The Performance of a Diaphragm type Boundary Pressure Transducer under Cyclic Loading

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Abstract

Investigation of soil-structure interaction involves understanding of the complicated rheology, and functioning of the pressure sensing devices. As earth pressure cell (EPC) output is used to interpret the stress in the soil at the point of installation of cell, experiments involving careful calibration of the pressure cells are very crucial. In view of the importance of in-soil calibration, the present study is focused on developing a relation between the applied stress and the measured output, when the soil is subjected to cyclic loading. The effect of soil type and its thickness on pressure cell output under cyclic loading is studied using two types of soils, viz. sand and Kaolin, and soil layer thickness in the range of $0.25D_{EPC}$ - $2.5D_{EPC}$, where D_{EPC} is the diameter of the EPC. In-soil calibration under the application of cyclic loading demonstrated substantial hysteresis and reduction in the EPC sensitivity. Increase in residual stresses is observed to increase with soil thickness, after the first cycle. It is also observed that the critical thickness for a given EPC is not a unique value, but varies with soil type.

Keywords: boundary earth pressure cell, cyclic loading, soil thickness, soil type

1 Introduction

Precise assessment of the stresses at the soil-structure interface and their changes due to various surrounding activities, such as nearby construction, pavement load [1], blasting [2], etc. is important for a good engineering design. Earth pressure cells (EPC) are used mainly under highway embankments, in earthen dams, on retaining walls and below foundations [3], to know the state of stress at the point of installation. As EPC output, generally obtained in terms of millivolts (mV), micro strain (με) or resistance (Ω), is used to interpret the stress condition, experiments involving the EPC calibration are very important. In order to obtain proper information about the stress at the point of installation, precise correlation between the applied pressure and the pressure sensed by the transducer is desired. The fluid calibration helps in assessing the instrument's physical condition; however, utilizing the fluid calibration for interpretation of the EPC output in soils can often lead to incorrect measurements [4]. In principle, when the modulus of the EPC diaphragm is greater than the modulus of the soil medium, the stress sensed by the EPC is higher than the free-field stress, termed as 'passive arching', and results in over-registration of the cell output [5]. On the other hand, when the modulus of the EPC diaphragm is smaller than that of the soil medium, the stress sensed by the EPC is smaller than the free-field stress, referred to as 'active arching', and results in under-registration of the cell output [5]. Most importantly, active/passive arching occurs in soil over deformable diaphragm of the EPC, and results in under/over-registration of the EPC output.

Laboratory in-soil calibration of the EPC involves placement of the EPC at the base of a stiff-walled chamber filled with a layer of sand, with a thickness of 3-5 times the diameter of the EPC, and subjecting it to uniform vertical pressure [6]. During this process, substantial hysteresis is generally observed in loading-unloading cycles [7-8]. In general, during cyclic loading, the observed output of an EPC for successive cycles is less compared to the first loading cycle with some hysteresis in the output [7-12]. The possible causes of non-linear response of EPC during cyclic loading are: 1) soil densification and subsequent increase in the modulus of deformation [2]; 2) formation of soil arch and pockets of denser soil around the cell during installation procedures or during previous loading cycles [11, 13]; 3) friction between the sand and the calibration chamber walls, where the sand grains lock and retain some amount of previously applied stress, causing increase in the residual strain and stresses [9-10, 14]; and 4) process of cyclic densification influencing the strength and the stiffness properties of the granular materials [8, 15-16]. Typically, the first load cycle data are used during in-soil calibration of the EPC, as field projects often do not involve repeated loading [6]. However, there are many practical situations like road and rail embankments, integral bridge abutments, reciprocating machine foundations, storage tank foundations, offshore and wind turbine foundations, etc., where the foundation soil is subjected to extended periods of cyclic loading [17]. Hence, in order to reliably measure the pressure in these conditions, it is essential to understand the behavior of the EPC under cyclic loading.

