# Evaluation of Soil Interaction with Laterally Loaded Minipiles Using Optic Fiber

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Driven minipile foundations are becoming common due to merits such as lightweight, easy installation and suitability for reinforcing in-situ structures with limited access. However, their interaction with the surrounding soil especially in battered conditions is not fully understood. To develop a better understanding of the interaction of minipiles with the surrounding soil, they were instrumented with Fiber Bragg grating (FBG) sensors. Open-ended steel minipiles of 1600 mm length were then driven at a site with cohesive soil vertically and at positive and negative 25˚ angle with the vertical and were tested for three in-situ lateral static loading cases. The near-continuous strain profile along the minipile shaft was reported using FBG. This helped in identifying the deformation pattern and the impact of load magnitude on this profile. The lateral load capacity was found to be maximum for positive 25˚, which decreased for 0˚, followed by negative 25˚ batter angle.

**Keywords:** lateral load; optic fiber instrumentation; minipile; soil-structure interaction.

## 1. Introduction

Laterally loaded piles are a very common type of foundation for tower and offshore structures which are subjected to forces due to wind and wave. Inclined piles have better lateral load-carrying capacity as compared to vertical piles [1, 2]. As the batter angle increases, the lateral pile capacity has been found to increase from negative to positive batter angle of 30˚ [3, 4]. The behaviour of short rigid piles subjected to lateral load has been studied earlier [5-8] however; long flexible type of piles lack sufficient investigation.

To understand the effect of lateral loading on vertical and battered minipiles, this study focuses on field experimentation of instrumented minipiles in cohesive soil. The minipiles studied here are hollow steel piles with a outer diameter of 42.4 mm, thickness of 2.5 mm, length of 1600 mm and they can be assumed as flexible given their slenderness (this will be corroborated later in the paper). These dimensions of the single minipiles are adopted from a system of driven battered minipile pile group [9, 10]. The ultimate aim is to investigate the performance of the minipile groups under laterally loaded conditions which will be addressed in future publications.

Single minipiles instrumented with optic fiber were driven into cohesive soil in vertical, and positive and negative batter angle of 25˚. The fiber Bragg grated optic fiber unvealed the deformation behaviour along the minipile shaft bringing insights about the soil-pressure distribution at the pile-surface.

## 1.1. Laterally loaded piles

The design of the micropile foundations is approximately similar to that of conventional pile foundation systems [11]. They can be installed in battered condition with varying inclination angle either individually or in groups. The driven minipile in focus is similar to the conventional micropiles except without grouting and the installation process, thus, this different nomenclature has been adopted herein.

In general, laterally loaded piles can be grouped into, short and rigid piles or long and flexible piles [12]. According to the equation proposed by Poulos and Davis [12], the rigidity of the pile ($K_{rs}$) can be determined as,

$$K_{rs} = E_p I_p / E_h L^4 \qquad \text{Equation 1}$$

where $E_p I_p$ is the flexural rigidity of the pile, $E_h$ is the horizontal Young‘s soil modulus at the pile tip and $L$ is the embedded depth of the pile. When the rigidity of the pile is greater than 10e-2 or 10e-3, the pile can be considered as rigid [13]. The $K_{rs}$ of the driven minipile studied here is in the order of 10e-5 which makes them flexible. In order to investigate the deformation pattern of these minipiles, a durable instrumentation technique was adopted which could survive the process of driving installation in clay.

## 1.2. Optic fiber sensing

An optical fiber is a glass cladded glass core which differs in refractive index. FBG or fiber Bragg grating is incorporated in the optic fiber at required spacing based on the desired measurement points. W.H. Bragg and W.L. Bragg laid out the Bragg’s law that forms the working principle for FBGs which states that when a source of broadband light is injected into the fiber, the FBG reflects a narrow spectral part of light at a particular wavelength. There is a shift of wavelength when these sensors are subjected to strain or temperature change from which the deformation pattern can be deduced.

Sensors like strain gauges and pressure cells or tactile pressure sheets have been used in the past, but either they come with an impractical number of cables or can not withstand the high underground forces or involves a high number of sensors due to their discrete nature. In this aspect, fiber Bragg grated sensors, a popular type of fiber optic sensing technology, has been recently being used by civil engineers worldwide. The technology has found its use in detection of failure [14] and monitoring structural health [15, 16]. Optic fiber-instrumented minipiles were used to study their interaction with soil under pullout load [10] and a similar technique will be adopted in this paper.

