction resistance, but beyond this threshold, higher contamination levels led to a decrease in liquefaction resistance [6]. Rajabi and Sharifipour (2018) research short term and long term influence on small strain shear modulus ($G_{\mathbf{max}}$) of hydrocarbon contaminated sand [7]. Hosseini and Hajiani Busherian (2019) studied the behavior of circular foundations resting on oil-contaminated sand under cyclic loading. Hosseini, and Hajiani Boushehrian, 2019 conducted experimental and numerical analysis and developed equations that predict the number of loading periods to achieve the required settlement based on the contaminated layer thickness and contamination percentage [8]. Nasiri et al. (2023) conducted tests to explore the time-dependent dynamic and static properties (shear modulus, damping ratio, and friction angle) of sands contaminated with 6% crude oil and with a relative density of 60% [9].

In this study, the effect of the leachate on the dynamic behavior of sand has been studied leaking from the unsanitary disposal or carelessly constructed clay barriers in sanitary landfills. The contaminated samples prepared in modified molds and cured for periods ranging from 3 to 299 days, and partly saturated clean sand samples prepared in standard molds were tested in the cyclic triaxial test system undrained to analyze the liquefaction behavior of samples. Firstly, the clean sand was prepared in standard and modified mold. Thus the behavioral effect was examined when exposed to dynamic loading under the same conditions. Then, the clean and leachate-contaminated samples were consolidated under 100 kPa pressure for one day, and then the day after, dynamic experiments were carried out by applying a constant strain in the range of $\pm\sigma_{dev}/2\sigma'_{con}$ = 0.28-0.30. As a result, the liquefaction behavior and critical deformation levels of the samples under the influence of contamination were compared with clean sands.

2. MATERIAL AND METHODS

2.1 Akpınar Sand

Sands used in this study have been obtained from Akpınar district in İstanbul, Turkey. The soil is poorly graded sand (SP). Table 1 gives the index properties of sand. The grain size distribution of sand is presented in Figure 1. The specific gravity of Akpınar sand is 2.69, the minimum void ratio is 0.558 and the maximum void ratio is 0.874.

Table 1. Soil properties of Akpınar sand.

Soil Properties	Value
Specific Gravity	2.69
Maximum void ratio	0.874
Minimum void ratio	0.558
D50 (mm)	0.30
D10 (mm)	0.23
Coefficient of Uniformity Cu	1.434
Coefficient of Curvature, Cc	0.96
Fines Content, FC	0

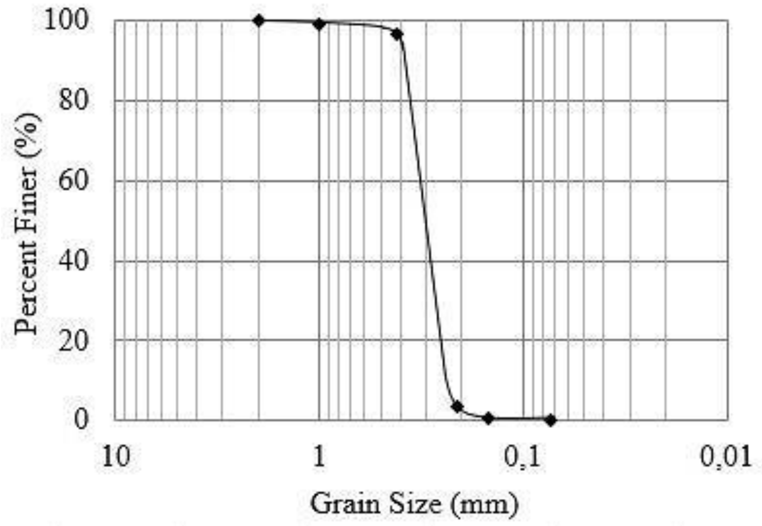


Figure 1. Grain size distribution of Akpınar sand.

2.2 Leachate Wastewater

Leachate wastewater obtained from the site of the Kemerburgaz sanitary landfill in Istanbul has been used in this research. The composition of leachate which is given in Table 2 was determined from tests conducted in Istanbul Technical University Environmental Laboratory. Sample 1 is the composition of young leachate about one week and sample 2 is old leachate about 22 months.

