

THE EFFECT OF UNLOADING AND RELOADING ON THE COMPRESSION BEHAVIOUR OF RECONSTITUTED CLAYS

*Farzad Habibbeygi and Hamid Nikraz

Faculty of Science and Engineering, Curtin University, Australia

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ABSTRACT: Oedometer tests were carried out on reconstituted clays to investigate the compressibility of soft clays with high initial water content under repetitive cycles of unloading/reloading. It is necessary to estimate the compression indices under repetitive loadings to predict the settlement of clayey layers. The results indicate that the unloading/reloading loop can be represented by a bi-linear line in a semi-logarithmic plane with three definite slopes (compression indices). Furthermore, the compression indices of unloading and reloading can be estimated using the compression and swell indices with reasonable accuracy. The reloading part can also be defined by two initial and final slopes. The difference in these two aforementioned slopes can be explained by the balance of physico-chemical and mechanical forces. When the consolidation stress is less than the remolded yield stress, the compression behavior is mainly controlled by the physicochemical effect. In fact, the change in the clay micro-structure is small; however, for stresses greater than remolded yield stress, the soil structure demolishes and the clay microstructure is completely affected. Consequently, the mechanical force controls the deformation which results in a sharp decrease in the void ratio .

Keywords: Reconstituted clays, Unloading/reloading cycles, Consolidation, Expansive, Compressibility.

1. INTRODUCTION

Soft clayey soils may experience cycles of unloading/reloading over decades for several reasons, such as preloading, stage construction, natural phenomena (e.g. shifting rivers, heavy rainfalls, drought) and groundwater fluctuation (e.g. dewatering and pumping for industrial or agriculture uses). The ongoing consolidation of these soft clayey deposits can lead to catastrophic problems in many metropolitan areas all over the world [1-3]. In some situations, even though external conditions influenced by humans are controlled, the groundwater still changes due to natural phenomena such as gradual changes in river alignment, heavy rainfall, drought, and so on; as a consequence, fluctuations in groundwater are often inevitable. The groundwater fluctuations induce cycles of unloading/reloading which results in irreversible deformation in clayey soils. Understanding the volumetric behavior of soft clayey soils in loading and unloading/reloading conditions can help engineers to predict the settlement (permanent and temporary deformation) of clayey deposits more accurately and to design an appropriate method to mitigate the damage to infrastructures.

Numerical modeling is a useful method to forecast the settlement of the clayey soils. An elastoplastic model is a simple model used to predict the behavior of the clayey deposit during consolidation; however, the estimated settlement

values with such simple models are not very accurate and can be over- or under-estimated, especially when complex conditions such as unloading and reloading occur. Recently, some more elaborate models have been developed to predict the ground deformation in such cases [4-8].

Experimental laboratory tests can be used to monitor the volumetric behavior of soft clays in cycles of loading, unloading and reloading. Based on the results of oedometer tests, the plastic deformation induced during the repetitive loads can be investigated. In this study, one-dimensional consolidation tests on reconstituted clayey samples with high initial water content were conducted under repetitive unloading and reloading conditions to investigate the compression behavior of the studied clay. Additionally, the consolidation tests were undertaken for various initial water contents to study the influence of this parameter on the results.

2. SAMPLE PREPARATION AND TEST PROCEDURES

2.1 Test Procedure and Materials

Five series of one-dimensional consolidation tests were conducted on reconstituted specimens to study the compression behavior of soft clays with high initial water content under several cycles of loading and unloading. Six different initial water content ratios (i.e. $w_0/w_L = 0.6, 0.7, 0.8, 0.9, 1.0,$ and 1.1) were adopted to investigate the effect of

Table 1 Vertical pressure increments and cycle of loading/reloading in oedometer tests

