Article

Prediction of Post-Yield Strain from Loading and Unloading Phases of Pressuremeter, Triaxial, and Consolidation Test Curves for Sustainable Embankment Design

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Abstract: Exponential development of post-yield strain (ϵ_{post}) is a pivotal indicator of failure in embankments constructed on soft saturated clays. This paper characterizes saturated clay stratum comprising very soft to very stiff stratigraphy, with plasticity index (PI) ranging from 19% to 31%, by performing widely used geotechnical engineering tests, i.e., the prebored pressuremeter (PMT) test, the triaxial (TXL) test, and constant-rate-of-strain (CRS) consolidation. PMT, TXL, and CRS tests were performed at a strain rate range of 0.18%/min to 0.21%/min to explore the yield stress (σ'_y), the pre-yield strain (ϵ_{pre}), and the post-yield strain (ϵ_{post}). Results indicate that $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$ for PMT, TXL, and CRS stress–strain curves range from 2.7 to 19 in the loading phase and 2 to 21 in the unloading phase. An exponential increase in $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$ is observed in the range of 10 to 21 for very soft to soft clay which is congruent with the realistic sustainable range of 4 to 30 for embankment failure on soft clays worldwide. The evaluated $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$ can be applied for sustainable prediction of post-failure evolution of strains in embankments on soft clays. Simplistic correlations are developed for approximation and prediction of ϵ_{post} as a function of σ'_y , ϵ_{pre} and maximum applied pressure (P_{max}) for loading and unloading phases with reasonable accuracy. The intuitive zone of critical ϵ_{post} is quantified for impending failure in embankments for maximum applied pressure (P_{max}), ranging from 36 kPa to 100 kPa for very soft to soft clay for use in sustainable embankment design and construction. Variation in predicted versus measured results of an individual site is observed to be within $\pm 10\%$ of line of equality.

Keywords: geotechnical engineering; clay; sustainability; embankments; strain; stress; pressuremeter; triaxial; consolidation

1. Introduction

The need to build the road embankments (usually 3 to 4 m high) on soft clay strata is observed worldwide; however, a number of embankments fail each year due to the development of exponential post-yield strain, which is the key parameter for slope design [1–3]. Post-construction settlements are very serious for the performance of road embankments [4].

Embankments fail mainly due to the onset of yielding in soft clay when the effective stress state moves from an overconsolidated condition to a normally consolidated condition, and the behaviour of clay moves from the partially drained phase to the undrained phase [5–7]. As mentioned for soft clays at Rio and Muar-F embankments, the prediction of large strain residual undrained shear strength is based on yield stress. The yielding is considered as a fundamental feature of lightly overconsolidated saturated clays, resulting in exponential post-yield strains [8–11]. The yield stress (herein denoted as σ'_y) acts as the separating point for the elastic (pre-yield) and plastic (post-yield) response of clays [11–13]. This describes the pre-failure (crest settlement) and post-failure (large displacement in the toe of an embankment slope) as significant stages of slope movement. Yielding of soft clays has been studied extensively in the past to understand the stress–strain behavior during failure of embankments [14–16].

A study on embankment failures provides the basis for an assessment of the performance of infrastructure built on soft saturated clays [17]. The prediction of embankment settlement is significant for stability [18]. Consolidation behavior of soft clay under embankment is critical [19]. The soft sub-soils under the embankments are critical for stability [20–23]. Due to excavation in soft clays, the lateral displacement of embankment's toe is significant to practicing engineers [24–30]. The development of strains causing settlement at the crest of embankment shows the initial sign of failure. Stress levels (due to height of embankment) which exceed the yield stress in stiff soils generate low excess pore pressures, whereas soft clays are prone to the development of high pore pressure, ultimately causing the onset of yielding and large post-yield strains [31].

An increase in the height of the embankment causes an increase in vertical stress, resulting in the yielding of clay and the enhancement of the horizontal deformation at the toe, which is sensitive to moisture content. Hence, the failure of embankment constructed on soft saturated soils is closely related to the embankment height; hence, the maximum pressure exerted due to height of the embankment is mainly related to the large post-yield strains which causes the embankment to fail. The strain-softening behavior in clay arises due to building up of excess pore-water pressure due to strains developed in saturated clay strata. The detailed parameters of these failure cases show that the post-failure deformation was very large as compared with pre-failure deformation as presented in Table 1 for embankment failure cases worldwide.

Table 1. Past studies on pre-failure and post-failure deformation during embankment failures.

	Name	Soil Type	Pre-Failure Lateral Def. at Toe (mm)	Post-Failure Lateral Def. (mm)	Ratio of Post to Pre-Failure Deformation	Reference
1	Rio de Janiero, Brazil	Very soft clay	155	700	4.5	Costa-Filho (1977) [32]
2	Thames, UK	Soft to very soft clay	450	2200	4.9	Marsland and Powell (1977) [5]
3	Cubzac-A, France	Soft to very soft clay	130	1400	10.7	Magnan, Humbert, and Mouratidis (1982), [33] Blondeau et al. (1977) [34]
4	Kalix, Sweden	Soft to very soft clay	>105	700	<6.7	Holtz and Holm (1979) [35]
5	Kings Lynn, UK	Soft clay	>125	1500	<12	Wilkes (1972), [36] Wroth and Simpson (1972) [37]
6	St. Alban-A, Quebec, Canada	Soft to very soft clay	>40	1200	<30	La Rochelle et al. (1974) [38]
7	Muar-F, Malaysia	Soft to very soft clay	370	1500	4.1	Poulos et al. (1990) [39]

Large vertical stress due to overburden load acts in embankment in the initial stage of failure which gradually transforms to the large horizontal stress acting at the toe resulting in generation of the large horizontal failure strain. Figure 1 shows the embankment failure due to excavation, where the effective major principal stress (σ'_1) and effective minor principal stresses (σ'_3) are shown at points A, B, and C. The axes of σ'_1 and σ'_3 are rotated through 45° at stage B and 90° at stage C. The principal stress axis rotation, in case of embankments on soft soils, is well described [40]. The stage C (last stage of the failure of embankment at the toe) simulates the stresses acting in pressuremeter testing, whereas the stress condition at stage A is simulated by the TXL and CRS tests (where the sample is compressed vertically up to failure), as shown in Figure 1.