## 2. Field experimentation program

A total of 6 quick lateral load tests were carried out at a clay site in University of Melbourne, Dookie campus.

### 2.1. Site condition

The driven piles were tested in a clay site in Dookie, a town in Goulburn region valley of Victoria, Australia. In total, 7 cone penetration tests were performed around the location of the tests. Three CPT results which were nearest to the test location are presented in Fig. 1. The in-situ investigation shows a fairly uniform site condition with no water table encountered up to 7m of depth. The soil unit weight up to 2 m of depth ranged from 18 to 19.2 kN/m$^3$. At each test location, Dynamic Cone Penetration tests (DCP) were conducted which is presented in Fig. 1c corresponding to the batter angles.

### 2.2. Instrumentation with optic fiber and calibration

The test minipiles were instrumented with fiber Bragg grated optic fibers. One groove, which is 4 mm wide and 1.5 mm deep was machined along the length of the pile shaft [10] as depicted in Fig. 2. The optic fibers were carefully laid in the grooves and protected with adhesive. Each optic fiber consisted of 6 FBGs, spaced apart at 270 mm, thus giving measurement points at 250, 520, 790, 1060, 1330 and 1600 mm of depth from the minipile tip.

The minipiles were prepared in the laboratory and calibrated before performing field experiments. The calibration process was done using strain gauges installed at different FBG locations [17]. The minipile was fixed at one end and loads were applied on the other end so that it behaved like a cantilever beam (Fig. 3a). The shift in the wavelength and strain gauge readings were recorded for each loading stage and plotted as shown in Figure 3b. The correlation between the shift of wavelength and strain was developed which was later used to convert the wavelength shift from the field experiments.

### 2.3. Test program

A total of six quick lateral load tests were conducted, two of positively battered, negatively battered and vertical each. The nomenclature is based on the loading direction with respect to the batter direction. When the load is applied in the direction of the batter angle, it is designated as 'positive', when the minipile is loaded in the direction opposite to the batter angle, it is 'negative' and 'vertical' is the condition of the minipile without any batter angle (Fig. 4). Fig. 5 shows a typical test setup with one instrumented and non-instrumented minipile. Two minipiles were tested together at one time, the minipiles acted as a reaction pile for each other which eliminated the need to use dead weight. The minipiles were driven into the ground through the guiding sleeves using a jackhammer. The embedded depth for the positive, vertical and negative minipile are 1368, 1300 and 1258 mm respectively. The standard loading procedure was adopted from ASTM D3966 [18] and each load was