Sample ID	Initial Water Content Ratio (w_0/w_L)	Loading/reloading Cycle	Vertical Consolidation Pressure Increments (kPa)
1	0.8	Cycle 1	1, 3, 6, 12.5, 3
		Cycle 2	6, 12.5, 25, 50, 100, 25, 6
		Cycle 3	12.5, 25, 50, 100, 200, 400, 100, 25
		Cycle 4	50, 100, 200, 400, 800, 200, 50
		Cycle 5	100, 200, 400, 800, 1600
2	0.9	Cycle 1	1, 3, 6, 12.5, 3
		Cycle 2	6, 12.5, 25, 50, 100, 25, 6
		Cycle 3	12.5, 25, 50, 100, 200, 400, 100, 25
		Cycle 4	50, 100, 200, 400, 800, 200, 50
		Cycle 5	100, 200, 400, 800, 1600
3	1.0	Cycle 1	1, 3, 6, 12.5, 3
		Cycle 2	6, 12.5, 25, 50, 100, 25, 6
		Cycle 3	12.5, 25, 50, 100, 200, 400, 100, 25
		Cycle 4	50, 100, 200, 400, 800, 200, 50
		Cycle 5	100, 200, 400, 800, 1600
4	1.1	Cycle 1	1, 3, 6, 12.5, 3
		Cycle 2	6, 12.5, 25, 50, 100, 25, 6
		Cycle 3	12.5, 25, 50, 100, 200, 400, 100, 25
		Cycle 4	50, 100, 200, 400, 800, 200, 50
		Cycle 5	100, 200, 400, 800, 1600
5	1.2	Cycle 1	1, 3, 6, 12.5, 3
		Cycle 2	6, 12.5, 25, 50, 100, 25, 6
		Cycle 3	12.5, 25, 50, 100, 200, 400, 800, 1600, 400, 100

initial water content on the results.

All samples were bulk collected from an under-developed suburb, south of the capital of Western Australia, Perth. X-ray diffractometer test results show that the dominant clay mineral of the studied soil is smectite [9]. Index tests undertaken on the samples, in accordance with ASTM D4318, show high values of Atterberg limits (liquid limit and plastic limit - $w_L = 82\%$ and $w_p = 35\%$ respectively) [10]. High values of liquid limit (i.e. 82%) and plasticity index (47%) result in high the potential of expansion and shrinkage with water content fluctuation. The specific gravity of the studied soil was measured using a hydro-pycnometer and assessed to be 2.60 (ASTM D854). More than 65% of the studied soil comprised clay; 20% sand; and the remainder was silt (ASTM D1140). As the colour of collected samples were dark grey to black, the studied clay is herein referred to as 'black clay'. The normalised shear strength of the black clay is measured to be between 0.25 and 0.5 [11].

2.2 Sample preparation

Sample preparation in this study followed the sample preparation procedure proposed by Head [12] for reconstituted samples. Firstly, all collected samples were dried at 105°C in the oven for at least 48 hours. Since samples were completely wet during collection, the constant weight method was

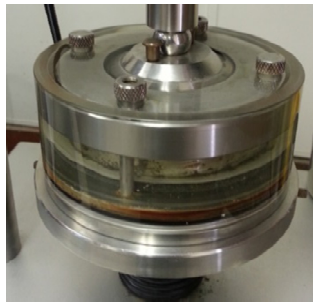
used to make sure that samples were fully dried before sample preparation. Secondly, some homogenous powder was prepared by grinding the oven-dried materials, then passing them through a 2.36 mm sieve. Later, a predefined volume of water was added to the clayey powder and mixed thoroughly for at least 15 minutes to prepare a homogenous slurry. The slurry was kept in several air-tight bags for more than 24 hours before consolidation tests. One-dimensional consolidation tests were performed on specimens prepared from the slurry in accordance with the incremental loading procedure (ASTM D2435). The wall of consolidation steel ring was covered by a thin layer of silicone grease to reduce friction and mitigate the effect of the ring on the results. One-dimensional consolidation tests were carried out by an automotive oedometer on specimens with a size of 63.5 mm diameter and 31 mm height. Specimens were drained in both upward and downward directions during the consolidation process by placing two porous stones with paper filters at the top and bottom of the specimen. Fig. 1 shows the set-up of the test and auto-consolidation apparatus used in this study. Table 1 presents the vertical consolidation stress and the related cycle of loading/reloading for each sample.

