Pore Pressure Response of Natural Soils Under Various Testing Conditions

Majid Hussain and Ajanta Sachan

Abstract Soil behavior under undrained conditions is governed by several factors, including soil density, fines content, plasticity index and loading conditions among many others. Constitutive behavior of soil being pressure-dependent, the undrained response of soils is dictated by the development of excess pore water pressure during the applied loading. In this study, the pore pressure response of the natural Kutch soils under monotonic compression triaxial (TX), cyclic triaxial (CTX), and cyclic simple shear (CSS) conditions was investigated at their in-situ density. The explored soils vary greatly in terms of gradation, fines content, and nature of fines. The development of excess pore water pressure was compared under the three loading conditions and was analyzed in the context of fines content and plasticity index of the soils. The excess pore pressure ratio at peak stress for TX was found to be lower than that during the first cycle for both the CTX and CSS. However, at critical state, the excess pore pressure ratio for TX was higher than that during the 5th cycle for CTX and CSS. Under cyclic conditions, for a given number of cycles, the excess pore water pressure ratio under CSS conditions was always higher than that under the CTX conditions, signifying overestimation of liquefaction resistance as evaluated from the CTX tests. With an increase in the fines content and plasticity index, excess pore water pressure was observed to decrease under all the three loading conditions.

Keywords Pore pressure · Triaxial · Cyclic triaxial · Cyclic simple shear · Fines content · Plasticity index · Kutch region

1 Introduction

Soil behavior under undrained conditions is governed by several factors, including soil density, fines content, plasticity index and loading conditions among many others [7, 8]. While density is the single most parameter affecting the response of cohesionless soils, plasticity index plays a dominant role in governing the response of

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cohesive soils. Constitutive behavior of soil being pressure-dependent, the response of soils is dictated by the magnitude and rate of volume changes and development of excess pore water pressure under drained and undrained loading conditions. Under undrained conditions, the findings available in the literature reveal that the development of excess pore water pressure occurs only if the applied strains are higher than a certain threshold [2]. Excess pore pressure is generated due to irreversible changes in the microstructure of the soil at shear strains higher than the threshold value. The shear-induced excess pore water pressure leads to a reduction in effective stress and hence the reduced load-carrying capacity. The nature of the excess pore water pressure development is dependent on the current material and stress states of the soil mass. It could be contractive or dilative for loose and dense soils, respectively. For loose sandy soils, the development of excess pore water pressure might be nearly equal to the initial effective confining pressure. This extreme condition subsequently leads to a state of liquefaction, a state in which the soils have nearly zero shear strength. The state of liquefaction can be reached under both the monotonic and cyclic loading leading to static and cyclic liquefaction, respectively. A number of researchers have explored the undrained response of geomaterials with focus on shear strength characteristics including liquefaction a well as cyclic degradation. Both the liquefaction and the degree of cyclic degradation are governed by the magnitude and rate of development of excess pore water pressure. Whereas cohesive soils experience lower and slower pore pressure generation, cohesionless soils display large and rapid development of the excess pore water pressure. The soils in the Kutch region, due to predominantly cohesioneless nature, have experienced large-scale liquefaction during past earthquakes including the 2001 Bhuj earthquake. However, only a few studies have been devoted to exploring the engineering behavior of the soils, particularly under undrained conditions. In other related studies by the authors, the undrained response under monotonic and cyclic conditions was explored [3, 4]. However, the pore pressure response of the soils under both the monotonic and cyclic conditions remains to be explored. In this study, the pore pressure response of Kutch soils under different loading conditions is studied.

Undrained behavior of 30 natural soils collected from 10 locations of the Kutch region in Gujarat, India is explored under monotonic triaxial (TX), cyclic triaxial (CTX), and cyclic simple shear (CSS) conditions. The soils explored consisted mainly of silty-sand and clayey-sand. In this study, excess pore pressure response of the saturated specimens under TX, CTX, and CSS testing conditions was evaluated as a function of fines content (FC), plasticity index (PI), and grain size index (I_{GS}). I_{GS} for soil was evaluated as the ratio of area under particle size distribution curve to the area encompassed between 0.001 and 75 mm, extreme soil particle size [1].