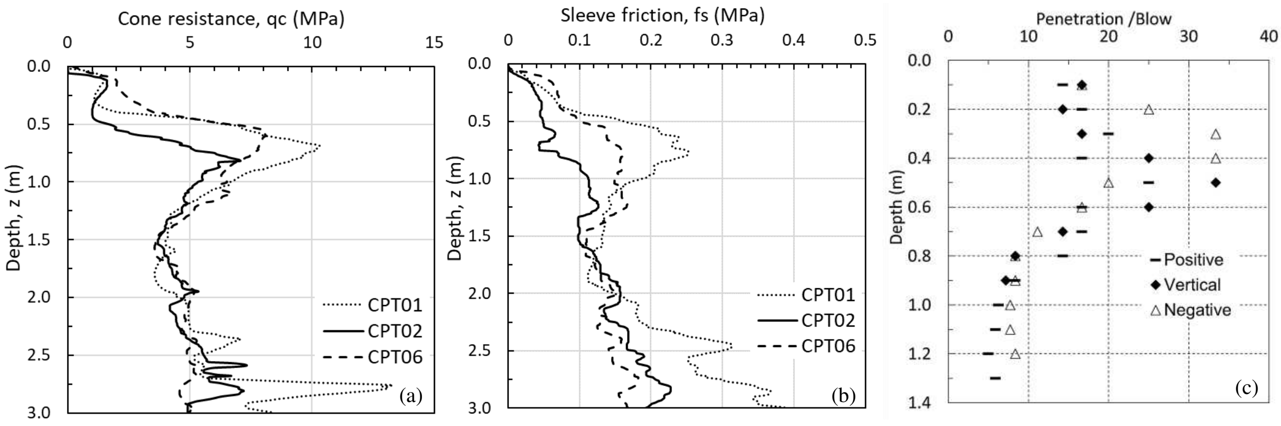


*Fig. 1 Site characterisation (a) and (b) CPT result (c) DCP result*

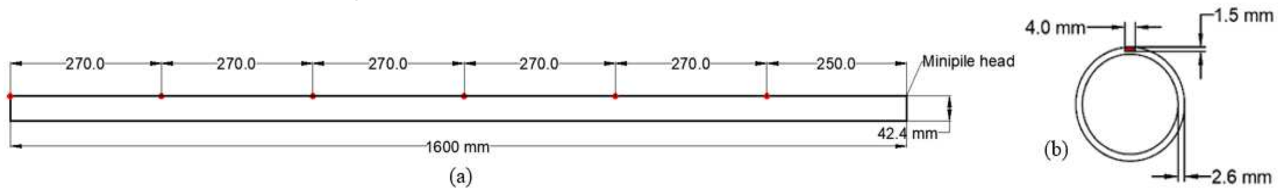


*Fig. 2 Location of FBGs along the minipile shaft (a) longitudinal view (b) cross-section showing the groove*

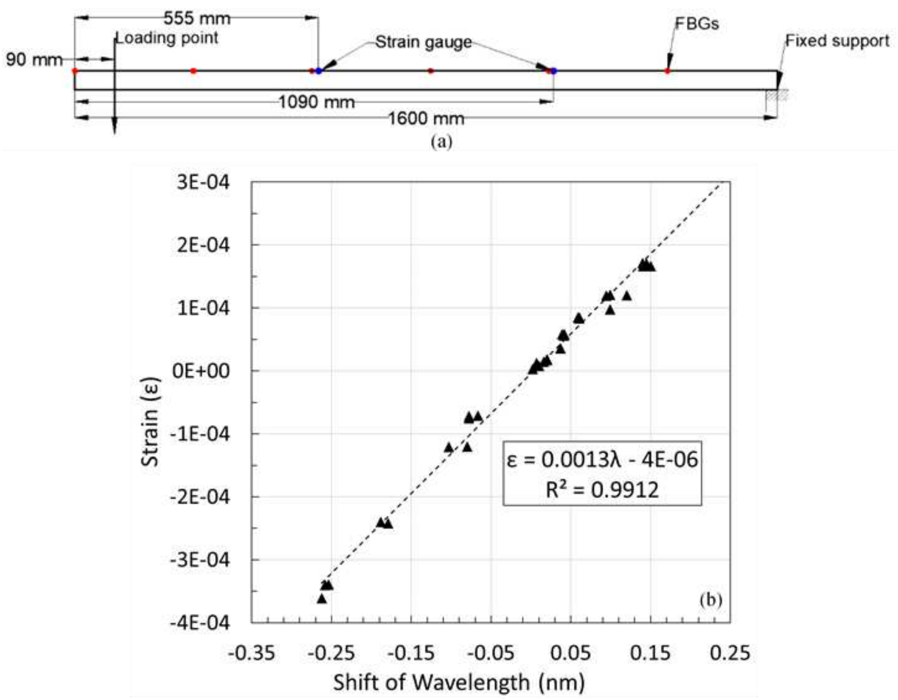


*Fig. 3 (a) setup for calibration (b) plot of shift of wavelength vs measured strain*