(a)

(b)

Figure 1. (a) Rotation of principle stress axis during embankment failure (Initial Stage “A”, Intermediate Stage “B” and Failure Stage “C”) (b) Pre-yield strain, post-yield strain, and yield stress shown in the pre-bored pressuremeter curve.

The in situ soil testing tool-like pressuremeter (PMT) can be used to obtain the stress–strain relation of saturated clay from which the pre-yield and post-yield strains can be evaluated. According to [41,42], the pressuremeter (PMT) test can be used effectively for

the study of horizontal strains in clays by stressing the soil in lateral direction. The PMT test is significant as it simulates the embankment failure at the toe where the direction of applied stress and the corresponding strain is horizontal, as shown in Figure 1. As the large deformation occurs in the case of embankment failure, the in situ prebored pressuremeter (PMT) test, hence, is an ideal tool compared to laboratory tests, including TXL and CRS tests. The pressuremeter test can be used as reference to the other tests for stress–strain analysis [43,44].

The prediction of short- and long-term tunnelling-induced ground movements was presented by [45] in London Clay, based on the stiffness of intact samples evaluated by oedometer and triaxial tests. Tavenas [6] predicted the large lateral deformation at the toe of embankment from settlement at the centre of the embankment. In light of previous studies, the yield stress (σ'_y), the pre-yield strain (ϵ_{pre}), and the post-yield strain (ϵ_{post}), based on pressuremeter (PMT), triaxial (TXL), and CRS tests, are presented in Tables 2–4, respectively, for clays of worldwide locations with diverse geologic origins.

Table 2. Yield stress and strains of saturated clays from previous studies on PMT (loading phase).

Sr. No.	Yield Stress (P_y), kPa	Pre-Yield Strain (ϵ_{pre})	Post-Yield Strain (ϵ_{post})	Max Pressure (P_L), kPa	(ϵ_{post}/P_y)	($\epsilon_{post}/\epsilon_{pre}$)	Type of Soil	PMT Type	Reference
1	535.7	0.00905	0.08523	809.5	0.00016	9.42	Stiff Gault Clay	SBPM	Windle and Wroth (1977) [46]
2	806.4	0.02524	0.37006	870.2	0.00046	14.66	Stiff to very stiff Gault Clay	FDP	Houlsby and Withers (1988) [47]
3	654.5	0.02010	0.08833	818.2	0.000135	4.39	Soft to stiff Fucino Clay	SBPM	Ferreira and Robertson (1992) [48]
4	401.3	0.01510	0.08980	497.1	0.00023	5.95			
5	437.5	0.01616	0.31767	531.2	0.00070	19.66	Soft Bothkenner clay	CPM	Nutt (1993) [49]
6	282.4	0.02070	0.32525	330.2	0.00115	15.71			
7	123.7	0.02424	0.28282	170.3	0.00228	11.67			
8	87.2	0.01923	0.16666	170.5	0.00191	8.67	Soft clay at British Columbia	SBPM	Ferreira and Robertson (1994) [50]
9	108.9	0.01794	0.25769	178.2	0.00236	14.36	Soft clay at British Columbia	FDP	
10	225.0	0.02254	0.46470	329.0	0.00206	20.61	Soft clay	FDP	Rehman, Akbar and Clarke (2011) [51]

PMT = pressuremeter; SBPM = self-boring pressuremeter; FDP = full-displacement pressuremeter; CPM = cone pressuremeter.

Table 3. Yield stress and strain of clays from previous studies on the triaxial test (loading phase).

Sr. No.	Yield Stress (P_y), kPa	Pre-Yield Strain (ϵ_{pre})	Post-Yield Strain (ϵ_{post})	P_{max} , kPa	ϵ_{post}/P_y	$\epsilon_{post}/\epsilon_{pre}$	Type of Soil	Test Type	Reference
1	33.2	0.00857	0.07071	28.9	0.00212	8.25	Bothkenner Soft Clay	Anisotropic Undrained	Hight, Bond, and Legge (1992) [52]
2	49.6	0.01035	0.04501	45.1	0.00091	4.34			
3	113.8	0.03148	0.15833	114.6	0.00139	5.03	Soft Shanghai clay	Isotropic Undrained	Huang, Liu, and Sheng (2011) [16]
4	80.7	0.03240	0.17963	81.5	0.00222	5.54			
5	67.6	0.02407	0.16851	61.5	0.00248	7.00			
6	53.1	0.02777	0.21388	42.3	0.00403	7.70			
7	86.1	0.01018	0.17685	65.0	0.00205	17.36			
8	65.6	0.01388	0.190741	45.0	0.00336	13.73	Soft Shanghai clay	Anisotropic Undrained	
9	1025.3	0.03839	0.119643	916.7	0.00011	3.12	Boulder Clay, Boulder, USA	Unconsolidated Undrained	Mun et al. (2016) [53]
10	703.4	0.02881	0.120339	908.3	0.00017	4.18			
11	225.1	0.01785	0.133929	441.6	0.00059	7.50			
12	166.7	0.01607	0.133036	301.4	0.00079	8.28			
13	131.1	0.00833	0.0638889	164.4	0.00048	7.67	Low plastic Soft Clay	Isotropic Undrained	Gluchowski et al. (2019) [54]
14	61.1	0.00444	0.0672222	120.8	0.00109	15.13			
15	246.1	0.03522	0.164773	267.3	0.00066	4.68	Expansive Clay, Nanyang, China	Consolidated Undrained	Dai et al. (2020) [55]
16	221.1	0.03181	0.167045	209.6	0.00075	5.25			
17	182.7	0.02386	0.173864	176.9	0.00095	7.29			
18	115.4	0.02045	0.176136	140.4	0.00152	8.61			
19	133.7	0.01619	0.0647619	101.2	0.00048	4.00	Soft Marine Clay	Consolidated Undrained	Tsuchida et al. (2020) [56]
20	143.5	0.01809	0.072381	103.2	0.00050	4.00			
21	158.3	0.02095	0.0619048	115.4	0.00039	2.95			
22	156.2	0.02201	0.0770102	93.3	0.00029	3.50			

Table 4. Yield stress and strain of clays from previous studies on the CRS test (loading phase).