The chemical composition of leachate will vary depending on the age of the landfill. If a leachate sample is collected during the acid phase decomposition the pH value will be low and the concentrations of BOD_5, COD, and nutrients will be high. Meanwhile the composition of leachate on the methane phase BOD_5, COD, and nutrients value will be significantly lower [10].

In this research, the pH value calculated at the one-week sample increased from 7.30 to 9.25 at the 22-month sample. The value of chemical oxygen demand obtained at the one-week sample decreased from 37665 to 3595 in the 22-month sample.

Table 2. The composition of leachate.

Parameter	Unit	Sample 1 (One Week)	Sample 2 (22 Months)
pH	-	7.30	9.25
Total Solids	Mg/l	29710	15350
Total Volatile Solids	Mg/l	13055	2670
Total Dissolved Solids	Mg/l	27950	12320
Total Volatile Dissolved Solids	Mg/l	13510	1385
Alkalinity	Mg/l CaCO3	14300	7740
COD	Mg/l	37665	3595
Soluble. COD	Mg/l	30000	1570
BOD5	Mg/l	24450	400
T.P	Mg/l	30	10
TKN	Mg/l	2780	1120
NH3-N	Mg/l	2550	820
Chloride	Mg/l	3266	4190
Sulfate	Mg/l	120	356
Ca Hardness	Mg/l CaCO3	6919	110
Total. Hardness	Mg/l CaCO3	8595	1808
Ca	Mg/l	2773	44
Mg	Mg/l	409	468
Na	Mg/l	2590	2853
K	Mg/l	1700	1700
Fe	Mg/l	41.2	184
Ni	Mg/l	0.82	1.16
Cr	Mg/l	0.64	0.76
Zn	Mg/l	1.27	3.04

2.3 Sample Preparation of Contaminated Sand

Dynamic tests have been conducted on laboratory sand samples. Sand samples have been prepared in a modified split mold. The diameter of the mold is 50mm and the height is 100mm. Mold has a bottom and upper cap (Figure 2). Both caps are perforated. To study the effect of wastewater leachate on the dynamic behaviour of sand, samples have been prepared at the same relative density but varied saturation degrees. The relative densities of sand samples change from 50% to 60% (Table 3). Sand samples have been prepared by the dry pluviation method in 3 layers [11]. The funnel has been used to pour the sand into the mold in every layer. Sand samples contaminated by 100% leachate wastewater have been used in this research and the results compared clean sand sample results.

Figure 2. Modified steel mold 3-D view and prepared sample in the modified steel mold.

2.4 Samples Curing

Contaminated sand samples were prepared at 100% cure ratio. The curing time was started by dipping the sand samples into the leachate pool, covering the upper level of the mold, as seen in Figure 3. It was observed that some of the air bubbles in the samples get out as a result of the leachate entering through the drainage holes into the samples prepared by dry pluviation. An increase in gaseous emissions occurred due to chemical reaction in the leachate tank. In order to prevent the methane gas accumulation, the gas outlet valve was periodically opened to release trapped air. During this process, samples were stored in the leachate tank for different curing times at 3 days, 10 days, 103 days, 146 days, and 299 days.