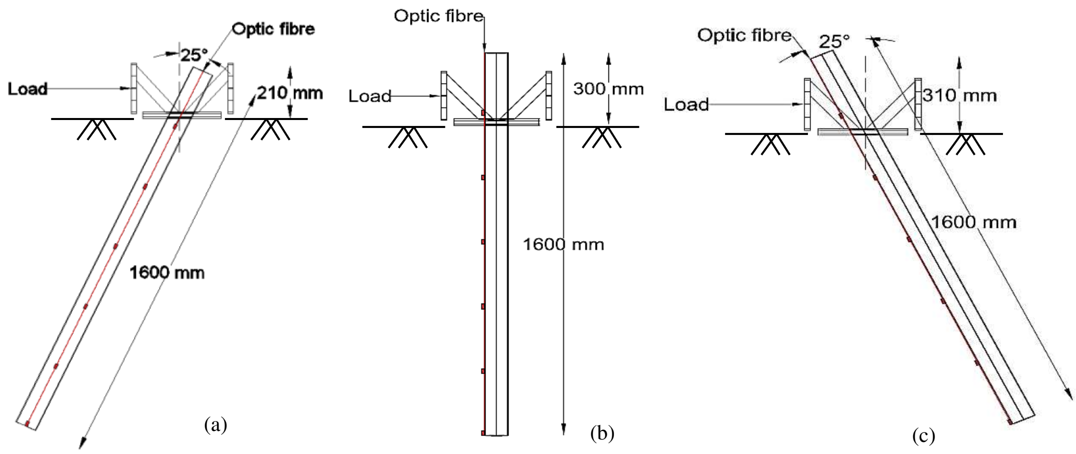


*Fig. 4 Batter angle of minipiles and loading direction (a) positive (b) vertical (c) negative*

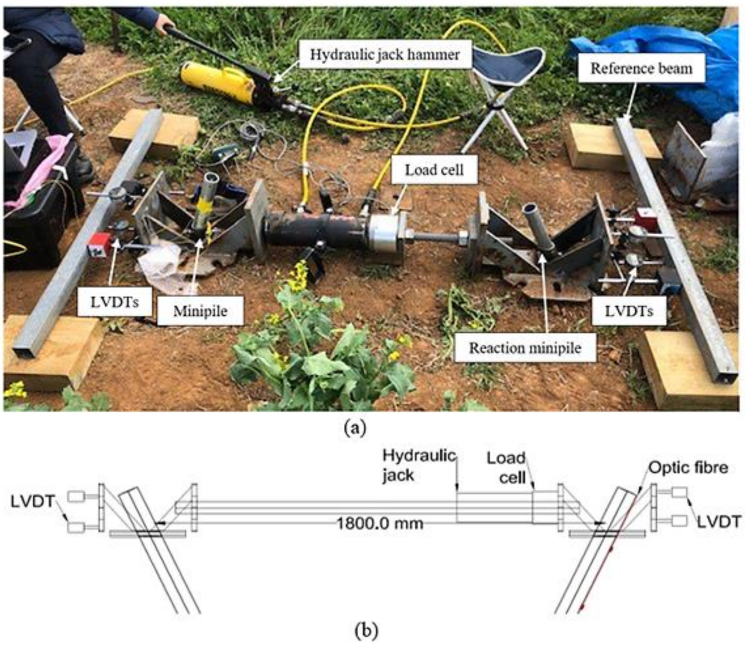


*Fig. 5 (a) Actual field setup for lateral negative (b) schematic for lateral positive condition* maintained for 15 mins. The 15 mins time limit was chosen so that the rate of the settlement was not greater than 0.25 mm/hour in accordance with ASTM D1143 [19]. The minipiles were subjected to a lateral load with an increment of 0.5-1 kN up to a lateral displacement of 30 mm which is much more than 5% of the micropile diameter as suggested for full-scale micropile tests [20]. The lateral displacement was measured using two LVDTs for both the minipile and reaction minipile. The strain profile along the minipile shaft was measured using the optic fiber.

## 3. Test results and discussion

### 3.1 Load displacement response

The load settlement response for positive and negative batter and vertical minipile subjected to lateral load is presented in Fig. 6. In order to determine the lateral load capacity, several criteria have been proposed over years. The load corresponding to a head displacement of 6.25 mm, 12 mm or 5% of the shaft diameter is among them [21]. The lateral load at 6.25 mm head displacement was chosen to compare the load capacity of the minipiles (depicted by the dashed line in Fig. 6). The minipile with positive batter angle of 25˚ gives the maximum load capacity of 4.35 kN followed by vertical minipile with 0.95 kN and the least load capacity of 0.65 kN for the negative battered minipile. This is in resemblance to the results reported by Kyung and Lee [22].