Sr. No.	Yield Stress (P_y), kPa	Pre-Yield Strain (ϵ_{pre})	Post-Yield Strain (ϵ_{post})	Max. Pressure P_{max} , kPa	ϵ_{post}/P_y	$\epsilon_{post}/\epsilon_{pre}$	Type of Soil	Reference
1	76.3	0.03022	0.23022	184.5	0.00302	7.61	Gloucester clay Canada	Leroueil, Samson, and Bozozuk (1983) [13]
2	90.1	0.04002	0.21955	241.6	0.00244	5.48		
3	74.5	0.01511	0.22044	199.1	0.00296	14.58		
4	106.7	0.02755	0.18844	238.9	0.00177	6.83		
5	117.4	0.00895	0.217911	235.6	0.00186	2.43	Batiscan clay	Leroueil et al. (1985) [57]
6	144.7	0.05447	0.18059	239.4	0.00125	3.32	St. Cesaire clay	
7	101.5	0.04010	0.24002	611.6	0.00236	5.98	Winnipeg clay	Grahams, Crooks, and Lau (1988) [10]
8	98.3	0.04571	0.08653	151.7	0.00088	1.89		
9	210.3	0.02782	0.05217	351.7	0.00025	1.87	Norwegian Clay	Lunne et al. (2008) [58]
10	157.1	0.04170	0.11915	246.4	0.00076	2.85		
11	59.5	0.03889	0.26528	305.4	0.00446	6.82	Ariake clay, Japan	Jia et al. (2010) [59]
12	30.2	0.03764	0.24167	176.2	0.00800	6.42		
13	30.2	0.03751	0.25417	204.1	0.00842	6.78		
14	102.5	0.04161	0.25138	503.6	0.00245	6.04		
15	50.2	0.04458	0.25278	261.3	0.00504	5.67		
16	110.3	0.07571	0.20857	180.3	0.00189	2.75	Maxico City clay	Diaz-Rodriguez, Tonix, and Carrizales (2017) [60]

The bilinear plotting technique was applied to determine the yield stress for the data of PMT, TXL and CRS tests from previous studies. This method describes the intersection of two straight line approximations, i.e., one from the pre-yield phase and another from the post-yield phase of stress–strain curves of PMT, TXL, and CRS tests conducted in clay.

The extent of post-yield strain is related to the pre-yield strain and yield stress for clays. For different values of yield stress and pre-yield strain, there are different values of post-yield strain which requires normalization so that clear effect of maximum pressure (P_{max}) due to embankment height can be evaluated in the form of post-yield strain.

PMT, TXL, and CRS tests are significant when studying the yielding behavior of clays. The yield point and yield zones in clay can be effectively observed in PMT and TXL stress–strain curves [61,62]. CRS tests are considered as standard for the evaluation of effective yield stress (σ'_y) of clays whereas σ'_y from in situ tests should be compared with standard oedometer tests (e.g., CRS) to validate proposed empirical correlations. The CRS test on clays critically depends on the strain rate and provides continuous data points as compared with incrementally loaded (IL) oedometer tests [63]. Both the loading and unloading stress–strain curves can be analyzed for the yield point in PMT, TXL, and CRS tests.

It is well established that strain energy is released during the unloading in embankment slopes and, resultantly, the progressive failure is observed [64]. Present research simulates to the release of strain energy in slopes in the way that the lowering in strain energy (work) occurs in the unloading phases of PMT, TXL, and CRS tests. Hence, the unloading phase of these tests is significant when evaluating yielding behaviors and large failure displacements for embankments where the embankment slope is unloaded due to excavation.

The specific level of dry density, moisture content, and plasticity index (PI) are the index properties to be studied for the stability analysis of embankments constructed on very soft to soft clays. The increase in density causes an increase in shear strength, whereas an increase in moisture makes the clay soft, resulting in a lower shear strength. It is necessary to study the changes in the profiles of dry density, moisture, and the PI of clay for the design of embankments.

Previous studies [6,17–31,64] on the failure of embankments explored the extent of post-failure movement of the toe and the settlement of apex of embankments in the case of very soft to soft clays due to pressure exerted by the increase in height of the embankment. Previous studies did not compare the loading and unloading behaviors of clay in the same

test. However, this research presents the novel correlations based on loading and unloading behavior in stress–strain curves of field tests (PMT) and laboratory tests (triaxial and CRS) to determine the critical post-yield failure strain before onset of embankment failure. Hence, this study will be useful to take prior safety measures to reduce the post-failure damages at and around the critical portion of the road or railway embankment for loading and unloading conditions of the embankments.

Very few studies have predicted post-yield strains (ϵ_{post}) using pre-yield strain (ϵ_{pre}), yield stress (σ'_y), and maximum applied pressure (P_{max}) for the loading and unloading phases of PMT, TXL, and CRS tests. This research is intended to explore the yielding behavior of very soft to very stiff saturated clay and is devoted to investigate the following specific aspects:

- (i) To evaluate yield stress (σ'_y) by the work method [65] and determine the pre-yield strains (ϵ_{pre}) and post-yield strains (ϵ_{post}) from loading and unloading phases of stress–strain curves;
- (ii) To explore the range of exponential critical post-yield strains (ϵ_{post}) in loading and unloading phases of very soft to soft clay;
- (iii) To develop correlations for the prediction of post-yield strains (ϵ_{post}) from yield stress (σ'_y), pre-yield strains (ϵ_{pre}), and maximum applied pressure (P_{max}) for loading and unloading curves;
- (iv) To benchmark this research, data were validated by past studies and by conducting testing on a separate saturated clay site.

2. Materials and Methods

An alluvial deposit comprising stratigraphy, divided into four units, i.e., very soft, soft, stiff, and very stiff saturated clay with medium plasticity, was selected in Lahore, Pakistan for the geotechnical characterization by field testing (PMT) and laboratory testing (triaxial and CRS) on undisturbed soils retrieved from the field.