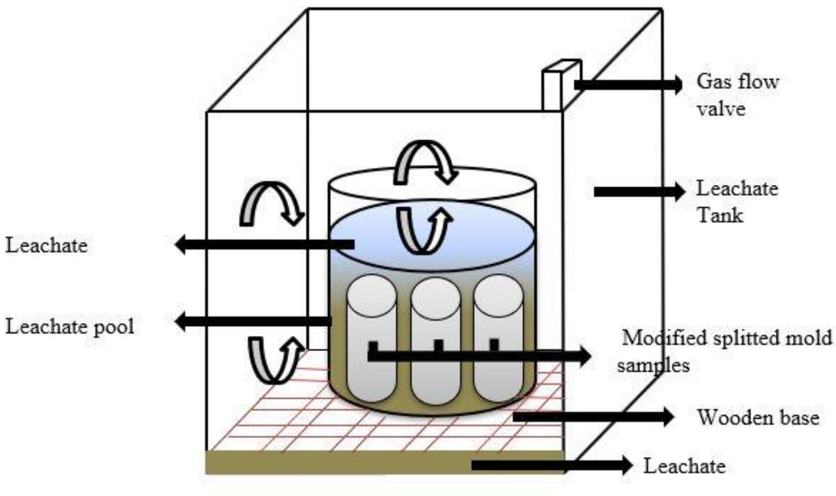
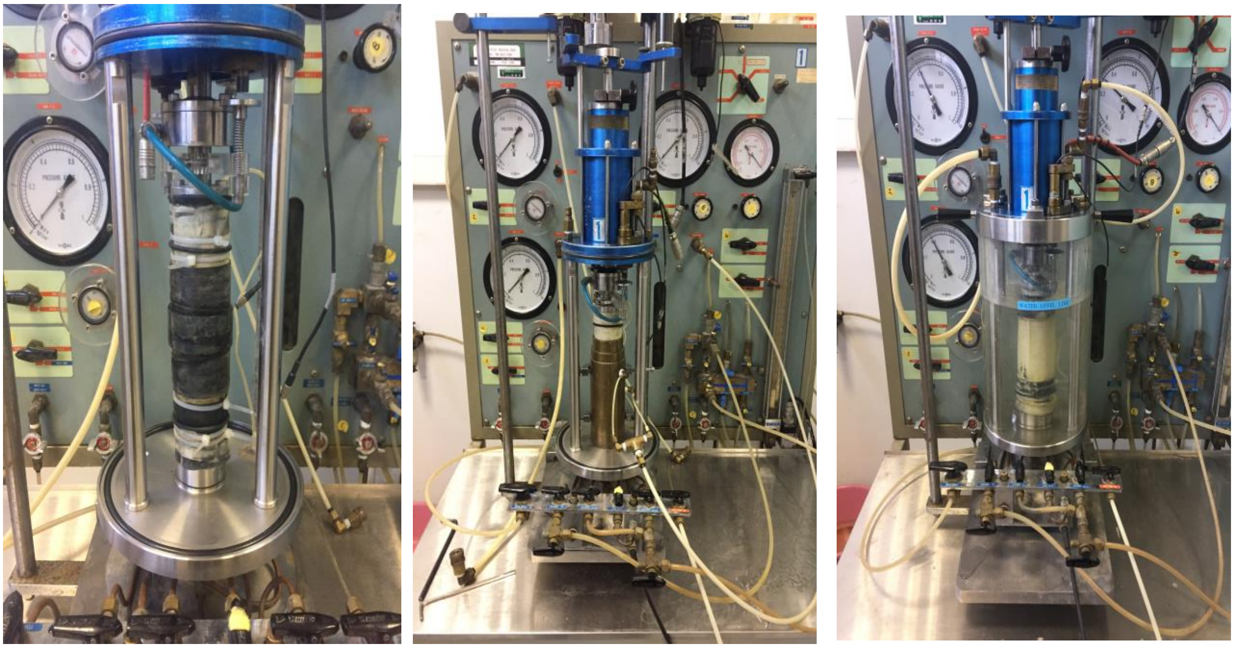


Figure 3. Leachate Tank Schema.

2.5 Cyclic Triaxial Test System

The stress-controlled cyclic triaxial test was used to evaluate the cyclic behaviour of undisturbed and reconstituted laboratory sand samples. DTC 311 - 0094 model, developed by the Japanese company "Seiken Inc" located in Istanbul Technical University, Soil Mechanics Laboratory, was used. The size of triaxial test samples varies between 5 cm and 7.5 cm in diameter, and 10 cm to 15 cm in height. In the apparatus, a pneumatic stress-controlled system is capable of generating cyclic axial triaxial stresses at frequencies between 0.001 Hz and 2 Hz. The testing system individually enables the measure and the record of axial vertical load, axial vertical displacement, pore water pressure; and the specimen volume change. The stress–strain relationships of the sand specimens can be determined under isotropic and anisotropic conditions by applying sinusoidal loads. It is possible to measure the initial elastic modulus of sands with the gap sensors connected to the top of the triaxial cell and monotonic loading with different loading rates.



a) b) c)

Figure 4. Cyclic-triaxial test system a) modified mold set-up b) standard mold set-up c) consolidated set-up.