2 Materials and Methods

2.1 Material Properties

In the present study disturbed representative soil samples were collected from 10 locations from low lying Kutch region of Gujarat, India. A total of 32 samples were collected by mechanical auger boring at depths ranging from 0.5 to 2.5 m. Hussain and Sachan [3] provide a detailed account of the geotechnical properties of the soils explored in the study. The soils had properties including dry density, water content, particle size distribution, fines content, and plasticity varying over a wide range. The basic geotechnical properties of the soils are presented in Table 1 [6]. While the dry density of the Kutch soils varied from 13.37 to 17.71 kN/m^3, the fines content varied from 11 to 83%. The plasticity index of the Kutch soils explored in the current study varied from being non-plastic to 22.9%. Out of the 30 soils 16 were classified as silty-sands, 9 as clayey-sands, 3 low plasticity clay, 1 high plasticity clay, and 1 as low plasticity silt.

2.2 Testing Equipment and Specimen Preparation

The excess pore pressure response of the soils in the current study was investigated under undrained triaxial, cyclic triaxial, and cyclic simple shear conditions. Moist tamping technique was adopted for the specimen preparation at in-situ density for all the three conditions [3, 4]. The specimens for TX and CTX were saturated by back pressure saturation whereas for CSS conditions de-aired water under the influence of gravity was percolated from the bottom of the specimen. However, the specimen size was different in the case of CSS as compared to that of the TX and CTX tests (Fig. 1). In the case of CSS tests, cyclic behavior of solid cylindrical specimens of diameter 70 mm and height 20 mm was explored whereas in TX and CTX the specimen size was 50 mm in diameter and 100 mm in height. Figure 1 shows the comparison of the specimen size used in the investigation of Kutch soils in the current study. The schematic shows the relative specimen size and loading configuration for the TX, CTX, and CSS conditions. For all the three conditions deformation controlled loading was applied. For TX tests, monotonic loading was applied at a deformation rate of 0.1 mm per minute. For CTX and CSS tests, the consolidated specimens were subjected to cyclic loading of shear strain amplitude of 0.6% at a frequency of 0.1 Hz. While the direction of loading for CTX was along the longitudinal axis, for CSS the direction of loading was horizontal.

Table 1 Geotechnical properties of soils of Kutch region

Soil name	Depth (m)	γ_{di} (kN/m^3)	w_c (%)	G_S	GSD				Atterberg limits			
					G (%)	*S* (%)	*M* (%)	*C* (%)	LL (%)	PL (%)	PI (%)	Soil class
Chang Dam			23° 27.591′ N		70° 24.408′ E							
S1 (L1)	0.5	15.00	19	2.67	6	78	11	5	–	–	–	SM
S2 (L2)	0.5	15.69	10	2.66	0	82	15	3	16	NP	NP	SM
S3 (L2)	1.5	15.70	14	2.68	5	76	17	2	20	NP	NP	SM
Kharoi			23° 28.367′ N		70° 23.330′ E							
S4	0.5	16.01	4	2.67	0	82	13	5	16	NP	NP	SM
S5	1.5	16.90	3	2.67	5	84	9	2	14	NP	NP	SP-SM
S6	2.5	16.00	2	2.67	1	86	11	2	13	NP	NP	SM
Suvai Dam			23° 36.428′ N		70° 29.821′ E							
S7	0.5	17.03	5	2.67	0	72	21	7	15	NP	NP	SM
S8	1	14.37	5	2.66	2	74	19	5	15	NP	NP	SM
S9	1.5	13.55	11	2.66	1	82	14	3	15	NP	NP	SM
Fatehgarh Dam			23° 41.369′ N		70° 48.057′ E							
S10	0.5	17.17	18	2.72	0	1	62	37	54	19	35	CH
S11	1.5	15.53	14	2.67	1	54	42	3	19	NP	NP	SM
S12	2.5	15.45	20	2.69	0	78	21	1	16	NP	NP	SM
Chobari			23° 30.722′ N		70° 20.881′ E							
S13	0.5	17.51	13	2.70	0	56	42	2	24	14	10	SC
S14	1.5	16.96	18	2.71	0	51	42	7	26	15	11	SC
S15	2.5	17.57	36	2.70	0	59	37	4	25	16	9	SC