Experimentation was performed at eighteen points in an area of about 100 m $\times$ 250 m size, as per layout the plan shown in Figure 2. The soil investigation approach was adopted to select a particular member of the soil group to test in a variety of test conditions. For this purpose, a comprehensive experimentation program (Figure 2) was planned for field sampling and in situ testing of site strata. Borehole drilling was conducted to retrieve one hundred and eighty undisturbed samples (UDSs) from eighteen boreholes of 10 m depth each. The pattern of boreholes is shown in Figure 2a and a plan of in situ PMTs and UDSs is presented in Figure 2b.

The drilling for UDSs was conducted by rotary drilling rig. As the quality of undisturbed samples depends on the precision of samplers for high-quality stress–strain curves, high-quality UDSs were taken by steel tubes by slow pressure on sampler during rotary drilling (ASTM D5783) [66]. The UDSs were retrieved at the average rotation speed of rotary drilling rig (ASTM D5783) [66], i.e., 42 rpm, and bentonite was used as a drilling mud with a 12 liters/min pumping speed to shift the material cuttings out of the borehole. Careful efforts were made to preserve the in situ arrangement of soil particles during undisturbed soil sampling using thin-walled steel tubes (ASTM D1587) [67]. The UDSs were transported to the laboratory according to ASTM D4220 [68]. Two additional boreholes (B_1 and B_2) were drilled up to a 20 m depth to determine the ground water table (GWT). The GWT was observed at a 15.7 m depth over an observation time of 72 h.

Figure 2. (a) Location plan of drilling/field testing points (b) plan of PMTs and UDSs.

A comprehensive field study was planned which comprised one hundred and eighty prebored pressuremeter (PMT) tests at site. The potential use of PMT as a tool to analyze the stress–strain behavior of clay is further explored for pre-yield strain and post-yield strain. Prebored pressuremeter (PMT) can be used to precisely determine the stress–strain curves of soil strata [69,70]. PMT tests were conducted as per ASTM D4719 in prebored boreholes at 1 m to 10 m depths. The drilling of boreholes for PMT testing was conducted by a mechanical drilling system with specially designed slotted sampler and an outer diameter of 49 mm, developed by [69,70], due to which the smooth surface of borehole walls with minimum disturbance (ASTM D5434 [71]) was achieved as a prerequisite for PMT testing according to ASTM D4719 [72]. The boreholes were prepared for acceptable smooth surface and a vertically aligned test cavity was used to satisfy the borehole diameter requirements mentioned in ASTM D 4719 [72], which are as follows:

$$1.03D < D_H < 1.2D$$

(D = diameter of the probe and D_H = diameter of the hole or test cavity).

The procedure outlined in ASTM D1452 [73] was adopted for extracting disturbed samples. The PMT equipment used in this research was the strain arm type with a length of 305 mm and an outer diameter of 48.2 mm. A PMT cylindrical probe was placed in a prebored borehole at specific depths, and the membrane of the probe was expanded with nitrogen gas to compress the wall of borehole to obtain stress–strain curves. The data logger and the pressure system were attached to the apparatus.

One hundred and eighty stress-controlled PMTs were performed at a very slow to slow rate of pressure application, ranging from 0.45 kPa/min to 4 kPa/min to maintain the low rate of strain in the range of 0.18%/min to 0.21%/min, which corresponds to the impending failure condition in embankments. The adopted strain rate in this study corresponds to the range of critical strain rate of the embankments for impending failure condition [74]. The hall-effect transducer (HET) was installed inside the probe to measure the displacement of the membrane from the surface of the probe. A pressure transducer

was used to measure the pressure inside the PMT membrane. The membrane and the HET were calibrated before the start of experimentation.

One hundred and eighty undisturbed samples (UDS) were subjected to laboratory testing. The clay samples retrieved from UDS were tested for the saturation level. Here, it was found that the strata up to a 10 m depth were in a saturated condition. The laboratory tests, i.e., gradation analysis for the grain sizes of particles comprising sand, silt, and clay (ASTM D6913) [75], as well as the dry density of soil (γ_d), were used by weighing and oven-drying the soil samples taken from the UDS tube (ASTM D7263 [76]). Furthermore, Atterberg limits, including the liquid limit and the plastic limit for the soil passing #40 sieve (ASTM D4318 [77]); the moisture content (MC) of the soil taken from UDS by weighing the natural and oven-dried soil (ASTM D2216 [78]); soil classification for the samples retrieved from 1 m to 10 m depths on the basis of grain size analysis and Atterberg limits (ASTM D2487 [79]); and the specific gravity (G_s) of soil were all determined for the UDS (ASTM D854 [80]).

Undisturbed samples (UDS) in thin-walled tubes were preserved in a controlled humidity room to avoid moisture loss. Samples for triaxial tests were extruded from thin-walled tubes into a split mold with a diameter of 38 mm and a length of 76 mm. The samples were installed in the triaxial cells and then subjected to a saturation phase up to $B = 0.98$, where B is the Skempton's parameter for assessment of saturation. Then, the samples were subjected to effective consolidation stress that was equal to the overburden stress. An undrained condition for anisotropically consolidated undrained (CK_oUC) triaxial tests was applied. Strain-controlled triaxial tests were performed according to ASTM D4767 [81]. Monotonic loading was applied throughout the shearing phase. The effective confining pressure was taken equal to the overburden pressure for samples from different depths. One hundred and eighty undrained anisotropic triaxial compression (CK_oUC) strain-controlled tests were performed on the UDS, as per ASTM D4767 [81]. Triaxial tests were conducted at a strain rate of 0.19%/min for comparison with average strain rate of pressuremeter tests for reasonable comparison of yield behavior.