The leachate-contaminated sand samples prepared with the modified splitted mold shown in Figure 4.a and the clean sand samples prepared in the standart mold shown in Figure 4.b placed in the cyclic triaxial test system. Both specimens with 5 cm diameter and 10 cm height were isotropically consolidated to the 100 kPa in the triaxial cell and the backpressures ranging between 200-300 kPa were applied one day to provide saturation (Figure 4.c). The calculated B values were between 45-93 %. After the consolidation process, a cyclic axial load was applied under the undrained condition (CU). The frequency of the cyclic load was 0.1 Hz during the tests. The cyclic test properties of sand samples are given in Table 3.

Table 3. Cyclic test properties of sand.

Test No	Cure Ratio (%)	$\pm\sigma_{dev}/2\sigma'_{con}$	N $\varepsilon=\pm2.5\%$	N $\varepsilon=\pm0.5\%$	Cure Time (days)	Dr (%)	B (%)	σ_{ef} (kPa)
DN13	0	0.28	98	91	-	60	0.52	100
DN18	0	0.28	82	76	-	56	0.58	100
DN38	0	0.28	77	69	-	57	0.60	100
DN40	0	0.28	32	24	-	57	0.93	100
DN52	0	0.30	52	42	-	53	0.72	100
DN29	100	0.30	248	238	146	56	0.45	100
DN31	100	0.30	35	23	103	57	0.60	100
DN58	100	0.30	34	17	299	55	0.57	100
DN72	100	0.28	59	50	3	50	0.65	100
DN87	10	0.28	90	82	10	60	0.53	100

3. RESULT AND DISCUSSIONS

3.1 Comparison of the Clean Sand Prepared with Modified and Standard Mold

As seen in Figure 5, in order to examine the effect of the sample preparation mold on the structure, a dynamic load at $\pm\sigma_{dev}/2\sigma'_{con}$ =0.28 stress level was applied to the clean sand samples prepared in the standard and the modified mold under the same conditions. The comparison focused on the relationship between porewater pressure ratio and number of cycles, as well as dynamic axial deformation and number of cycles. The DN18 sample was prepared in a standard mold and Dr = 56% and B = 0.58 value were obtained. The DN38 sample was prepared in a modified sample preparation mold, and in order to be in similar conditions to the contaminated samples, it was soaked in a clean water tank for 24 hours before being set-up to the dynamic triaxial test cell. The DN38 sample was consolidated to 100 kPa under the same conditions as the DN18 sample, and Dr was obtained as 57% and the B value was measured as 0.60. Figure 5. shows the relationship between the pore water pressure ratio and the number of cycles for the DN18 sample prepared in the standard mold with a Skempton-B value of 0.58 and the modified mold with a Skempton-B value of 0.60. Both show similar behavior up to N=60 cycles. Likewise, in the dynamic deformation – number of cycles shown in Figure 6, at the $\varepsilon=\pm2.5\%$ deformation level defined as the failure criterion, the porewater pressure ratio of the DN38 sample up to N = 77 cycles is r_u = 0.95, and the porewater pressure ratio of the DN18 sample up to N = 82 cycles is r_u = 1.00. It has been observed that the dynamic behaviours of sand samples prepared in the standard mold and the modified mold are generally similar.