(continued)

Table 1 (continued)

Soil name	Depth (m)	γ_{di} (kN/m^3)	w_c (%)	G_S	GSD				Atterberg limits			
					G (%)	S (%)	M (%)	C (%)	LL (%)	PL (%)	PI (%)	Soil class
Khadir			23° 50.82′ N		70° 14.39′ E							
S16	0.5	15.94	3	2.66	2	79	17	2	17	NP	NP	SM
S17	1.5	16.82	2	2.66	1	74	22	3	16	NP	NP	SM
S18	2.5	16.96	1	2.66	2	88	9	1	14	NP	NP	SP-SM
Tappar Dam			23° 15.017′ N		70° 07.586′ E							
S19	0.5	17.36	13	2.67	0	58	24	18	34	11	23	SC
S20	1.5	16.39	17	2.66	5	66	14	15	31	10	21	SC
S21	2.5	17.67	23	2.68	4	72	14	10	22	10	12	SC
Budharmora			23° 20.634′ N		70° 11.501′ E							
S22	0.5	17.71	6	2.68	2	69	21	8	23	15	8	SC
S23	1.5	14.27	15	2.71	1	34	46	19	44	16	28	CL
S24	2.5	12.26	22	2.70	2	18	57	23	66	27	39	CH
Banniari			23° 24.299′ N		70° 09.910′ E							
S25	0.5	13.37	6	2.74	0	17	81	2	26	NP	NP	ML
S26	1.5	14.59	24	2.75	0	5	68	27	47	19	28	CL
S27	2	16.26	12	2.68	0	68	26	6	25	12	13	SC
S28	2.5	17.60	11	2.69	1	78	13	8	28	12	16	SC
Shivlakha Dam			23° 24.659′ N		70° 35.128′ E							
S29	0.5	14.43	2	2.69	0	71	25	4	17	NP	NP	SM

(continued)

Table 1 (continued)

Soil name	Depth (m)	γ_{di} (kN/m^3)	w_c (%)	G_S	GSD				Atterberg limits			
					G (%)	S (%)	M (%)	C (%)	LL (%)	PL (%)	PI (%)	Soil class
S30	1.5	14.88	4	2.70	1	88	9	2	17	NP	NP	SP-SM
S31	2	16.37	9	2.69	1	74	18	7	15	NP	NP	SM
S32	2.5	13.40	20	2.68	0	28	50	22	39	16	23	CL

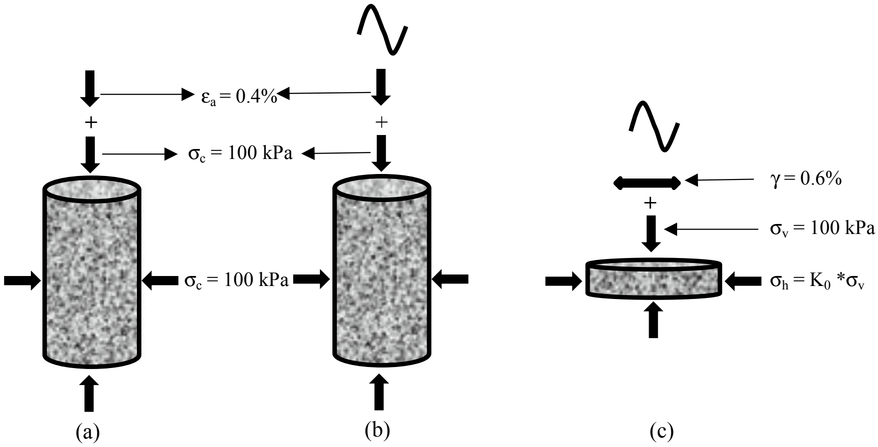

Fig. 1 Specimen size and loading configuration for various boundary conditions **a** TX, **b** CTX and **c** CSS