One hundred and eighty controlled-rate-of-strain (CRS) consolidation tests (ASTM D4186) [82] were performed on the undisturbed soil samples (UDS) at a specific strain rate of 0.19%/min. This choice was only made to attain the matching strain with the strain rate for initiation of the failure of embankments. The sample diameter of 63.7 mm and thickness of 20 mm were selected for the use of specimens in CRS tests. The CRS tests economically and promptly determined the consolidation properties of the clays. The strain rate was also selected for the incrementally loaded consolidation tests.

3. Results

Figure 3 shows the typical grain size distribution results of soil strata encountered at sites up to 10 m deep. The soil classification (ASTM D2487 [79]) shows that the strata up to 10 m depth are "lean clay" with a medium plasticity index (PI). Figure 4 shows the profiles of moisture content (MC), dry density (γ_d), plasticity index (PI), and SPT blows for the soil strata up to 10 m deep.

The MC ranges from 26% to 36% in a decreasing trend; γ_d ranges from 1.31 g/cm³ to 1.63 g/cm³ in an increasing trend; and PI ranges from 19% to 31%, showing the decreasing trend from the surface to a 10 m depth. The average value of G_s is 2.73 for the soil encountered up to a 10 m depth. Very soft clay was observed up to a 2 m depth, whereas soft clay, stiff clay, and very stiff clay strata were encountered from a 2 m to 5 m depth, a 5 m to 7.5 m depth, and a 7.5 m to 10 m depth, respectively.

Figure 3. Typical grain size distribution curves of field strata up to 10 m deep.

Figure 4. Profiles of moisture content, dry density, plasticity index, and SPT blows of the strata on the site.

The yield stress is precisely determined with a bilinear plotting technique by use of work-effective pressure ($W-p'$) curves, as per procedure mentioned in [83] from the data of PMT, TXL, and CRS tests. This method describes the intersection of two straight line approximations, i.e., one from the pre-yield phase and another from the post-yield phase [83] from stress–strain curves of PMT, TXL, and CRS tests conducted in clay.

Typical loading and unloading curves of PMT, TXL and CRS tests are presented in Figure 5 which show the yield stress at 1 m, 5 m, and 10 m depths. The test curves are presented in the form of strain versus p' (log scale) for purpose of comparison of shape of curves. It was observed that shape of stress–strain curves becomes round at the maximum curvature which makes it difficult to determine yield stress (σ'_y) by using graphical method

at simple stress–strain curves. Hence, pre-yield and post-yield strains from PMT test curves are evaluated by work method i.e., determining effective yield stress (σ'_y) at the intersection of two straight lines. The adopted strain range in PMT, TXL and CRS tests is very narrow, hence the effects of strain rate on soil behaviour are not discussed in this research.

Figure 5. Yield stress at PMT, TXL, and CRS typical curves at 1 m, 5 m, and 10 m depths.

The work per unit volume versus effective pressure (W versus p') graphs of PMT at 1 m, 5 m, and 10 m depths, as presented in Figure 6, show yield stresses (σ'_y) of 38 kPa, 206 kPa, and 311 kPa, respectively, in the loading phases. Figure 6 shows the abrupt change in slope of W - p' graph at the point of yield stress. The unloading behaviour of PMT curves at 1 m, 5 m, and 10 m depths are analyzed by the W - p' trend, which resulted in yield stresses of 40 kPa, 212 kPa, and 304 kPa, respectively, as shown in Figure 7.

Figure 6. Yield stress from PMT typical curves (loading phase) at 1 m, 5 m, and 10 m depths.

Figure 7. Yield stress from PMT typical curves (unloading phase) at 1 m, 5 m, and 10 m depths.

The yield stresses (σ'_y) for the triaxial curves at 1 m, 5 m, and 10 m depths (Figure 8) were analyzed by work method (W versus p') and resulted in the σ'_y values of 39 kPa, 200 kPa, and 265 kPa, respectively, for the loading phases. The unloading phases of PMT curves at 1 m, 5 m, and 10 m depths showed σ'_y values of 37.3 kPa, 207 kPa, and 278 kPa, respectively, as presented in Figure 9.

Figure 8. Yield stress from TXL typical curves (loading phase) at 1 m, 5 m, and 10 m depths.

Figure 9. Yield stress from TXL typical curves (unloading phase) at 1 m, 5 m, and 10 m depths.

Constant-rate-of-strain (CRS) stress–strain curves of 1 m, 5 m, and 10 m depths are analyzed by the work method which showed σ'_y values of 33.2 kPa, 208 Pa, and 284 kPa in the loading phases (Figure 10) and 33.8 kPa, 206 kPa, and 298 kPa (Figure 11) in the unloading phases, respectively.

Figure 10. Yield stress from CRS typical curves (loading phase) at 1 m, 5 m, and 10 m depths.

Figure 11. Yield stress from CRS typical curves (unloading phase) at 1 m, 5 m, and 10 m depths.

After the evaluation of σ'_y from PMT, TXL, and CRS stress–strain curves, the pre-yield strain (ϵ_{pre}) and post-yield strain (ϵ_{post}) were determined to compare these three types of test curves.

4. Discussion

Relations between post-yield strain/yield stress [i.e., $\epsilon_{post \text{ PMT}} / \sigma'_y$] versus P_{max} (the maximum pressure observed in stress–strain curves) are presented in Figures 12 and 13 for the loading and unloading phases, respectively. The exponential rise in post-yield strain starts from $\epsilon_{post \text{ PMT}} / \sigma'_y$ values of 0.0017 (loading) and 0.00019 (unloading), which points out the P_{max} of about 201 kPa (loading) and 202 kPa (unloading).

Figure 12. Post-yield strain/yield stress versus maximum pressure (PMT loading phase).

Figure 13. Post-yield strain/yield stress versus maximum pressure (PMT unloading phase).

Figures 14 and 15 present the relations of post-yield/pre-yield strains (i.e., $\epsilon_{\text{post PMT}} / \epsilon_{\text{pre PMT}}$) versus P_{max} in the loading and unloading phases, respectively, for PMT test curves which depict that $(\epsilon_{\text{post PMT}} / \epsilon_{\text{pre PMT}})$ values abruptly increase at the value of about 6.96 (loading) and 8.47 (unloading), corresponding to a P_{max} of about 207 kPa (loading) and 213 kPa (unloading). The relations proposed in Figures 12–15 are validated by renowned past studies (Table 2) for the loading phase of pressuremeter (PMT) tests in clays.