Another important factor affecting the pressure cell output is the thickness of the soil layer above the pressure cell. Past studies revealed that for a soil thickness less than D_{EPC} (where, D_{EPC} is the diameter of the EPC), the cell output was inconsistent and under-registered for the same input pressure, probably due to non-uniform vertical pressure on the base of the test container [8, 18]. On the other hand, for soil thickness greater than D_{EPC}, the cell output depicted minimum arching effect and better sensitivity [19-22]. However, further increase in soil thickness resulted in reduction of the EPC output and more pronounced hysteresis during the unloading phase, due to increase in the side friction [10]. In relation to the EPC, the critical soil thickness is defined as the minimum soil thickness, beyond which no further arching will develop, when the peak shear strength of the soil is mobilized. The critical thickness would vary depending on the stiffness of the diaphragm of the EPC, and the soil type. Using the modified triaxial setup and large calibration chamber tests, the effect of soil thickness on the pressure cell output was evaluated and the critical soil thickness was observed to be less than D_{EPC} [5] and 1.5 D_{EPC} [23], respectively, under static loading.

It is worthy to mention that soil arching, soil type, soil thickness and stiffness of the EPC diaphragm would not influence the EPC output, if the EPC working on the null-principle is adopted [8]. In this type of EPC, the diaphragm deformation due to applied soil pressure is nullified by applying air pressure to the cylindrical volume behind the diaphragm and the earth pressures can be measured precisely. Use of the EPC working on null principle helps to obtain a similar response during loading and unloading, for loading frequencies of 1 Hz or less, such as ocean wave loading. However, for higher frequency cyclic loading, such as seismic loading (frequency 2-3 Hz) and railway loading (frequency 8-10 Hz), the EPC based on the null-principle is of limited use. In addition, the requirement of an advanced air compressor makes the system complicated and uneconomical.

2 Background and motivation

Study of past literature highlighted that while in-soil performance of the EPC subjected to static loading is well understood, the knowledge on behavior of the EPC under cyclic and/or dynamic loading is sparse, in spite of wide usage of the EPC to study the soil-structure interaction phenomena during dynamic loading. In addition, the effect of soil type and soil layer thickness on the EPC calibration under cyclic loading has not received much attention. Earth pressure cell working on the null-principle is certainly useful for frequencies less than 1 Hz, however, due to their inefficiency at higher frequencies, the commercially available EPCs with stiff diaphragm are still a popular choice. In view of the above, the present study is aimed at investigating the effect of soil type and soil layer thickness on the behavior of diaphragm type EPC during cyclic loading, and to enhance the understanding of the EPC performance.

3 Test Apparatus and procedures

In the present study, commercially available diaphragm type boundary earth pressure cells (Haris Make, 200 kPa capacity) of 40 mm diameter were used. A calibration device, as shown in Fig. 1, developed by modifying a conventional triaxial apparatus [25], was used to calibrate the EPC in the present study. A stiff plastic tube (2.5 mm thickness and 100 mm internal diameter) was placed tightly on the brass pedestal to retain the sand/clay during testing. The EPC was installed in such a way that its diaphragm was flushed with the top surface of the pedestal. Greased polyethylene sheets of 60 μm thickness were pasted on the inner surface of plastic tube in order to reduce the friction between the soil particles and internal surface of the plastic tube.