3 Results and Discussion

3.1 Results

Figure 2 shows the relationship of excess pore pressure ratio (r_u) with FC for the specimens of Kutch soils under the conditions of TX, CTX and CSS. Pore pressure response under monotonic compression loading at peak deviatoric stress could be observed to be lower as compared to that of cyclic loading during the first cycle (Fig. 2a). The r_u values at peak deviatoric stress for TX conditions ranged from 0.15 to 0.57 with an average value of 0.43. For CTX and CSS conditions, r_u values during the first cycle were evaluated to be ranging from 0.04 to 0.80 and 0.16 to 0.91, respectively. The corresponding average values for CTX and CSS conditions were found to be 0.53 and 0.65 respectively. The r_u values were observed to decrease with increase in the FC. It is evident from Fig. 2 that the pore pressure generation is higher during cyclic loading as compared to that during the monotonic loading. Further, the magnitude and rate of pore pressure generation were observed to be higher under CSS conditions as compared to those during CTX conditions. Specimens with lower fines content exhibited higher r_u values (Fig. 2). For a given FC it was observed that specimens with non-plastic fines displayed higher and rapid development of excess pore pressure. Figure 2b shows the relationship of r_u values with the FC for TX, CTX, and CSS conditions at the critical state and 5th cycle, respectively. It is evident from Fig. 2b that the critical state pore pressure for TX conditions is higher as compared to that at the 5th cycle for CTX and CSS conditions. For cyclic conditions, the difference between the r_u values at the 5th cycle was lower compared to that in the first cycle. However, r_u values were still higher for CSS conditions. The lower difference between the two could be attributed to the lower liquefaction resistance

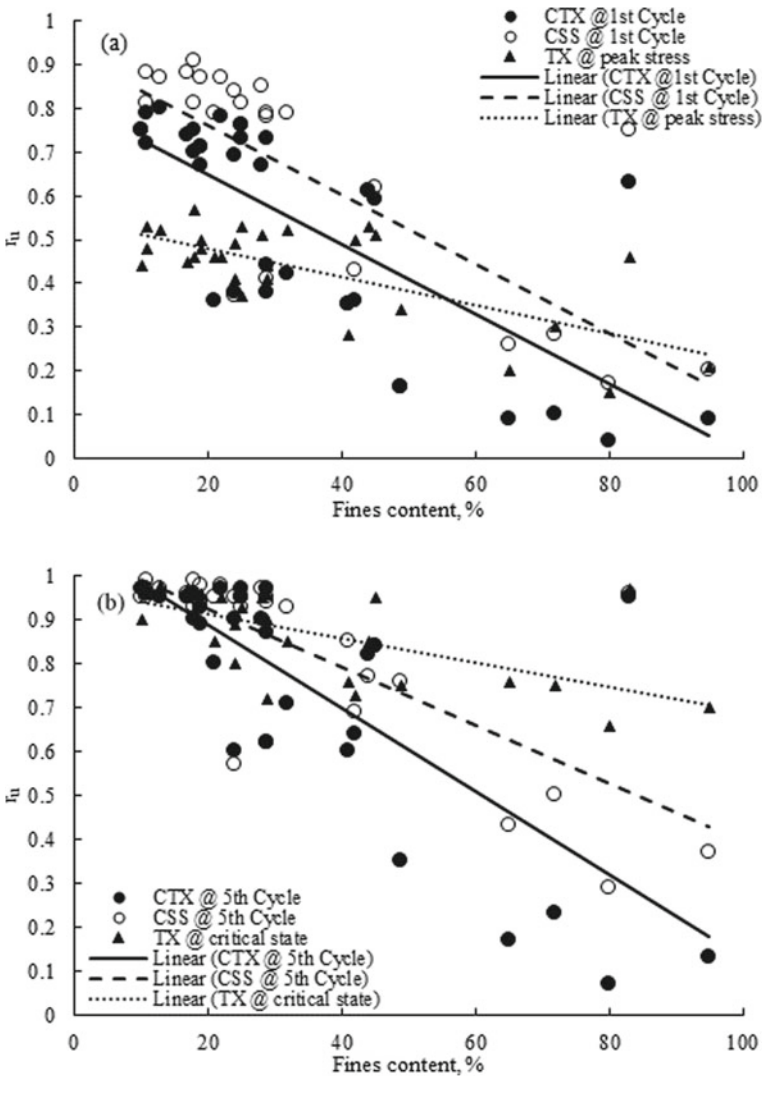

Fig. 2 Variation of pore pressure ratio with fines content under various boundary conditions. **a** Peak @ TX and 1st cycle @ CTX and CSS. **b** Critical state @ TX and 5th cycle @ CTX and CSS