Figure 14. Post-yield/pre-yield strain versus maximum pressure (PMT loading phase).

Figure 15. Post-yield/pre-yield strain versus maximum pressure (PMT unloading).

Figures 16 and 17 show the relations of post-yield strain ($\epsilon_{\text{post TXL}} / \sigma'_y$) versus maximum pressure ($P_{\max}$) for the loading and unloading phases, respectively, for triaxial test curves. It is observed that $\epsilon_{\text{post TXL}} / \sigma'_y$ increases in an exponential pattern after achieving the value of about 0.00075 (loading) and 0.00018 (unloading), corresponding to a $P_{\max}$ value of about 209 kPa (loading) and 203 kPa (unloading), respectively.

Figure 16. Post-yield strain/ yield stress versus maximum pressure (TXL loading phase).

Figure 17. Post-yield strain/ yield stress versus maximum pressure (TXL unloading phase).

Figures 18 and 19 show the loading and unloading phases, respectively, of triaxial test curves. Here, the $\epsilon_{\text{post}}(\text{TXL})/\epsilon_{\text{pre}}(\text{TXL})$ starts rising exponentially after attaining values of about 5.25 (loading) and 6.3 (unloading), which correspond to the $P_{\max}$ values of 209 kPa (loading) and 213 kPa (unloading), respectively. The data in Figures 16–19 are congruent to the well-documented past studies on the loading phase of triaxial tests conducted on clays (Table 3).

Figure 18. Post-yield/pre-yield strain versus maximum pressure (TXL loading phase).

Figure 19. Post-yield/pre-yield strain versus maximum pressure (TXL unloading phase).

Figures 20 and 21 present the relations of post-yield strain/yield stress (i.e., $\epsilon_{\text{post(CRS)}} / \sigma'_y$) versus maximum pressure ($P_{\max}$) for the loading and unloading phases of CRS tests. It is observed that the $\epsilon_{\text{post(CRS)}} / \sigma'_y$ increases rapidly after reaching about 0.001 (loading) and 0.001 (unloading), corresponding to the $P_{\max}$ values of about 217 kPa (loading) and 210 kPa (unloading), respectively.

Figure 20. Post-yield strain/yield stress versus maximum pressure (CRS loading phase).

Figure 21. Post-yield strain/yield stress versus maximum pressure (CRS unloading phase).

Figures 22 and 23 show that the $\epsilon_{\text{post}}(\text{CRS})/\epsilon_{\text{pre}}(\text{CRS})$ also rises rapidly after starting from about 5.2 (loading) and 5.8 (unloading), which correspond to the P_{max} values of 219 kPa (loading) and 217 kPa (unloading), respectively. The data in Figures 20–23 correspond to previous studies for the loading phase of CRS tests conducted on clays (Table 4). Figure 22 shows the scattered data up to 300 kPa maximum pressure (P_{max}) due disturbance in the compression phase for very soft to soft nature of soil, whereas Figure 23 shows more consistent results in the unloading phase.

Figure 22. Post-yield/pre-yield strain versus maximum pressure (P_{max}) (CRS loading phase).

Figure 23. Post-yield/pre-yield strain versus maximum pressure ($P_{\max}$) (CRS unloading phase).

Figures 12–23 show that the unloading phase of PMT, TXL, and CRS tests generates values of $(\epsilon_{\text{post}}/\sigma'_y)$ and $(\epsilon_{\text{post}}/\epsilon_{\text{pre}})$ close to those determined from the loading phase. Furthermore, the initiation of an exponential rise in the post-yield strain was observed at the $P_{\max}$ value, starting from 100 kPa for soft clay, and then increased for the upper layer of very soft clay which failed even at $P_{\max}$ of 36 kPa due to the high moisture content and very low dry density near ground surface. The range of 36 kPa to 100 kPa is equivalent to overburden pressure of embankment height of about 2 m to 5 m which is congruent to the range of vertical overburden pressure of most of the embankment failure cases presented in Table 1. It also shows the precision and closeness of the $P_{\max}$ values determined from different tests, such as PMT, TXL and CRS tests used in this research.

It is observed from Figures 14, 15, 18, 19, 22 and 23 that the post-yield strains (ϵ_{post}) are 3 to 14, 3.3 to 19.2, and 2.7 to 13.7 times higher in the loading phase and 4.7 to 15.9, 3.4 to 21, and 2 to 14 times higher in the unloading phase when compared with the pre-yield strains (ϵ_{pre}) for PMT, TXL, and CRS tests, respectively.

Figure 24 presents the predicted chart showing the relation of post-yield strain/yield stress ($\epsilon_{\text{post}}/\sigma'_y$) versus $P_{\max}$ for PMT, TXL, and CRS tests shown collectively. At a glance, it is observed that the ratio ' $\epsilon_{\text{post}}/\sigma'_y$ ' increases for soft clays even at low $P_{\max}$ for all the PMT, TXL, and CRS tests. Hence, for a specific value of $\epsilon_{\text{post}}/\sigma'_y$, $P_{\max}$ can be predicted for a wide range of soil stiffness, i.e., very soft to very stiff clays. If the yield stress ' σ'_y ' for the embankment is determined from any of PMT, TXL, and CRS tests, and $P_{\max}$ (maximum overburden stress) is known, then a critical and significant parameter, i.e., a post-yield strain (ϵ_{post}), can be estimated to manage the expected damage for embankment failure to save money and avoid life-threatening situations. In these situations, the failure of embankment can be averted by stopping the construction of embankment at or before the predicted value of $P_{\max}$ (i.e., a maximum overburden stress for the maximum height of embankment).

Figure 24. Post-yield strain/ yield stress for PMT, TXL, and CRS (loading and unloading phases).