Considering D_{EPC} as reference, a series of experiments were carried out by placing soil layer thicknesses of 10 mm ($0.25D_{EPC}$), 20 mm ($0.5D_{EPC}$), 40 mm (D_{EPC}), 60 mm ($1.5D_{EPC}$) and 100 mm ($2.5D_{EPC}$) above the EPC. A rigid wooden block followed by a rubber pad was placed on the soil layer for transfer and uniform distribution of pressure between the loading ram of triaxial apparatus and the EPC, as shown in Fig. 1. In order to increase/decrease the pressure applied to the soil layer, upward/downward movements (incremental displacement) were applied to the base of triaxial apparatus. The applied displacement resulted in pressure application to the wooden block and finally to the EPC through loading ram. The pressure applied to the soil layer and induced strains in the EPC were continuously monitored. Application of manual displacement facilitated better control over the applied pressure compared to motorized displacement, as the rate of change in pressure was not in linear agreement with the rate of application of displacement. The calibration studies were carried out to maximum applied stress of 180 kPa. Cyclic loading was applied in the form of sequential incremental static loading and unloading, to account for the soil nonlinearity, as this procedure help to understand the detailed behavior under a particular cycle of loading [26]. Pressure was applied in increments of 20 kPa from the initial reading of 0 kPa to 180 kPa and decrement of 20 kPa in similar pattern. The EPC output was set to zero before the start of each experiment to nullify the effect of placement and overburden stresses on the EPC output. This study was restricted to five loading-unloading cycles, as it was observed from the preliminary findings that after five cycles the differences between the EPC output were quite marginal. Two soils, viz., sand and Kaolin, with quite different particle size distributions were used in this study, to demonstrate the influence of their in-soil and fluid calibration response. Several trials were conducted using fluid calibration and in-soil calibration with sand and Kaolin, and the deviations among these trial results were very insignificant, and there exist high repeatability of the results. In view of the above, only results from one set of experiments were presented in the following section.

4 Results and Discussion

In the present study, a series of calibration experiments were performed using sand and Kaolin for thicknesses in the range of 0.25 D_{EPC} to 2.5 D_{EPC}. Performance of the EPC under applied pressure in the range of 0-180 kPa was monitored for five consecutive loading-unloading cycles, and the results are presented in Figs. 3-4. Performance of the EPC subjected to cyclic loading with sand layer thickness less than D_{EPC} is shown in Fig. 3 (a-b). For sand layer thickness of 0.25 D_{EPC}, the response of the EPC was non-uniform and inconsistent as no definite trend in cell behavior was noted. For example, considering an applied pressure of 60 kPa, percent changes in the EPC output between cycles 1 & 2, 2 & 3, 3 & 4, and 4 & 5 were observed to be 87%, 18%, 10% and 2.5%, respectively. Furthermore, for an applied pressure of 120 kPa, these values were 13%, 9%, 5% and 3%, respectively, and for applied pressure of 180 kPa, these were 11%, 2%, 2% and 2%, respectively. Calibration studies using sand layer thickness of 0.25 D_{EPC} might have resulted in stress concentration around the EPC causing uneven settlement on the pedestal surface due to difference in stiffness between the pedestal material and the diaphragm of the EPC [10]. This mechanism may also cause hysteresis in the EPC response, due to loading-unloading process. This non-uniform transfer of pressure due to arching in sand over the EPC diaphragm and partial mobilization of shear strength of the soil would probably result in inconsistent behavior [10, 19-22].

For sand layer thicknesses of 0.5 D_{EPC} and D_{EPC}, the EPC response to the first loading cycle was different from that of the second and subsequent loading cycles. The EPC output for sand layer thickness of 1.5 D_{EPC} was quite consistent for the first and subsequent loading-unloading cycles, and almost no reduction was noted in the EPC output. For example, for an applied pressure of 60 kPa, percent changes in the EPC output between cycles 1 & 2, 2 & 3, 3 & 4, and 4 & 5 were observed to be 1%, 2%, 1% and 1.5%, respectively. Further, for applied pressure of 120 kPa, these values were 1%, 2%, 1% and 1%, and for applied pressure of 180 kPa, these were 2%, 1%, 2% and 0.2%, respectively. Thus, soil layer thickness of 1.5 D_{EPC} may be regarded as the critical thickness of sand for the EPC used in this study. With further increase in sand layer thickness to $2.5D_{EPC}$, the EPC output was reduced, which may be attributed to material stiffening, particle re-orientation, and stress accumulation. In case of cyclic loading, during the unloading phase, the soil retains a part of applied stress and becomes substantially stiffer than that during the loading phase. Further, the compaction effect of cyclic loading causes an increase in the density of material by re-orientation of sand particles [4, 27].