where the sandy specimens liquefied within 5 cycles of cyclic loading. The pore pressure values under TX, CTX, and CSS conditions for Kutch soils are presented in Table 2. Among the cohesionless (silty-sand) specimens, r_u values were strongly influenced by the FC as compared to cohesive soils (clayey-sand) (Table 2). Figure 3 shows the relationship of excess pore pressure ratio with the PI for the specimens of Kutch soils under TX, CTX, and CSS conditions. The r_u values are same as in Fig. 2, however, the values on the x-axis reveal a reduction of pore pressure ratio

Table 2 Excess pore water pressure ratio under TX, CTX and CSS conditions for Kutch soils

Soil name	FC (%)	PI (%)	Excess pore water pressure ratio, r_u					
			TX		CTX		CSS	
			Peak	Critical state	1st cycle	5th cycle	1st cycle	5th cycle
S2	18	NP	0.46	0.96	0.75	0.96	0.91	0.99
S3	19	NP	0.48	0.96	0.67	0.89	0.87	0.98
S4	18	NP	0.57	0.92	0.70	0.90	0.81	0.93
S5	11	NP	0.53	0.96	0.79	0.96	0.81	0.95
S6	13	NP	0.52	0.98	0.80	0.95	0.87	0.97
S7	28	NP	0.51	0.95	0.67	0.90	0.85	0.97
S8	24	NP	0.49	0.89	0.69	0.90	0.84	0.95
S9	17	NP	0.45	0.97	0.74	0.95	0.88	0.96
S11	45	NP	0.51	0.95	0.59	0.84	0.62	0.84
S12	22	NP	0.46	0.95	0.78	0.97	0.87	0.98
S13	44	10.0	0.53	0.85	0.61	0.82	0.61	0.77
S14	49	11.4	0.34	0.75	0.16	0.35	0.16	0.76
S15	41	8.4	0.28	0.76	0.35	0.60	0.35	0.85
S16	19	NP	0.5	0.96	0.71	0.93	0.71	0.94
S17	25	NP	0.53	0.93	0.76	0.97	0.76	0.93
S18	10	NP	0.44	0.90	0.75	0.97	0.75	0.95
S19	42	22.9	0.5	0.73	0.36	0.64	0.43	0.69
S20	29	21.3	0.41	0.72	0.38	0.62	0.41	0.62
S21	24	11.7	0.41	0.80	0.38	0.60	0.37	0.57
S22	29	8.6	0.44	0.90	0.44	0.87	0.78	0.94
S23	65	28.6	0.2	0.76	0.09	0.17	0.26	0.43
S24	80	38.9	0.15	0.66	0.04	0.07	0.17	0.29
S25	83	NP	0.46	0.97	0.63	0.95	0.75	0.96
S26	95	28.6	0.21	0.70	0.09	0.13	0.20	0.37
S27	32	13.0	0.52	0.85	0.42	0.71	0.79	0.93
S28	21	16.3	0.46	0.85	0.36	0.80	0.79	0.95
S29	29	NP	0.44	0.96	0.73	0.97	0.79	0.95
S30	11	NP	0.48	0.98	0.72	0.96	0.88	0.99
S31	25	NP	0.37	0.96	0.73	0.95	0.81	0.95
S32	72	23.5	0.3	0.75	0.10	0.23	0.28	0.50