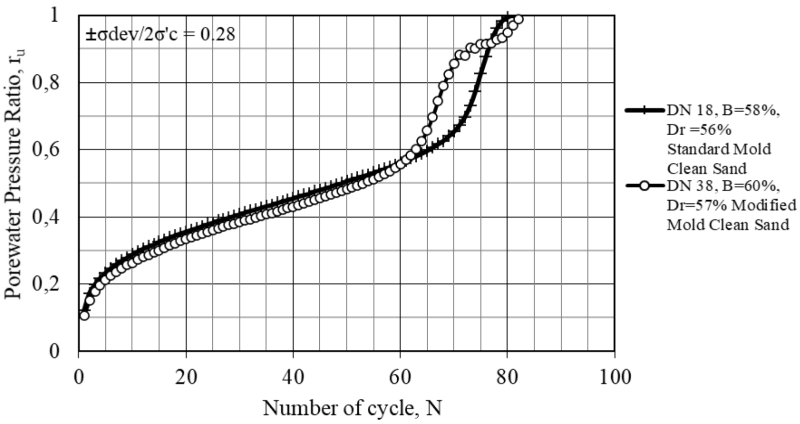


Figure 5. DN 18- DN38 Pore water pressure – Number of cycle.

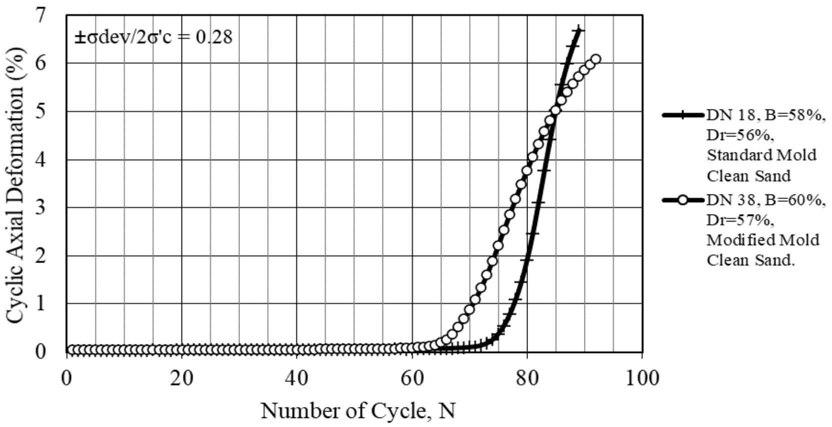


Figure 6. DN 18 - DN38 Cyclic axial deformation – Number of cycle.

3.2 Comparing the Cyclic Triaxial Test Results of Clean and Contaminated Sand

Figure 7 shows the relationship between the pore water pressure and the number of cycles and figure 8 shows the cyclic axial deformation and the number of cycles of clean sand samples. To study the effect of contamination on pore water generation and the cyclic axial deformation, ±σdev/2σ'con=0.28-0.30 dynamic stress level was applied to the sand samples prepared at the relative density varied from Dr=%50 to Dr=%60.

According to figure 8 the clean DN13 sample, which has the same saturation value as the contaminated DN87 sample with t=10 days curing time, reached failure deformation levels at N=90 and N=98 cycle numbers, respectively with a similar movement. As seen in Figure 7 the pore water pressure ratio is ru=1.00 in both samples at this level. Leachate-contaminated DN69 sample with curing time of t=45 days and the saturation value B=0.51 reaches ε=±2.5% dynamic axial deformation level at N=69 cycles and the pore water pressure ratio at this cycle was measured ru=0.98. The contaminated and clean sand samples with similar saturation degrees, DN69 sample with t= 45 days curing time liquefied first, then DN87 sample with t=10 days curing time, and finally clean DN13 sample shows liquefaction behaviour. As the curing time increase pore water pressure generation and cyclic axial strain increment occur at a lower number of cycles.