In-soil calibration studies with sand layer revealed significant under-registration and hysteresis in the EPC output compared to that of fluid calibration, mainly during loading cycles [4, 10]. For example, for the first loading cycle with sand layer thickness of 0.25 D_{EPC}, cell output was under-registered by 288%, 78% and 40% for applied pressures of 60 kPa, 120 kPa and 180 kPa, respectively. Also, with sand layer thickness of 2.5 D_{EPC}, cell output was under-registered by 20%, 50% and 71% for applied pressures of 60 kPa, 120 kPa and 180 kPa pressures, respectively. In addition, for thicknesses of 0.5 D_{EPC}, D_{EPC} and 1.5 D_{EPC}, the EPC output was lower than that of fluid calibration during loading cycles. However, due to the factors discussed previously, the EPC output during unloading cycles may even be greater than that of fluid calibration.

Performance of the EPC, using dry Kaolin powder with soil layer thickness of 0.25 D_{EPC} revealed better repeatability with little hysteresis (Fig. 4a), and can be considered as the critical thickness of Kaolin for the EPC considered in this study, as compared to the value of 1.5 D_{EPC} for sand [23]. The Kaolin layer thickness of 0.25 D_{EPC} would be sufficient to transfer the pressure to the diaphragm of the EPC and to mobilize full arching in soil, and hence, it allowed uniform transfer of load on the EPC diaphragm. Considerable reduction in the EPC output with increase in Kaolin layer thickness is illustrated in Fig. 4 (c-e). This behavior may be attributed to stiffening of Kaolin layer due to high compressibility, which might have utilized larger portion of applied stress, and further, resulted in increase in the residual stress. In general, laboratory in-soil calibration with Kaolin revealed non-linear behavior, and hysteresis in the EPC output increased significantly with increase in the material thickness.

In case of dry Kaolin powder of thickness 2.5 D_{EPC}, percent changes in the EPC output between the cycles 1 & 2, 2 & 3, 3 & 4, and 4 & 5 were observed to be 91%, 6%, 3% and 0.3%, respectively, for applied pressure of 60 kPa. However, for applied pressure of 120 kPa, these values were 15%, 5%, 1% and 3%, and for applied pressure of 180 kPa, these were -2%, 0.4%, -3% and 0.04%, respectively. This shows that a greater amount of applied pressure was utilized in stiffening of Kaolin powder. It may be the main reason behind the residual stresses during subsequent cycles of loading, as observed in Fig. 4. A further increase in the layer thickness causes an increase in the amount of energy utilized for stiffening, which would be retained during unloading.

The results of in-soil and fluid calibration of the EPC under cyclic loading corresponding to 180 kPa pressure are presented in Table 1. The table shows performance of the EPC for soil thickness in the range of $0.25D_{EPC}$-$1.5D_{EPC}$. In case of sand, for 0.25 D_{EPC}, increase in the EPC output from first to fifth cycle was 23.87%, however, for sand thickness of D_{EPC} and higher, the EPC output reduces with increase in number of cycles. There was around 5-7% reduction in the EPC output for the 5th loading cycle, compared to the first loading cycle. The reduction of the EPC output was higher in Kaolin compared to sand, which might be attributed to the difference in compressibility characteristics of these two soils [4]. In view of the above, it may be prudent to use fluid calibration results directly in interpreting the earth pressures in Kaolin. It can also be noted that the observed non-uniform output of the EPC with change in material thickness was not due to deflection of the EPC diaphragm, as the deflection was well within its elastic range, but rather, attributed to the non-linear stress-strain behavior of soils.

Further, the observed EPC output in fluid calibration was almost constant with increase in number of cycles, and minor differences in the EPC output (of the order of 0.3%) at higher cycles can be neglected, in view of the sensitivity of the data logging system [4]. Arching in sand, stress-accumulation and particle re-orientation would cause only a part of the applied pressure to be transferred to the EPC causing under-registration and hysteretic behavior of the EPC during the in-soil calibration with sand [5, 10]. While for Kaolin, part of applied pressure was utilized for material stiffening and compaction of the layer. This was retained by the soil even after complete removal of pressure and caused hysteretic behavior of the EPC and under-registration with an increase in layer thickness. Further, it was noted that the in-soil calibration response of the EPC in sand deviates significantly from that of fluid calibration. Conversely, the in-soil calibration of the EPC in Kaolin does not differ much from that of fluid calibration, as evident from Fig. 3 & 4.