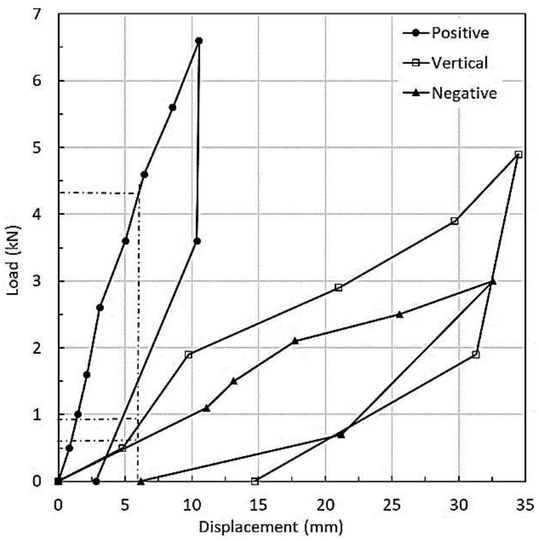


*Fig. 6 Load settlement response*

### 3.2 Deformation pattern

The optic fiber for the positive battered minipile was installed on the face as depicted in Fig. 4a. The negative battered and the vertical minipile was installed such that the optic fiber was on the face on which the load was applied (refer to Fig. 4b).

For the laterally loaded vertical minipile, Fig. 8a depicts the strain profile along the shaft with the increment of load and Fig. 7 represents the bending moment along the pile shaft calculated from the measured strain, the profile obtained is similar to that reported by Randolph [23] for a flexible type pile. As the lateral load was increased, the strain along the shaft increased. The maximum strain was recorded at an embedded depth of 490 mm. A similar trend was observed for negative battered minipile where the FBGs were installed on a similar face. The plot only shows four measurement points because of faulty 1st and 6th FBG (8c). The maximum strain was observed at a vertical embedded depth of 366 mm. As the optic fibres were installed on the similar face for vertical and negative battered minipile, the recorded strain can be compared for further analysis. The strain at any particular load was higher for vertical than negative battered case. This implies that at same incident load, the lateral soil pressure for vertical minipile is higher than negatively battered minipile which is suggestive of the lower load carrying capacity of a negatively battered minipile.

For the positive battered minipile, the maximum strain was obtained at a vertical embedded depth of 271 mm and the strain consistently increased with increasing load at this depth. As the optic fibre was installed on a different face than the other two cases, direct comparsion can't be drawn between them. However, the pattern with maximum strain at certain depth was similar to the other battered conditions discussed earlier.

## 4. Conclusion

In this paper, the lateral load capacity of driven minipiles was investigated for three different inclination angles, positive 25˚, vertical and negative 25˚ as shown in Fig. 6. A series of quick load tests were performed at a clay site for this purpose. Three minipiles were instrumented with optic fiber to understand their deformation pattern in the soil with increasing lateral load. The research outcomes can be summarized as follows:

- The ultimate lateral load was found to be maximum for a positive battered minipile followed by vertical and negative battered cases respectively.
- The bending moment profile of the vertical minipile shows a typical deflection pattern of a laterally loaded vertical pile.
- The maximum tensile strain developed for the vertical minipile under lateral loading was two times more than the strain developed for negative battered minipile.

The instrumented minipiles showed how the deformation profile is different for various batter angles and thus justifying the different load-carrying capacities for each of them.