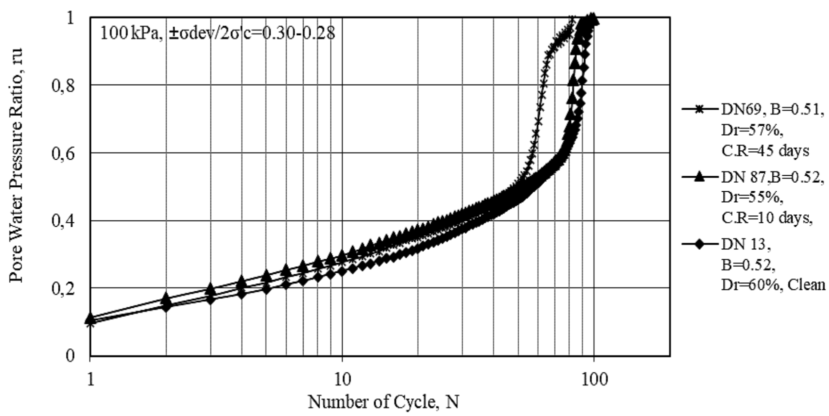


Figure 7. DN69, DN87, DN13 Pore water pressure – Number of cycle.

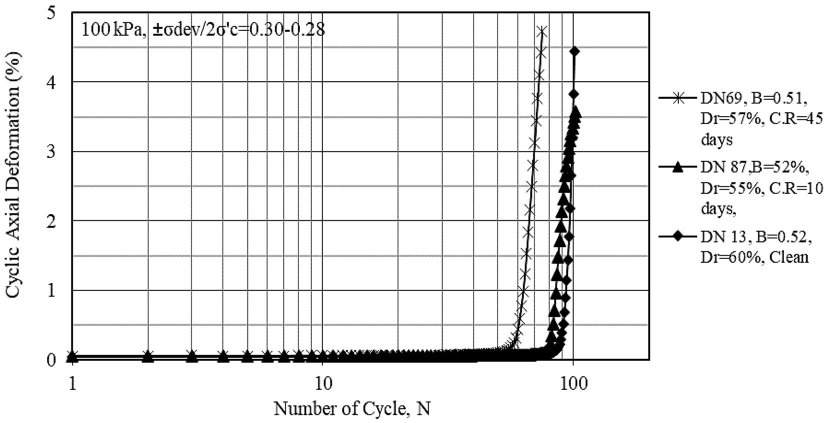


Figure 8. DN69, DN87, DN13 Cyclic axial deformation – Number of cycle.

Another study to compare the contaminated and clean sand samples is given in Figure 9 and Figure 10 below. The saturation value of the clean DN40 sample is B=0.93 and the relative density is Dr= 55%, the saturation value of the DN31 sample with t=103 days curing time is B=0.60 and the relative density is Dr= 57% and DN58 sample with t=299 days of curing time saturation value was calculated B=0.57 and relative density Dr=52%. Dynamic tests were carried out at the stress level $\pm\sigma d_{ev}/2\sigma'_c$=0.30-0.28 on the samples that were kept for one day under 100 kPa consolidation pressure.

As shown in Figure 10 clean sand sample with a saturation value of B=0.93 reaches the end of N=32 cycles, DN31 sample with t=103 days and saturation value of B=0.60 at N=35 cycles, and DN58 sample with a saturation value of B=0.57 and cure time of t=299 days reached at the end of N=34 cycles ε=±2.5% dynamic axial deformation level. Clean and contaminated sand samples at different saturation values reach a similar number of cycles caused to liquefaction. The pore water pressure ratio reaches all samples r_u = 1.00 at the end of the test (Figure 9). Partially saturated contaminated sands exposed to long-term contamination liquefy at a similar number of cycles with clean sand at a saturation degree of B=0.93.

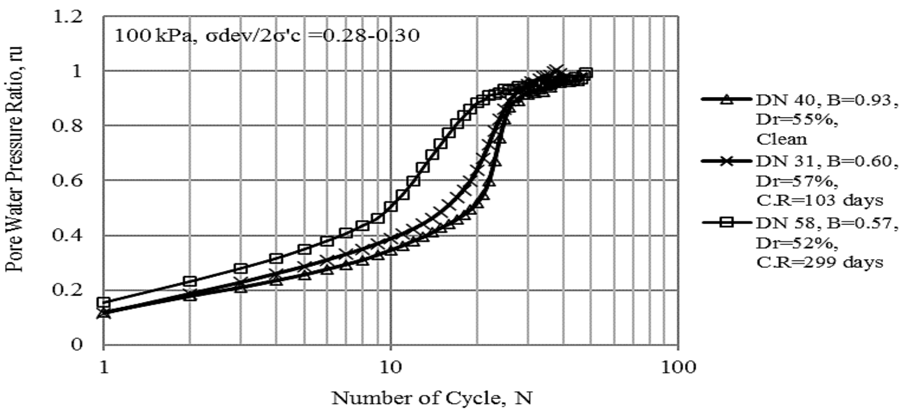


Figure 9. DN40, DN31, DN58 Pore water pressure – Number of cycle.