5 Conclusions

In the present study, the performance of a diaphragm type boundary EPC was evaluated through a series of calibration tests performed with two types of soils and five different soil thicknesses. The effect of material thickness on the EPC output under cyclic loading and critical material thickness for both the materials was also evaluated. The following conclusions were drawn:

- Laboratory in-soil calibration with sand revealed significant under-registration of the EPC output compared to that of fluid calibration, mainly during loading cycles.
- Results of in-soil calibration with Kaolin do not differ much from that of fluid calibration, and fluid calibration results may directly be used in interpreting the earth pressures in Kaolin.
- In-soil performance of the EPC under cyclic loading demonstrated significant effect of soil layer thickness.
- Based on the present study, the observed critical thickness for a given EPC is not a unique value, but varies with the soil type. The critical thicknesses of sand and Kaolin layers were observed as $1.5D_{EPC}$ and $0.25D_{EPC}$, respectively.

- It can be concluded that the in-soil calibration of the EPC should be performed under the conditions and with soil type identical to its intended use, for obtaining reliable results.

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6 References

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Table 1 Results of in-soil and fluid calibration of the EPC

Cycle	Pressure cell output (με)						
	Fluid	Sand Grade I			Kaolin		
		$0.25D_{EPC}$	D_{EPC}	$1.5D_{EPC}$	$0.25D_{EPC}$	D_{EPC}	$1.5D_{EPC}$
1st loading	372	259	298	301	379	336	343
5th loading	373	321	282	295	380	312	314
% reduction	-0.27	-23.87	5.37	1.99	-0.37	7.14	8.53

