

SOIL DISPLACEMENT MEASUREMENT DEVICE

Technical Field

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[0001] Various embodiments generally relate to a soil displacement measurement device. In particular, various embodiments generally relate to a soil displacement measurement device for measuring horizontal soil displacement and/or vertical soil displacement.

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Background

[0002] Soil displacement monitoring is very important to ensure safety, in particular in construction sites. Soil displacement can be in the form of horizontal soil displacement, e.g. landslides, or vertical soil displacement, e.g. settlement or heave.

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[0003] In monitoring horizontal soil displacement, typically, displacement measurement tool such as inclinometer may be used. The inclinometers may be used to measure the landslide due to the heavy construction activities, heavy rainfall, foundation settlement etc. For example, the soil may experience force towards the excavation/tunnelling site in the nearby area and therefore moves in a certain direction. The slope of soil may also deform due to heavy rainfall too. Thus, it is of high importance to monitor such movements/deformations of the soil to analyse and detect slope failures or landslides. In the current conventional practices, an inclinometer plastic casing which has two sets of grooves in mutually perpendicular directions is installed in the borehole (typically 40m deep). An inclinometer probe is lowered manually into the grouted-in-place casing with the help of an electrical cable through these grooves to maintain its direction (twist). The horizontal displacement of soil is measured at regular depths along the inclinometer casing/borehole in two perpendicular directions (one perpendicular and another parallel to the excavation site). The inclinometer casing undergoes some twisting because of the high pushing force used against the buoyancy force from the liquid grout during the installation of the casing. The twist of the casing is undesirable but is unavoidable. The measurement of twist suffered by the inclinometer casing is necessary to calculate the displacement of casing/soil accurately. Moreover, the inclinometer probe must be lowered into the casing manually for each inspection which is labour intensive and time-consuming. Furthermore, real-time continuous monitoring of soil movement is not possible with this method.

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[0004] A fully/semi-automated in-place inclinometer system with automated data logging may be desirable to replace the existing practice of manual measurement of ground movement. A number of electrical systems for automation were developed for monitoring of ground movement. However, there are issues such as waterproofing, signal drifting, long-term reliability etc. with these systems which need to be addressed. Further, most of the electrical sensors are non-distributive and multiplexing is not possible with them. Moreover, an inclinometer site might need over 50 sensors arranged vertically at regular depths in a borehole of 30-40m depth. Therefore, over 50 data lines would be coming out of the borehole, which makes such systems highly impractical.

[0005] In recent years, fiber Bragg grating (FBG) based inclinometer/tilt sensor is gaining popularity. In the field of soil deformation monitoring, several FBG based inclinometers have been developed. In one such development, rigid pipes are connected in series with elastic joints. The bending angle at every joint is measured through embedded FBGs in the elastic joints to calculate the soil displacement. In another development, a fiber optic ground monitoring system (inclinometer) has also been developed based on the beam theory. A series of FBGs are mounted on the outer surface of a flexible plastic pipe. The distribution of ground/soil displacement along the inclinometer casing is calculated using simple beam theory. In yet another development, a similar slope monitoring system using aluminum casing instead of a flexible pipe was developed. In this case, the inclinometer is divided into three segments to increase the longevity of FBGs. The proposed method works well only if the initial boundary conditions are known. However, it is not possible to know the exact boundary conditions in the practical scenarios. In another development, the inclinometer configuration consists of inclinometer casings and a series of connected flexible pipes, each flexible pipe with two FBGs embedded on opposing sides of the flexible pipe. Further, US 7,388,190 B2 disclosed a FBG based inclinometer system to monitor the ground displacement which uses a segmented configuration that consists of flexible tube and rigid segments forming a double hinged FBG segmented deflectometer. For field installation, multiple segments of deflectometers are connected in series. However, the configuration of the deflectometer and the assembly of deflectometers are quite complex.

[0006] While all the above-mentioned inclinometer systems provided some form of automation or real-time monitoring capability, all of them are installed along the respective inclinometer casing wall in order to maintain the direction of the inclinometer perpendicular to the direction in which the soil is expected to move or deform throughout its height. Accordingly, in these systems, it has to be assumed that the inclinometer casing is not twisted

at all while being installed into the borehole. However, in actual installation, the inclinometer casing is always twisted during installation and this twist or spiral could be as high as 10° in some cases. The twist of inclinometer casing varies with the depth and therefore, the corrections are required in order to offset the effect of twist during the soil displacement calculation in the conventional methods above. However, such twist/spiral corrections have not been even considered in the case of inclinometer systems (FBG based or otherwise) currently known. Since, the accuracy of such inclinometer systems depends on how accurately (without twisting) the inclinometer casing is installed, the soil displacement profile obtained through such known methods might not be very accurate. Moreover, the installation of inclinometer casing is itself very expensive and labour intensive.