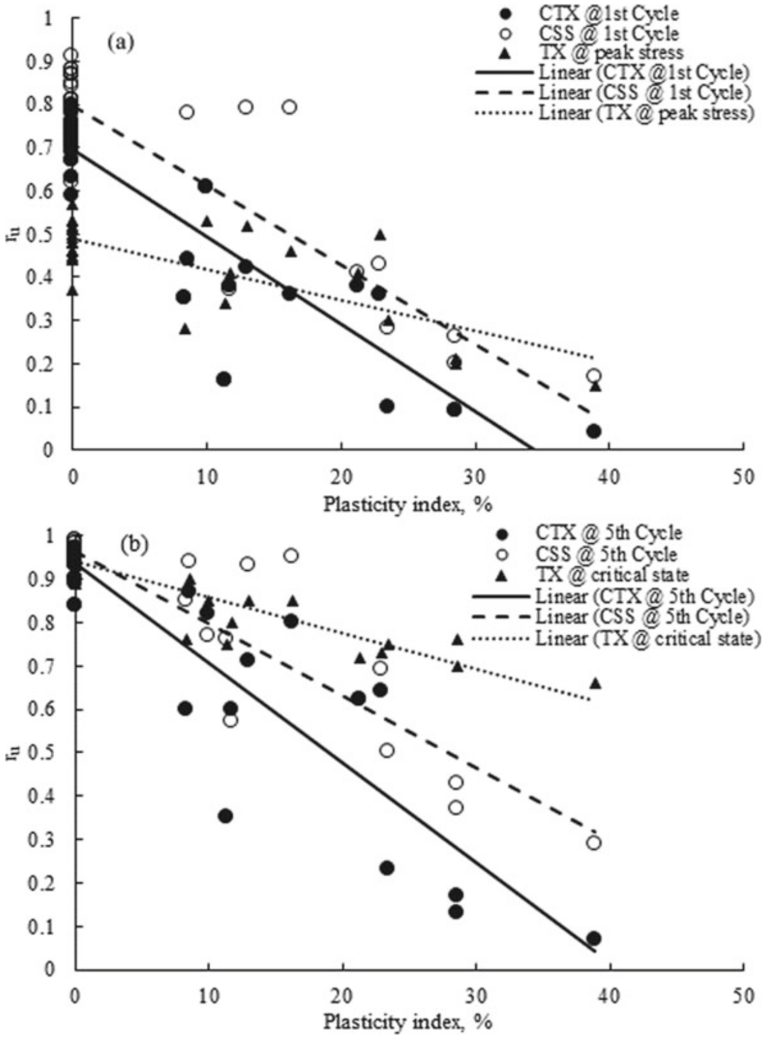

Fig. 3 Variation of pore pressure ratio with plasticity index under various boundary conditions. **a** Peak @ TX and 1st cycle @ CTX and CSS. **b** Critical state @ TX and 5th cycle @ CTX and CSS

with increasing PI. The variation of pore pressure with PI for all the three conditions (TX, CTX, and CSS) shows that the soils with non-plastic fines (PI = 0) exhibit large pore pressure values as compared to soils with some plasticity. The pore pressure at peak deviatoric stress and critical state for TX conditions and at the 1st and 5th cycles for CTX and CSS decreased rapidly with PI for cohesive soils. Figure 3b displays that the non-plastic soils developed r_u values higher than 0.89 and 0.85 for monotonic and cyclic loading, respectively.

Figure 4 illustrates the relationship between the pore pressure ratio and grain size index (I_{GS}) for Kutch soils. Grain size index is a direct measure of the range of particle size distribution and is higher for well-graded soils as compared to the poorly graded soils. For a given I_{GS} value the development of pore pressure was higher under monotonic compression loading as compared to the cyclic loading. Since by the definition of I_{GS}, it does not distinguish much about clean base sand and pure clay,