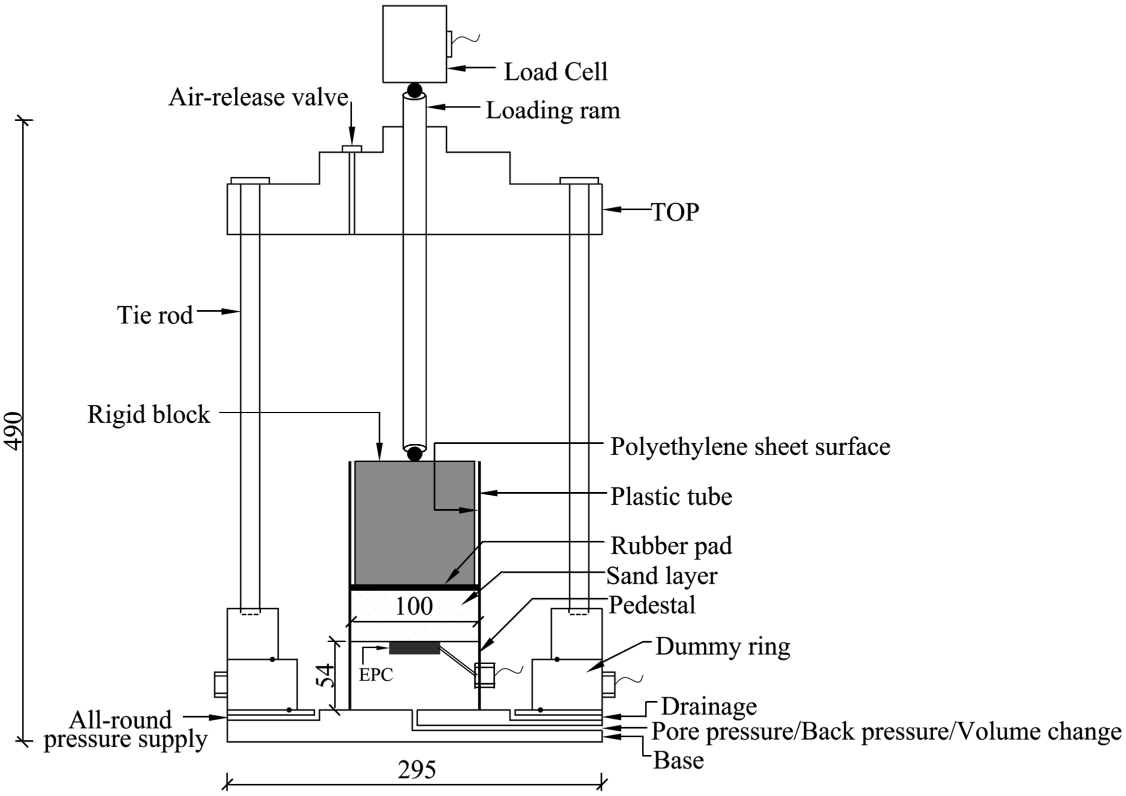

Figure 1. Modified triaxial set up to obtain in-soil performance of the EPC

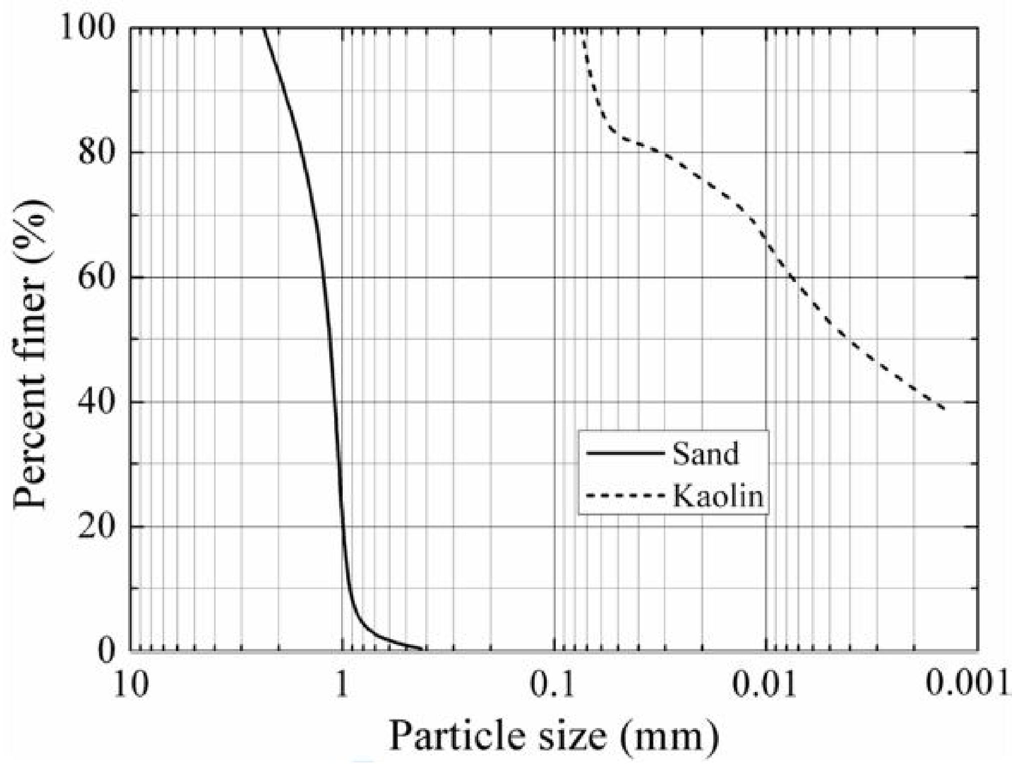

Figure 2. Particle size distribution of materials used in the present study