[0007] On the other hand, vertical soil displacement/movements can be measured with various instrumentations such as precise levelling plugs, plates and rods, deep settlement probes, and extensometers. The extensometers are important geotechnical instrumentations, whose applications include monitoring vertical displacement/movements in excavations, foundations, embankments, and tunnels etc. The extensometers may be used to measure soil displacements (settlement/heave) at various depths within a soil mass along the axis of a borehole.

[0008] Currently, there are two major types of conventional extensometers namely, rod extensometers and magnetic extensometer. A rod extensometer works by measuring the relative movement between the bottom anchor and the reference tube. The bottom anchor is anchored to the surrounding soil and it moves with the soil. This movement is read through a dial gauge. The limitation of the rod extensometer is that it is an expensive unit with limited measurement range (typically, 50 mm to 100 mm). Further, only 3-4 rods can be installed in a borehole, limiting the number of measurement points to 3-4 along the borehole. In some cases, the borehole can be 50m-60m deep and more measurement points (e.g. 6-8 points) are needed along the entire depth of the borehole.

[0009] For magnetic extensometer, spider magnets (e.g. magnets with spider legs) are installed at different depths outside, but along the borehole pipe. The spider legs are anchored to the soil. The positions of these spider magnets are known by lowering a probe into the borehole and thus, the soil movement can be measured. The magnetic extensometer is not expensive and provides good measurement range (typically about 100mm). However, operation of the magnetic extensometers is manpower intensive and time-consuming. Automatic and real-time continuous monitoring of soil movement is also not possible with the magnetic extensometers.

[00010] With fiber Bragg grating (FBG) based sensors gaining popularity, several types of fiber optic sensor based extensometers have been developed recently. In one such development, an FBG-based monitoring system to monitor the filled soil layered settlement consists of a distributed FBG sensing system with 10 divided monitoring units to monitor filled soil with a height of 30m. Each unit has a gauge, and an FBG displacement meter. The measurement range of these units is 150 mm. However, multiplexing of such units along a borehole for settlement monitoring at different depths is not possible. In another development, a long-range extensometer based on FBG for relative movement between two adjacent buildings was developed. However, this requires identification of two discrete movement bodies which is not possible in soil monitoring.

[00011] Accordingly, there is a need for a more reliable and effective soil displacement measurement device.

Summary

[00012] According to various embodiments, there is provided a soil displacement measurement device. The soil displacement measurement device may include a cylindrical hollow housing. The soil displacement measurement device may further include an outer ring-magnet slidably arranged on an exterior surface of the cylindrical hollow housing in a manner such that the cylindrical hollow housing is inserted through a central cavity of the outer ring-magnet. The soil displacement measurement device may further include an inner magnet disposed within the cylindrical hollow housing. The soil displacement measurement device may further include a suspension arrangement holding the inner magnet with respect to the cylindrical hollow housing so as to suspend the inner magnet within an interior space of the cylindrical hollow housing. The soil displacement measurement device may further include a strain measurement element provided to a region of the suspension arrangement. According to various embodiments, relative movement between the outer ring-magnet and the cylindrical hollow housing along a longitudinal axis of the cylindrical hollow housing may cause the outer ring-magnet to coact with the inner magnet in a manner such that a magnetic force between the outer ring-magnet and the inner magnet changes a corresponding strain at the region of the suspension arrangement. Further, the change in the strain may be detected by the strain measurement element as a measure of the relative displacement of the outer ring-magnet along the longitudinal axis of the cylindrical hollow housing.

[00013] According to various embodiments, there is provided a soil displacement measurement device. The soil displacement measurement device may include an elongate hollow housing having a first partition and a second partition defining a closed section of the cylindrical hollow housing. The soil displacement measurement device may further include a
5 suspended-body which has a shape having circular symmetry about a main axis passing through the suspended-body between a first surface-intersection-point and a second surface-intersection-point, and which is disposed within the elongate hollow housing and suspended between the first partition and the second partition with the first surface-intersection-point directed towards the first partition and the second surface-intersection-point directed towards
10 the second partition. The soil displacement measurement device may further include a first suspension-line-segment extending from the first surface-intersection-point of the suspended-body towards a center of the first partition of the elongate hollow housing. The soil displacement measurement device may further include a second suspension-line-segment extending from the second surface-intersection-point of the suspended-body towards a center
15 of the second partition of the elongate hollow housing. The soil displacement measurement device may include a strain measurement element disposed along the second suspension-line-segment. According to various embodiments, a ratio of a length of the first suspension-line-segment to a length of the second suspension-line-segment may be equal or more than 1.