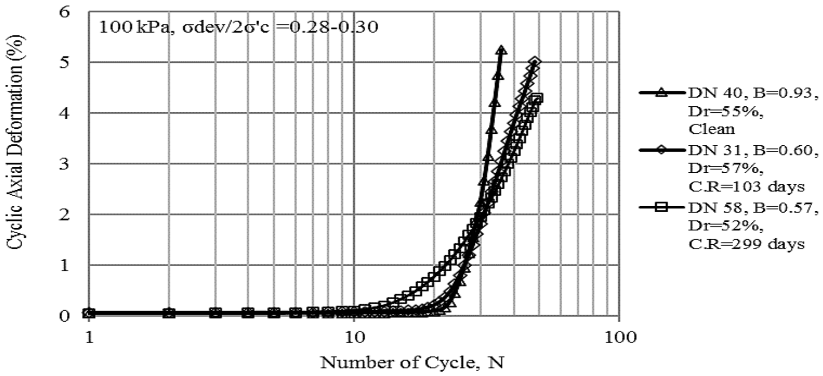


Figure 10. DN40, DN31, DN58 Cyclic axial deformation – Number of cycle.

3.3 Determination of Critical Deformation Values of Clean and Contaminated Sand

When the shear stresses on soils are large enough to generate axial unit stresses and pore water pressures, the axial unit impacts in the soil increase due to the softening of the soil. There is a deformation level at which axial strains and pore water pressure begin to increase rapidly as the effective stress decreases [12-13]. This level, which occurs before the failure deformation, is defined as the critical deformation level. The critical deformation level is determined by where the tangents drawn from the mean effective stress and axial strain cycles intersect, indicating the point of critical deformation.

In this part of the research, the critical deformation level is determined by both partly saturated clean and contaminated sand. For this purpose, three partly saturated sand samples were used and tested $\pm\sigma d_{ev}/2\sigma'_c$=0.30-0.28 cyclic ratio. Figure 11 shows the axial strain percentage and mean effective stress relation partially saturated clean sand at Skempton-B value at 0.73, Figure 12 shows the same relation with leachate-contaminated sand at B value 0.6 and short-period curing time (3 days) and Figure 13 illustrate the axial strain percentage and mean effective stress long-period curing time (146 days) at B value 0.45. As shown in the figure, the point where the tangents intersect is defined as the critical deformation level. The behaviors of the both contaminated and clean samples were similar and the critical deformation value is estimated ε_c = ±0.50%. It seems that contamination has no effect on changing the critical deformation value.

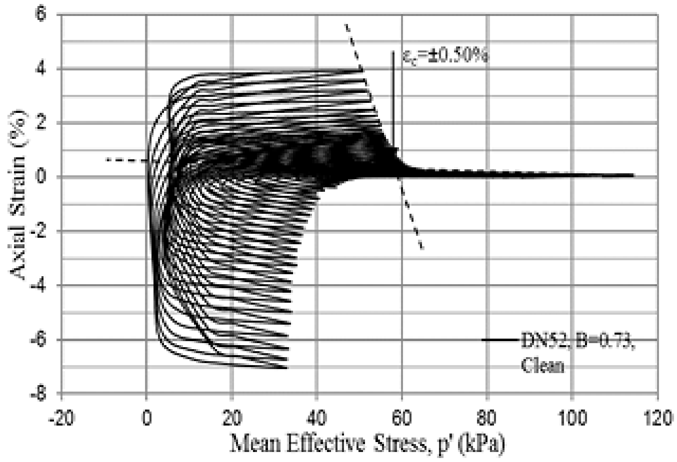


Figure 11. DN52, Axial strain – Mean effective Stress.