3. DISCUSSION AND RESULTS

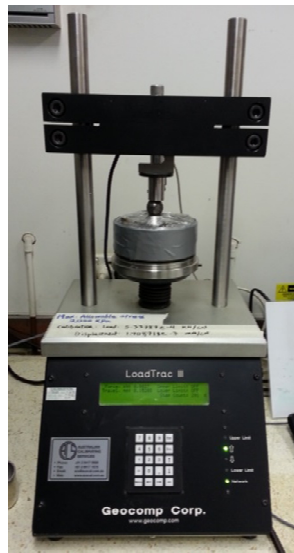
Fig. 2 presents the definition of compression

indices for a cycle of unloading/reloading. As shown, the slope of a Virgin Compression Line (VCL) is denoted as C_c ; the slope of the unloading (swelling) line is C_s ; the initial and final slopes of the reloading line are C_r and C_{rc} , respectively.

Fig. 3 shows the results of consolidation tests on the black clay (i.e. $e - \log \sigma'_v$ curves in a semi-logarithmic scale) under repetitive cycles of unloading and reloading (3 to 5 cycles).



(a)



(b)

Fig. 1. Consolidation test set-up (a) Consolidation cell (b) Auto-consolidation apparatus

The results of simple consolidation tests on the samples, including single loading and unloading, at the last stage of loading, are also replotted on the figure for comparison. As shown, the reloading curve of the consolidation curves is converging to the VCL and coincides with the VCL for stresses greater than the maximum applied consolidation stress before unloading. Fig. 3 also shows that the VCL is almost linear for a wide range of consolidation stresses (i.e. 50 – 800 kPa). Moreover, the unloading part of loading/reloading curves is linear for all initial water contents, which is in agreement with the results of other researchers for soils under a cycle of loading and reloading [4]; however, the unloading part for the

single loading/reloading graphs is clearly non-linear for a stress of 1600 kPa. The slope of the unloading line for a constant value of initial water content is almost the same for different cycles of unloading independent of the number of cycles.

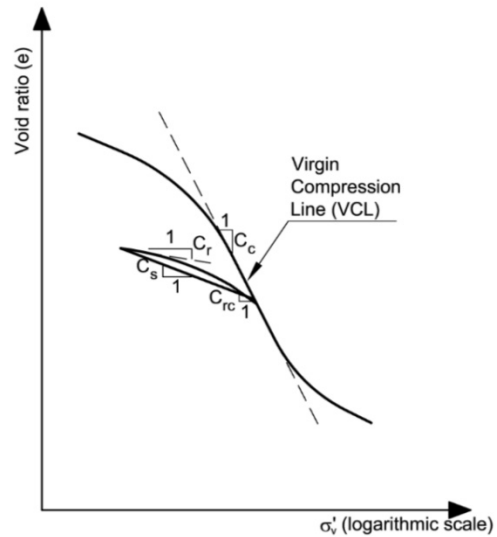


Fig. 2. Compression indices definition on a semi-logarithmic plane

The results of consolidation tests can be used directly to measure the compression indices; for instance, the compression indices measured using compression curves for $w_0/w_L = 1.0$ are shown in Table 2.

Table 2 Compression indices for $w_0/w_L = 1.0$

Cycle	C_c	C_s	C_r	C_{rc}
1	-	0.0452	0.0450	0.0445
2	0.5756	0.1004	0.0230	0.1957
3	0.5746	0.1205	0.0281	0.1954
4	0.5750	0.1264	0.0290	0.1955
Single loading	0.5748	0.0950	0.0282	0.1897

As can be seen, the compression reloading indices for the reloading/loading cycles are nearly consistent; however, the compression indices for the first cycle is far less than for the other cycles. The reason can be found in the change of the structure of clays with the increase of consolidation stress. It states that there is a definite structure for the studied clay even at the initial stage. Furthermore, the deformation in the initial stage is reversible and the soil behaves almost linearly elastic. Subsequently, when the deformation increases gradually with the increase in consolidation stress, the structure weakens.