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Brief description of the drawings

[00014] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead
25 generally being placed upon illustrating the principles of the invention. In the following description, various embodiments are described with reference to the following drawings, in which:

FIG. 1 shows a schematic diagram of a soil displacement measurement device being configured as an inclinometer according to various embodiments;

30 FIG. 2(a) and FIG. 2(b) show the soil displacement measurement device of FIG. 1 with connection fixtures according to various embodiments;

FIG. 2(c) shows an elongate link member according to various embodiments;

FIG. 2(d) shows two soil displacement measurement devices of FIG. 1 connected together to form a soil displacement measurement system according to various embodiments;

FIG. 3 shows a graph illustrating a comparison between experimental and simulation results;

FIG. 4 shows a graph illustrating a comparison among the simulation results while materials with different tensile strength (optical fiber, 16.5 GPa; aluminum wire, 69 GPa; steel wire, 117 GPa) are used in the upper half of the soil displacement measurement device of FIG. 1;

FIG. 5 shows a graph illustrating the simulated response of the soil displacement measurement device of FIG. 1 with different length ratios of the upper half and lower half hanging fiber (l_1/l_2);

FIG. 6 shows a photograph of three identical soil displacement measurement devices of FIG. 1 filled with water;

FIG. 7 shows calibration test results of all three identical units of FIG. 6;

FIG. 8(a) shows a schematic diagram of three identical soil displacement measurement devices of FIG. 6 forming a soil displacement measurement system according to various embodiments;

FIG. 8(b) shows a photograph of the actual soil displacement measurement system experimental setup for FIG. 8(a);

FIG. 9(a) shows a force applied on the top of the soil displacement measurement system of FIG. 8(a);

FIG. 9(b) shows an expected bending profile of FIG. 9(a);

FIG. 9(c) shows a graph illustrating the comparison between actual and experimental bending profile of the soil displacement measurement system of FIG. 9(a);

FIG. 10(a) shows a force applied on the top of the soil displacement measurement system of FIG. 8(a) fixed at the lowest connection point;

FIG. 10(b) shows an expected bending profile of FIG. 10(a);

FIG. 10(c) shows a graph illustrating the comparison between actual and experimental bending profile of the soil displacement measurement system of FIG. 10(a);

FIG. 11 shows a schematic diagram of the soil displacement measurement device of FIG. 1 being configured as an inclinometer according to various embodiments;

FIG. 12 shows a schematic diagram of a soil displacement measurement device being configured as an extensometer according to various embodiments;

FIG. 13 shows a schematic diagram of a soil displacement measurement device being configured as an extensometer according to various embodiments;

FIG. 14 shows a graph illustrating strain induced for a given thickness (d_I) and different radii (R_I) of an inner magnet of the soil displacement measurement device of FIG. 12;

FIG. 15 shows a graph illustrating strain induced for a given radius (R_I) and different thicknesses ($2d_I$) of an inner magnet of the soil displacement measurement device of FIG. 12;

5 FIG. 16 shows a photograph 1692 of an experimental setup of the soil displacement measurement device of FIG. 12;

FIG. 17 shows a graph illustrating experimental, analytical, and simulation results of strain induced as an outer ring-magnet moves downwards (closer to the inner magnet) verse the axial distance (z) between the magnets of the soil displacement measurement device of
10 FIG. 12;

FIG. 18 shows a graph illustrating strain induced for a given thickness (d_I) and different radii (R_I) of an inner magnet of the soil displacement measurement device of FIG. 13;

FIG. 19 shows a graph illustrating strain induced for a given radius (R_I) and different thicknesses ($2d_I$) of an inner magnet of the soil displacement measurement device of FIG. 13;

15 FIG. 20 shows a photograph 2092 of an experimental setup of the soil displacement measurement device of FIG. 13;

FIG. 21 shows a graph illustrating experimental and simulation results of strain induced as an outer ring-magnet moves downwards (closer to the inner magnet) verse the axial distance (z) between the magnets of the soil displacement measurement device of FIG. 13;

20 FIG. 22 shows a photograph of three soil displacement measurement devices of FIG. 13 forming a soil displacement measurement system according to various embodiments;

FIG. 23 shows a graph illustrating a response of the three soil displacement measurement devices forming the soil displacement measurement system of FIG. 22;

FIG. 24 shows a schematic diagram of a single soil displacement measurement device
25 which may be made up of the soil displacement measurement device of FIG. 1 (which is configured as an inclinometer) being joined together with the soil displacement measurement device of FIG. 13 (which is configured as an extensometer) according to various embodiments;
and

FIG. 25 shows a schematic diagram of the single soil displacement measurement
30 device of FIG. 24 (which is configured as an inclinometer and an extensometer) being connected with the soil displacement measurement device of FIG. 1 (which is configured as an inclinometer) via link members forming flexible joints to form a soil displacement measurement system according to various embodiments.