Figure 25 presents the predicted collective curves which show post-yield strain/pre-yield strain trends ($\epsilon_{\text{post}}/\epsilon_{\text{pre}}$) versus P_{max} for PMT, TXL, and CRS for the loading and unloading phases. These curves are significant in the way that, on the ground, embankments may provide pre-yield strain which can initiate exponential post-yield strains. Hence, the proposed chart in Figure 25 shows that by using ϵ_{pre} and P_{max} , the post-yield strain (ϵ_{post}) can be determined for the embankments in very soft, soft, stiff, and very stiff saturated clays. The zone of exponential post-yield strain is also shown in Figure 25 where the post-yield strain increases rapidly from a $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$ value of 10 to 11 at an applied pressure of 36 kPa to 100 kPa for very soft clay to soft clay, respectively.

Figure 25. Post-yield/pre-yield strain for PMT, TXL, and CRS (loading and unloading phases).

The exponential post-yield strain was observed with very soft clay having high moisture content and very low dry density, which caused failure even when low pressure was applied, i.e., 36 kPa. Hence, the predictive correlations for the post-yield strain can be applied confidently to embankments with very soft saturated clay, as well as for soft, stiff, and very stiff clays.

It is worth mentioning that the charts in Figures 24 and 25 enable geotechnical engineers to interconvert the laboratory and in situ data for very soft to very stiff saturated clays. The in situ post-yield strains can be estimated by conducting solely triaxial or CRS tests to anticipate the behavior of saturated clay in existing embankments after failure. The yielding behavior observed in PMT, TXL, and CRS tests in the loading and unloading phases is observed to be in a narrow range, in the case of very soft and soft clay, as well as in the case of the ratio of post-yield/pre-yield strain. However, some differences are shown by stiff to very stiff clay (Figure 25). The CRS tests were conducted to evaluate yield stress against triaxial (TXL) and in situ pressuremeter tests (PMT), as mentioned in [11].

The values of pre-yield and post-yield strains are not known in the case of embankment failures; thus, correlation for post-yield strains is very important for the critical study of stability of embankments involving very soft to very stiff saturated clay. The data of past studies are used to validate this research; however, data from previous research was not used in the proposed correlations. Expedient correlations of σ'_y , ϵ_{pre} , ϵ_{post} , and P_{max} in PMT, TXL, and CRS tests for the loading and unloading phases for clays with very soft to very stiff consistency are presented in Table 5.

Table 5. Proposed correlations for post-yield strain for saturated clay.

Sr. No.	Proposed Correlation	Parameters	R ²	Test	Loading/Unloading
1	$\epsilon_{post} (PMT) / \sigma'_y = 0.537 (P_{max})^{-1.03}$	$\epsilon_{post}, \sigma'_y, P_{max}$	0.946	PMT	Loading
2	$\epsilon_{post} (PMT) / \sigma'_y = 0.011 (P_{max})^{-0.751}$	$\epsilon_{post}, \sigma'_y, P_{max}$	0.847	PMT	Unloading
3	$\epsilon_{post} (PMT) / \epsilon_{pre} (PMT) = 90.2 (P_{max})^{-0.459}$	$\epsilon_{post}, \epsilon_{pre}, P_{max}$	0.813	PMT	Loading
4	$\epsilon_{post} (PMT) / \epsilon_{pre} (PMT) = 64.0 (P_{max})^{-0.366}$	$\epsilon_{post}, \epsilon_{pre}, P_{max}$	0.814	PMT	Unloading
5	$\epsilon_{post} (TXL) / \sigma'_y = 0.216 (P_{max})^{-1.049}$	$\epsilon_{post}, \sigma'_y, P_{max}$	0.936	TXL	Loading
6	$\epsilon_{post} (TXL) / \sigma'_y = 0.012 (P_{max})^{-0.823}$	$\epsilon_{post}, \sigma'_y, P_{max}$	0.888	TXL	Unloading
7	$\epsilon_{post} (TXL) / \epsilon_{pre} (TXL) = 125 (P_{max})^{-0.561}$	$\epsilon_{post}, \epsilon_{pre}, P_{max}$	0.810	TXL	Loading
8	$\epsilon_{post} (TXL) / \epsilon_{pre} (TXL) = 156 (P_{max})^{-0.576}$	$\epsilon_{post}, \epsilon_{pre}, P_{max}$	0.785	TXL	Unloading
9	$\epsilon_{post} (CRS) / \sigma'_y = 0.085 (P_{max})^{-0.755}$	$\epsilon_{post}, \sigma'_y, P_{max}$	0.834	CRS	Loading
10	$\epsilon_{post} (CRS) / \sigma'_y = 0.143 (P_{max})^{-0.903}$	$\epsilon_{post}, \sigma'_y, P_{max}$	0.865	CRS	Unloading
11	$\epsilon_{post} (CRS) / \epsilon_{pre} (CRS) = 139.3 (P_{max})^{-0.581}$	$\epsilon_{post}, \epsilon_{pre}, P_{max}$	0.750	CRS	Loading
12	$\epsilon_{post} (CRS) / \epsilon_{pre} (CRS) = 146.7 (P_{max})^{-0.582}$	$\epsilon_{post}, \epsilon_{pre}, P_{max}$	0.812	CRS	Unloading

PMT = pressuremeter; TXL = triaxial; CRS = constant-rate-of-strain consolidation.

A regression index for proposed correlations is reasonable for PMT, TXL, and CRS tests. The yield stress (σ'_y) is the initial point and the P_{max} is the last point of the stress–strain travel for post-yield strain; hence, both the stresses play a key role in the failure phenomenon of soft clay in embankments. This study shows that ϵ_{pre} and ϵ_{post} evaluated from the unloading phase of clay are equally precise, as observed in the loading phase. Charts are developed to serve the inter-conversion of in situ and laboratory test results for expedient evaluation of in situ post-yield strains (ϵ_{post}) for embankments comprising saturated clay, especially very soft to soft clay.

An individual site comprising lean clay with a range of PI from 28 to 38, dry density from 1.362 g/cm³ to 1.675 g/cm³, and MC from 26% to 38% was investigated by PMT, TXL, and CRS tests. Six boreholes were drilled to retrieve undisturbed samples (UDS). Prebored in situ PMTs were performed at six points. It was observed that the GWT of a separate site was stable at 11.2 m. The soil strata were found to be very soft to very stiff.