Then, it increases sharply when the clayey sample de-structures. The results also show that the unloading/reloading compression curve is a hysteresis loop. In fact, the unloading (swell) part is almost linear, but the reloading part is clearly non-linear. It is understood that irreversible deformation is controlled by the orientation of clay particles. Moreover, the balance of mechanical and physicochemical forces governs the volumetric behavior of clayey soils [13]. The compressibility of clayey soils is controlled by physicochemical forces when the clay particles are parallel. On the other hand, compressibility is more affected by mechanical forces when the contact of clay particles are more skewed relative to each other [13]. As shown in the compression curves, the swell occurs during unloading and is mostly controlled by physico-chemical forces. The higher void ratios under unloading show the higher repulsion caused by the parallel orientation of the clay particles. This reasoning also explains how a small change in the void ratio (i.e. volume decrease) in the reloading stage is a result of balancing external loads with the repulsive force. Afterward, when the external force exceeds the repulsive force (i.e. the consolidation stress is greater than the remoulded yield stress), it results in higher deformation and a steeper slope of the compression curve. At stress levels greater than the yield stress, the behaviour is mainly controlled by mechanical effects; correspondingly, this phenomena is repeated for each cycle of the unloading/reloading loop.

Based on Table 2, it can be concluded that compression indices can be estimated using the compression and unloading indices as follow:

$$C_r = 0.23C_s \quad (1)$$

$$C_{rc} = 0.34C_c \quad (2)$$

Similarly, Eqs. 1 and 2 can estimate the reloading compression indices for the other initial water content ratios (i.e. $w_0/w_L=0.8, 0.9, 1.1$ and 1.2). As shown in Fig. 4, the VCL of the studied clay in both single loading/reloading and multiple cycles of loading/reloading are not completely linear, especially when the consolidation stress increases and reaches the higher stress levels (i.e. greater than 800 kPa). This result can be explained by the de-structuring effect as the reconstituted samples lose their micro-structure during the sample preparation procedure. This result is in good agreement with other experimental tests on various reconstituted clays which support the idea that the VCL is non-linear [9, 14-15].

The results also show that plastic deformation (irreversible void ratio) occurs when the consolidation stress is greater than a specific stress level. This specific stress level was named as the preconsolidation stress for natural clays; however,

for the purpose of clarifying between natural and reconstituted clays, this definite stress level is referred to as remoulded yield stress (σ'_{yr}) [9, 16]. There are several methods to estimate the remoulded yield stress for reconstituted clays. One of the most used methods is to replot the compression index on a bi-logarithmic plane and present the compression line with two straight lines in this space; the intersection of these two lines (i.e. pre-yield and post-yield stages) defines the remoulded yield stress [17].

The bi-linear compression curves for various initial water content were plotted on Fig. 4 ($\ln(1+e)$ vs $\log \sigma'_v$). As shown, the bi-linear technique can be employed to predict the value of remoulded yield stress of reconstituted clays with reasonable accuracy. Findings depict how the compression index increases slightly with an increase in initial water content ratio (w_0/w_L); however, the variation is not significant. The compression index for initial water content ratios greater than 1.0 is almost constant, which is in agreement with Burland [18].

4. CONCLUSIONS

Oedometer tests were carried out with repetitive unloading/reloading cycles on reconstituted samples of black clay from Western Australia. The effect of loading/unloading/reloading on compression curves has been explained in this paper by using the mechanical and physicochemical effects. The oedometer tests were undertaken on reconstituted samples with different initial water contents to investigate the influence of water content in the preparation stage (i.e. $w_0/w_L = 0.6, 0.7, 0.8, 0.9, 1.0$, and 1.1). The following conclusions are drawn to interpret the findings:

- Deformation is reversible for stresses smaller than the initial remoulded yield stress of the reconstituted samples, at very low-stress levels. Moreover, the reloading compression indices are almost constant for the very first reloading stage, while being far smaller than the reloading indices of the other cycles.
- The balance between the physicochemical and the mechanical effects controls the volumetric behavior of clayey soils. When the stress level is less than the remoulded yield stress, compressibility is governed by the physicochemical effect. The compressibility is governed by mechanical forces when the consolidation stress exceeds the remoulded yield stress.
- The swell (unloading) index for the first cycle is 45% and 38% of the one for cycles 2 and 3 respectively.
- The final reloading index for the first cycle is

approximately 22% of the one for the cycles 2 to 4.