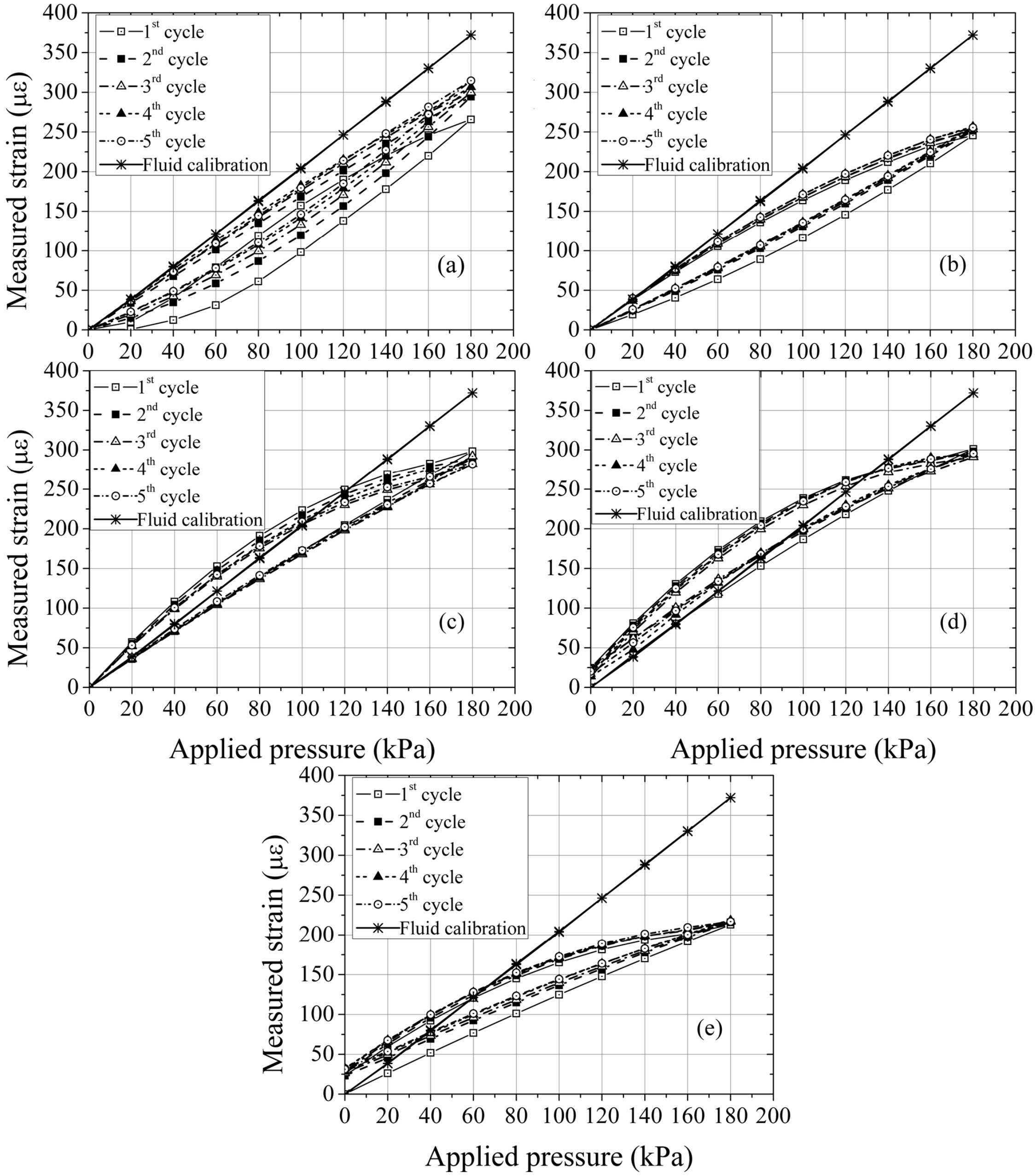

Figure 3. In-soil performance of the EPC for Grade I sand for sand thickness equal to (a) 0.25D$_{EPC}$ (b) 0.5D$_{EPC}$, (c) D$_{EPC}$ (d) 1.5D$_{EPC}$ (e) 2.5D$_{EPC}$