The results from Figures 12–23 show that for the pressure level $P_{max} < 300$ kPa, the data are distributed in a wider range; thus, there was lower accuracy (i.e., lower R²) in this zone, i.e., in a zone up to 5 m deep, which comprises very soft clay to soft clay. These strata are considered to be critical in sample extrusion, in sample preparation, and in the loading stage; hence, they are prone to some disturbance, showing scattered values of resulting strains which lowers the R² value in the zone of very soft to soft clay.

The proposed empirical equations can only be used for approximation of post-yield strain for prior to embankment failure and to take precautions to avoid damages of a post-failure situation. These equations are presented for very soft to very stiff range of clay; hence, the R^2 values are less. These equations have limitation to the precise design of embankment for which specific testing program on site and laboratory is required for specific consistency of soil i.e., very soft, soft, stiff, or very stiff.

The application of the zone of critical post-yield strain (ϵ_{post}) will help to augment the existing knowledge of failure of embankments constructed on very soft to soft clay strata. It will also help to achieve sustainable and long-lasting design, durable/sustainable construction of embankments, and a major reduction in embankment failures due to pre-emptive measures taken by using the zone of critical strain. The proposed equations can be used for the approximation of post-yield failure strain of clays with a plasticity index (PI) ranging from 19% to 31%.

The PI level affects the undrained shear strength of clays significantly [84]. The results of this study shown in Figures 12–23 are validated by previous studies mentioned in Tables 1–4. The past research selected for the validation covers the plasticity index (PI) of the clay investigated in this study. Ref [85] described that the increase in plasticity index (PI) causes an increase in the shear strength of clay. Ref [86] argued that the undrained shear strength of clay decreases with an increase in the initial moisture content. In the present study, the strata with a high plasticity index (PI), i.e., from NSL to 2 m depth, showed lower strength due to high moisture content, as observed in soil samples recovered from field, as the governing factor for the shear strength of clays is the moisture content. For the same level of plasticity, the clays show a low shear strength on high level of moisture content, i.e., soft clays. From NSL to down up to 10 m depth, the PI is reduced; however, the decrease in moisture content and increase in dry density caused an increase in the shear strength of soil. Hence, this study showed effect of PI in combination with field moisture and dry density. The proposed correlations can be used for the clays of a specific range of PI investigated in this research.

The anisotropic stress state of soil was determined by the use of a pressuremeter, by evaluating horizontal stress alongside the expansion of the membrane and vertical stress from the effective overburden pressure. This anisotropic stress state was used to define the lateral stress to be applied in triaxial tests. This aspect is mentioned in [85].

The soil consistency classification mentioned in Figure 4 for the clay investigated in this research is based on a description in [87]. Hence, this study can be used for very soft to very stiff clays to design and construct embankments. It is worth mentioning that the post-yield strain can also be an issue, causing failure of natural slopes across many railways and roadways, as reported in site investigation by [88].

Figures 26 and 27 show the measured versus predicted data sets of $\epsilon_{\text{post}}/\sigma'_y$ and $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$, respectively, for PMT, TXL, and CRS tests, which validate the data of this research. The measured versus predicted data sets fall within a line of equality of $\pm 10\%$. The cost-effective and prompt prediction of post-yield strains suggests that the geotechnical community are required to carry out stability analysis of embankments on very soft to soft clays. The analysis of soft clay strata is a hot issue in relation to sustainable embankment design [89–91].

Figure 26. Measured versus predicted post-yield strain/yield stress for PMT, TXL, and CRS (loading and unloading phases).

Figure 27. Measured versus predicted post-yield/pre-yield strain for PMT, TXL, and CRS (loading and unloading phases).

5. Conclusions

The following conclusions can be drawn from the results and analysis of this study.

- (1) Characterization of saturated clay stratum by PMT, TXL, and CRS tests presents that stress–strain curves can be used to evaluate the yield stress (σ'_y), the pre-yield strain (ϵ_{pre}), and the post-yield strain (ϵ_{post}). This infers that the $\epsilon_{post}/\epsilon_{pre}$ ranges from 2.7 to 19 in the loading phase and 2 to 21 in the unloading phase. An exponential increase

in $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$ was observed in very soft to soft clay stratigraphy at the values in range of 10 to 21 (a critical range), which is congruent with the range of 4 to 30 found in renowned embankment failure cases of saturated clays worldwide. Application of the critical strain (ϵ_{post}) zone will help to augment the existing knowledge of failure of embankments constructed on very soft to soft clay strata, and will help to achieve sustainable and long-lasting design and construction of embankments.

- (2) This study showed that increase in maximum applied pressure (P_{max}) (which corresponds to height of embankment) causes an increase in the post-yield strain (ϵ_{post}) in very soft to very stiff clay. This inference can be used for prediction of exponential post-yield strain (leading to embankment failure) by the use of embankment height.
- (3) The zone of exponential development of critical post-yield strain was observed for the maximum applied pressure (P_{max}) ranging from 36 kPa to 100 kPa, corresponding to very soft and soft clay, respectively. It is worth mentioning that pressure ranging from 36 kPa to 100 kPa corresponds to the approximate embankment height of 3 m to 5 m, which is observed as a common height in embankment failure cases worldwide.
- (4) Simplistic and expedient correlations are proposed for $\epsilon_{\text{post}}/\sigma'_y$ and $\epsilon_{\text{post}}/\epsilon_{\text{pre}}$ versus P_{max} for PMT, TXL, and CRS tests, as the yield stress (σ'_y) and the pre-yield strain (ϵ_{pre}) are precursors of abnormal development of post-yield strain. To benchmark this research, the proposed correlations are validated by past studies on PMT, TXL, and CRS tests for very soft to very stiff saturated clay. Variations in predictions versus the experimental data of an individual site are observed to be within $\pm 10\%$ of the 1:1 line.
- (5) The proposed correlations are developed on the basis of limited test data for a specific soil, i.e., saturated clay. Hence, these correlations may not work well in other soils of different origins and index properties.

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