- Rebound compression indices of the reloading stage can be estimated with good accuracy using the compression and swell indices.
- The bi-logarithmic technique can be used to

derive the remolded yield stress of reconstituted clays both for single loading and multiple unloading/reloading conditions.

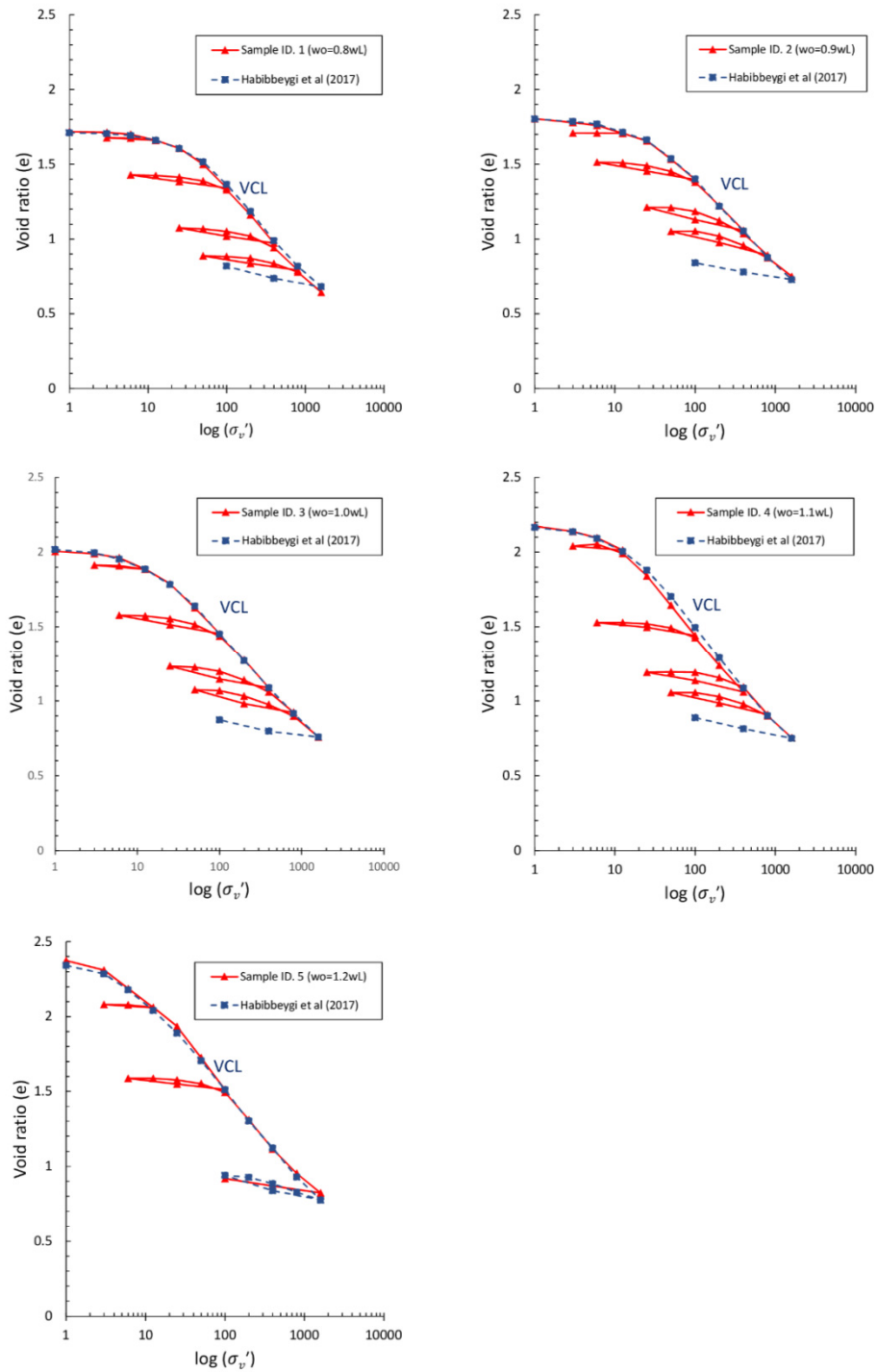


Fig. 3. Oedometer test results with unloading/reloading on the black clay

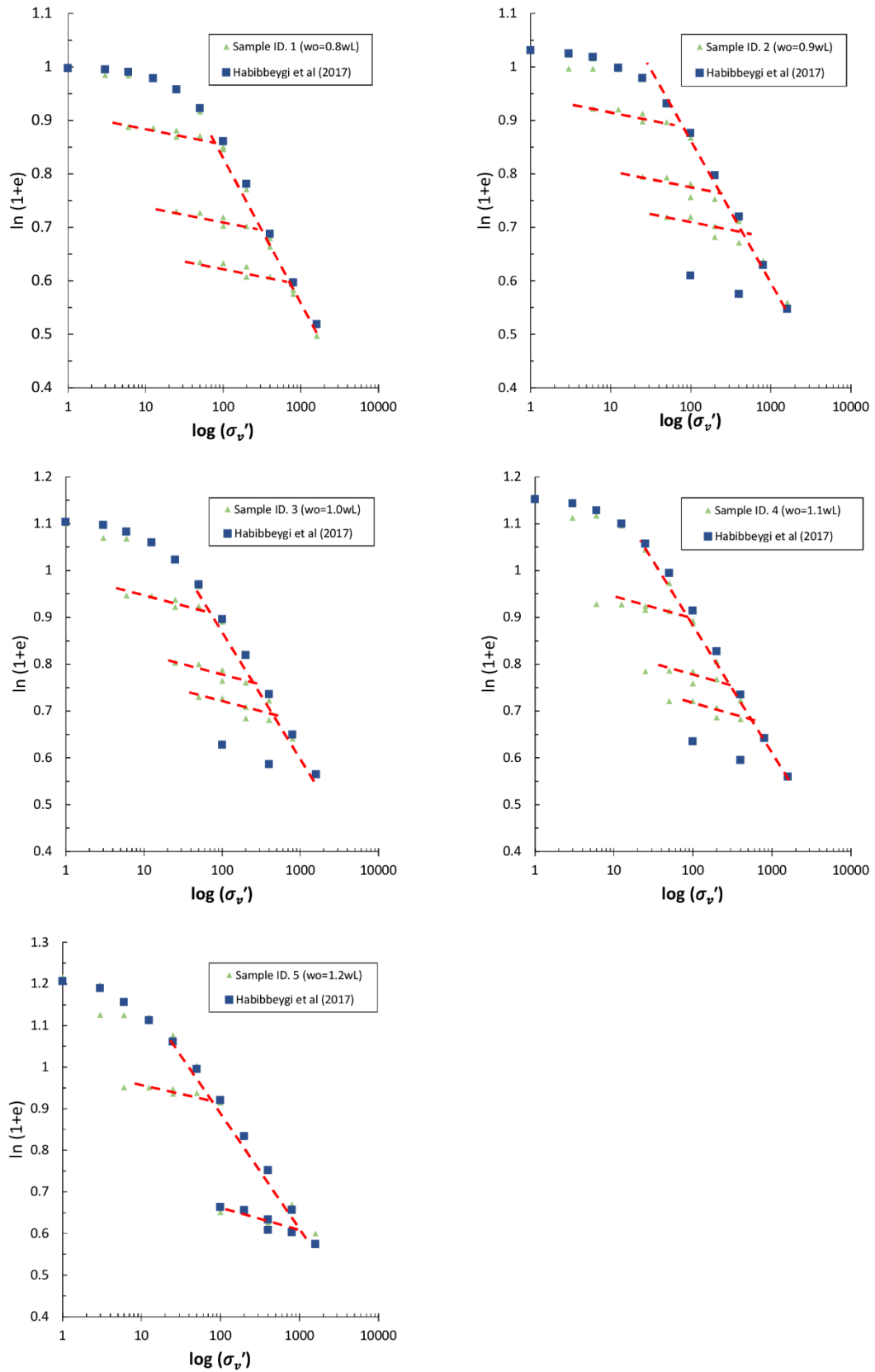


Fig. 4. Oedometer test results with unloading/reloading

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