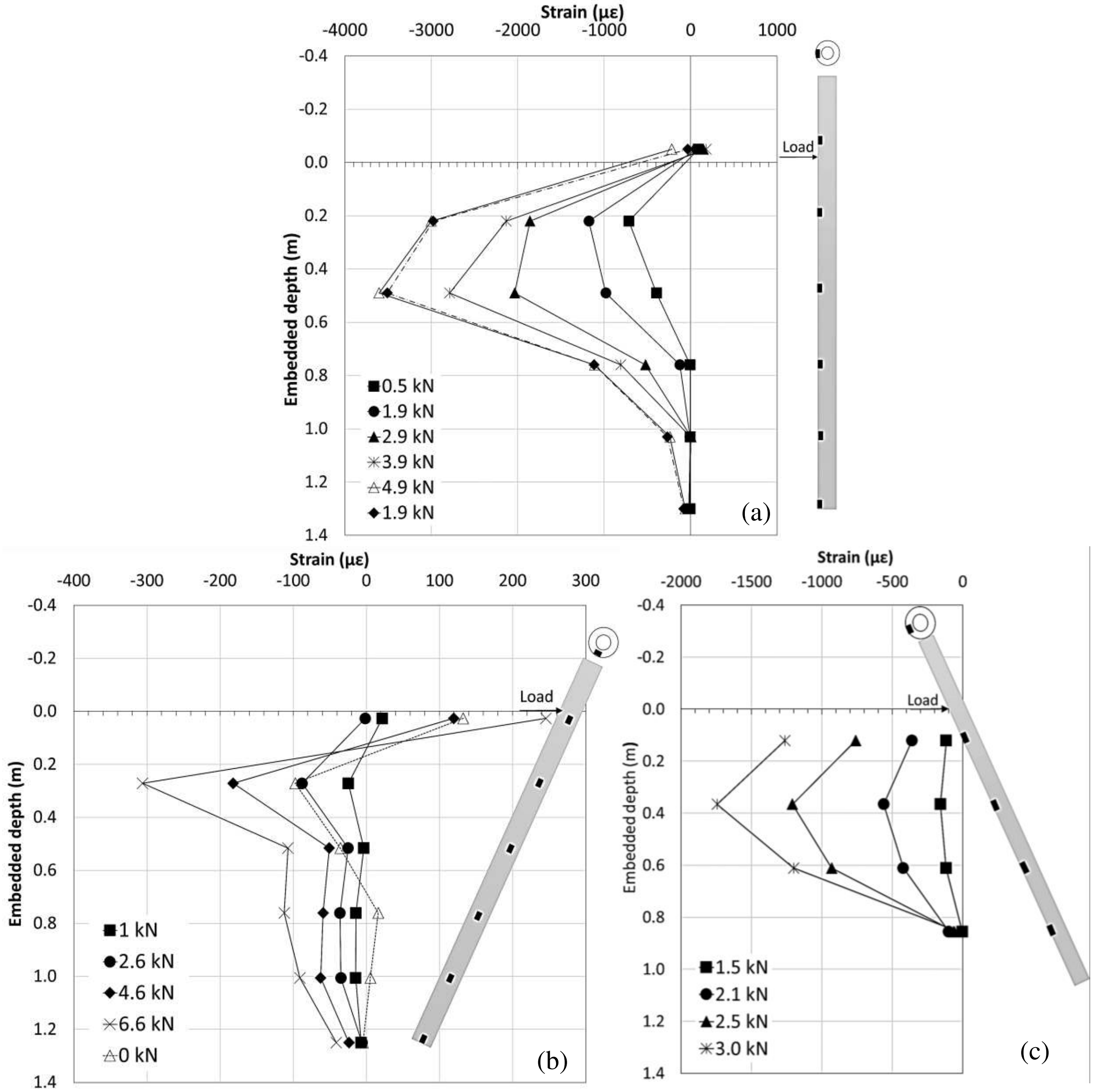


*Fig. 8 Deformation pattern along the minipile shaft, strain curve for (a) vertical (b) positive 25˚ (c) negative 25˚*

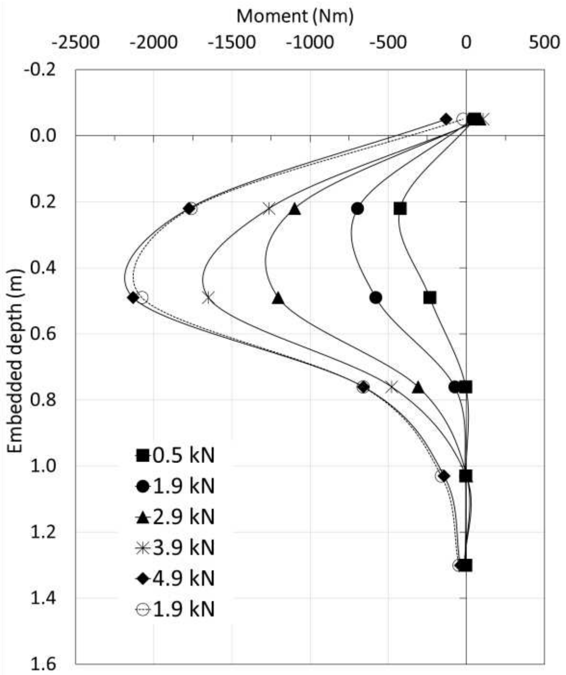


*Fig. 7 Bending moment profile for the vertical case*

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