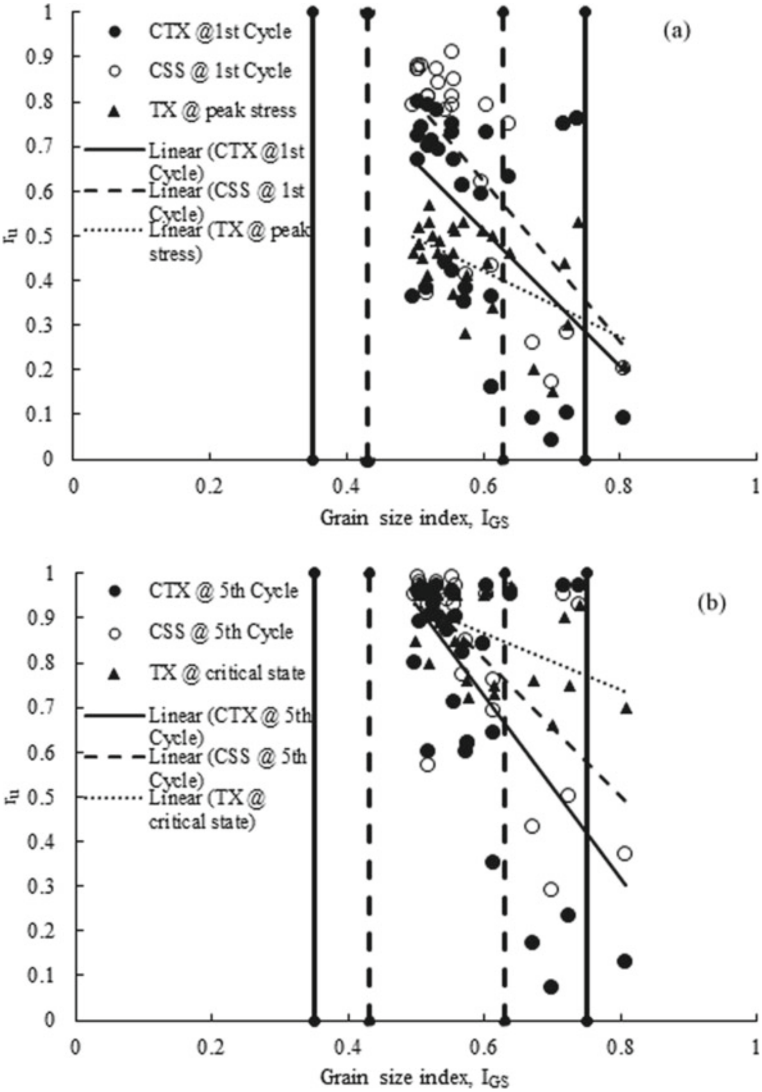

Fig. 4 Variation of pore pressure ratio with grain size index under various boundary conditions. **a** Peak @ TX and 1st cycle @ CTX and CSS. **b** Critical state @ TX and 5th cycle @ CTX and CSS

the data points lying low in Fig. 4b are those of cohesive Kutch specimens. The r_u values for Kutch soil specimens are lying between the bold and dashed vertical lines which indicate the boundary for the potential liquefiable and most liquefiable soils, respectively, it is therefore evident that the Kutch specimens due to their nature of grain size distribution are highly prone to high pore pressure generation and hence susceptible to liquefaction both the static and cyclic liquefaction.

3.2 Discussion

The test results indicated that irrespective of the loading condition large excess pore pressures were generated under undrained conditions for the Kutch soils. Such r_u values are indicative of a large reduction in shear strength, which in extreme conditions leads to static and cyclic liquefaction under monotonic and cyclic loading, respectively. Owing to the generation of large excess pore pressures, cohesionless soils from the Kutch region are highly susceptible to both the static and cyclic liquefaction whereas cohesive soils are prone to large degradation in shear strength under both the monotonic and cyclic loading. The detailed account of the static and cyclic liquefaction characteristics of the Kutch soils under different loading conditions can be found elsewhere, [3–5]. The pore pressure response as presented in Figs. 2–4 and Table 2 reveals that for cohesionless soils, FC controls the magnitude and rate of pore pressure generation whereas for cohesive soils it is the plasticity index that governs the soil response. Hussain and Sachan [3, 5] describe in detail the mechanism and effect of both FC and PI on the undrained behavior of Kutch soils.

4 Conclusions

Pore pressure response of natural Kutch soils from ten locations including five dams under different loading conditions including TX, CTX, and CSS was explored in the current study. The analysis of the test results revealed the following.

(a) Irrespective of the loading conditions Kutch soils exhibited very high pore pressure response indicting large reduction in strength under both the monotonic and cyclic loading subsequently leading to static and cyclic liquefaction.
(b) Fines content plays a decisive role in governing the pore pressure response in cohesionless soils whereas in cohesive soils it is the plasticity index that dictates the soil response.
(c) Under cyclic conditions, CSS results in higher pore pressure generation as compared to that of CTX by a factor of approximately 1.3.
(d) The rate and magnitude of pore pressure generated decreased with both the fines content and plasticity index.

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