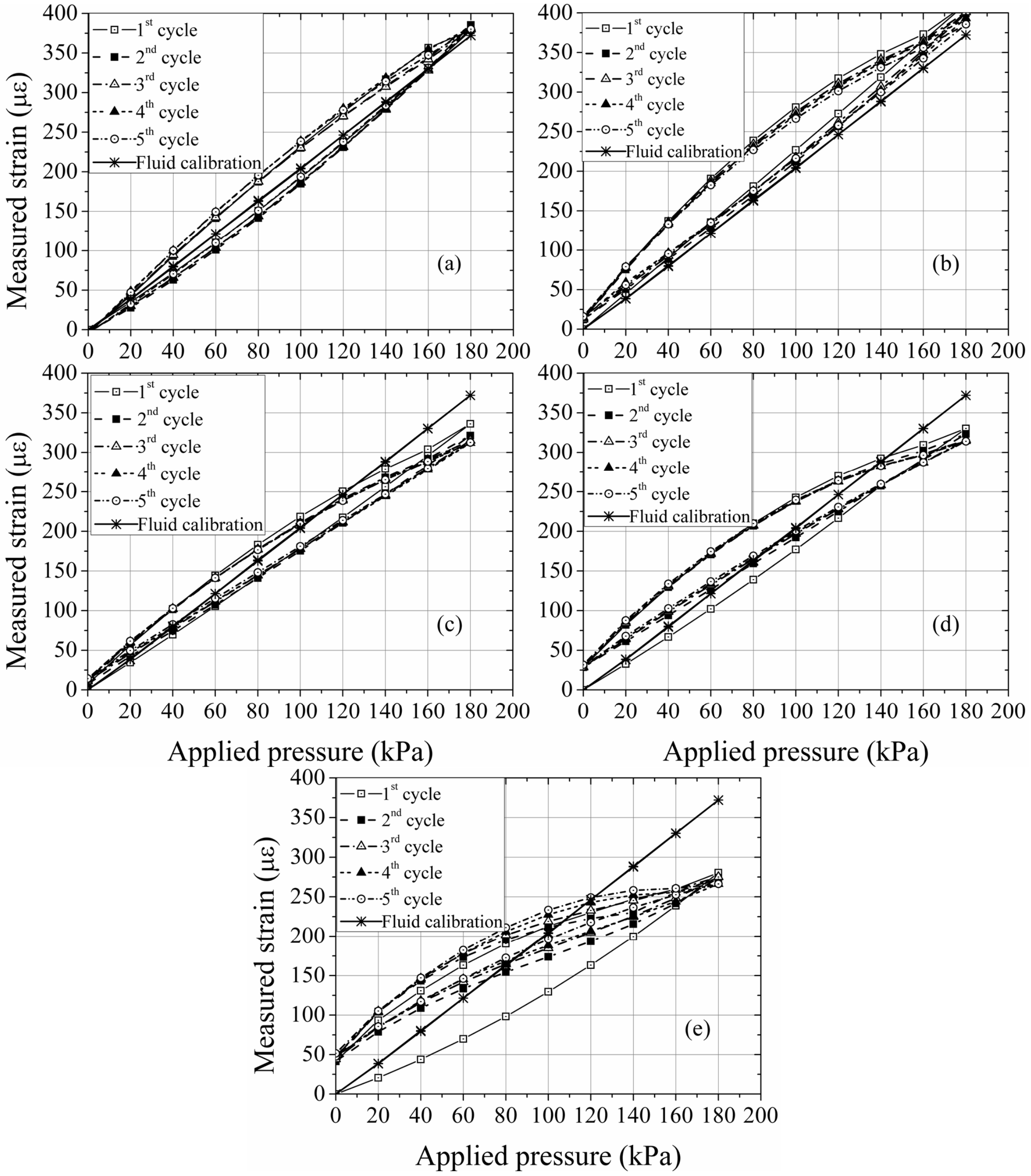

Figure 4. In-soil performance of the EPC for Dry Kaolin Powder of thickness equal to (a) $0.25D_{EPC}$ (b) $0.5D_{EPC}$, (c) D_{EPC} (d) $1.5D_{EPC}$ (e) $2.5D_{EPC}$