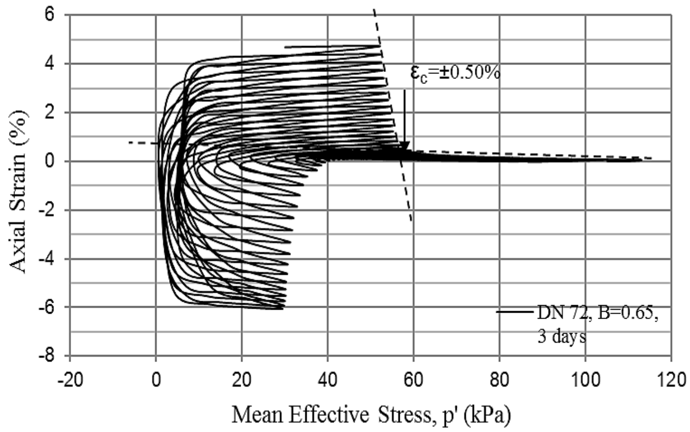


Figure 12. DN72, Axial strain – Mean effective Stress.

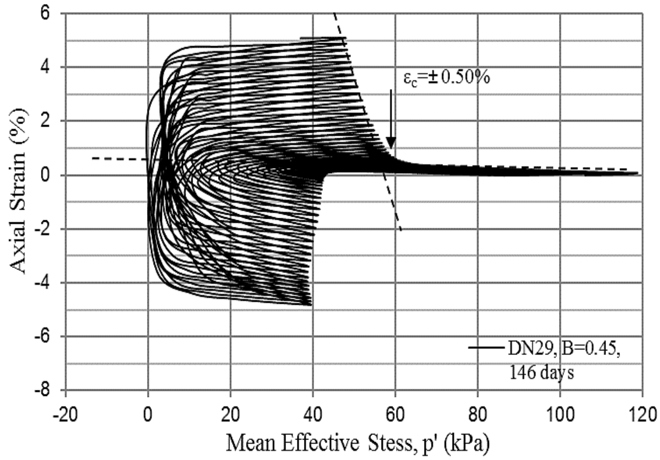


Figure 13. DN29, Axial strain – Mean effective Stress.

4. CONCLUSION

In this study, the effects of leachate on the dynamic behavior of sand were investigated. Clean sand samples and leachate-contaminated sand samples at different curing time were prepared and consolidated at 100kPa pressure for one day were tested. Experiments were carried out at different saturation values at a constant dynamic stress level in the dynamic triaxial test system, and the effect of leachate on liquefaction was investigated by comparing the behavior of clean sand samples with contaminated sand samples. According to the experiments conducted, it was observed that contaminated sands from partially saturated samples having similar saturation value and relative density were more liquefiable than clean sands, and contamination (curing time) in the samples increased the liquefaction potential. It has been previously demonstrated by many researchers that decreasing saturation, increases the liquefaction resistance of clean sands through studies conducted with partially saturated sands in a dynamic triaxial test system [14-15-16-17]. In these studies, researchers revealed that saturated samples were more liquefiable than partially saturated samples.

This study indicates that sand samples contaminated with leachate exhibit higher liquefaction susceptibility compared to clean sand samples, and a longer curing period leads to a rise in liquefaction potential. It has also been observed that long-term contaminated sand at saturation value between B=0.57-0.60 liquefies at a nearly same number of cycles with clean sand at saturation value B=0.93 show similar behavior.

Considering the critical deformation levels, it was calculated that the critical deformation value in clean and contaminated partially saturated samples at different saturation values was approximately $\varepsilon_c = \pm 0.50\%$. Although the contamination effect increases the liquefaction potential, there is no variation observed in terms of critical deformation behavior. However, it is thought that it affects the liquefaction behavior of leachate contaminated sand samples by physical effect due to the precipitation of organic and inorganic materials it contains, rather than the chemical and biological reaction of leachate components.

Acknowledgements

This research is a part of the Ph.D. thesis prepared by the researcher at Istanbul Technical University.

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