Detailed description

[00015] Embodiments described below in the context of the apparatus are analogously valid for the respective methods, and vice versa. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment.

[00016] It should be understood that the terms “on”, “over”, “top”, “bottom”, “down”, “side”, “back”, “left”, “right”, “front”, “lateral”, “side”, “up”, “down” etc., when used in the following description are used for convenience and to aid understanding of relative positions or directions, and not intended to limit the orientation of any device, or structure or any part of any device or structure. In addition, the singular terms “a”, “an”, and “the” include plural references unless context clearly indicates otherwise. Similarly, the word “or” is intended to include “and” unless the context clearly indicates otherwise.

[00017] Various embodiments generally relate to a soil displacement measurement device or a device for measuring soil displacement. Various embodiments also relate to a soil displacement measurement system comprising two or more soil displacement measurement device arranged or connected or joined in series one after another. According to various embodiments, the soil displacement measurement device and/or the soil displacement measurement system may be configured to detect and/or measure and/or sense and/or determine soil displacement in the horizontal/lateral direction and/or the vertical direction with respect to a ground when installed into the ground. According to various embodiments, the soil displacement measurement device may be configured to be lowered into and installed (or mounted or grouted or fixed) to a borehole. According to various embodiments, the soil displacement measurement devices may be configured to connecting or joining to each other so as to form the soil displacement measurement system. According to various embodiments, the soil displacement measurement device may include an inclinometer and/or an extensometer. According to various embodiments, the soil displacement measurement device may be an in-place or in-situ inclinometer and/or extensometer. According to various embodiments, the soil displacement measurement device may be configured for real-time monitoring of soil displacement at different depths.

[00018] According to various embodiments, the soil displacement measurement device may be configured as an inclinometer (or in-place inclinometer) which may be cylindrical in shape and which may have a fiber Bragg grating (FBG) running through the centre of the cylinder

(or along the axis of the cylinder). Or in other words, the inclinometer (or the soil displacement measurement device) according to the various embodiments may be symmetric about the sensing element (i.e. the FBG). Therefore, according to various embodiments, the response of the inclinometer may be independent of its twist/rotation (or free from any influence due to twisting/rotating of the inclinometer). Hence, the inclinometer according to the various embodiments purely reads the angle of inclination or the displacement of soil. No correction or additional measurement is required to offset the effect of casing twist. According to various embodiments, several such inclinometer units may be connected through flexible joints and the whole system can be lowered and grouted into a borehole to monitor the soil movement or slope deformation. According to various embodiments, the installation does not need the expensive inclinometer casing which is an essential part of the conventional system.

[00019] According to various embodiments, the soil displacement measurement device may be configured as an inclinometer. For example, the soil displacement measurement device may be configured to detect and/or measure and/or sense and/or determine a tilt in the soil displacement measurement device as a measure of horizontal/lateral soil displacement when in use. In various embodiments of the soil displacement measurement device, the inclinometer may be configured to be simple and the FBG sensors may be enclosed in a cylindrical chamber and hence, well protected from the outside environment. Accordingly, once installed successfully, its long-term performance may be guaranteed. In various embodiments of the soil displacement measurement device, the inclinometer may be configured to be symmetric about the FBG which may be at the axis of the cylinder and therefore, the performance of the system may be independent of the twist that it might undergo during installation. Hence, no correction in the measured angle of inclination will be required for the soil displacement measurement device according to the various embodiments. Since, in various embodiments of the soil displacement measurement device, the inclinometer is configured to be independent of twisting, the expensive inclinometer casing is not required at all, thus saving money and manpower. According to various embodiments of the soil displacement measurement device, the inclinometer may be configured for temperature compensation by incorporating an extra FBG in the casing.

[00020] According to various embodiments, the soil displacement measurement device may be configured as an extensometer. In various embodiments of the soil displacement measurement device, the extensometer may be based on FBG sensors and may be configured for borehole application. In various embodiments of the soil displacement measurement device, the extensometer may capitalize on the interaction force between two permanent

magnets. Further, the extensometer may be capable of real-time monitoring of soil settlement/heave at different depths in a borehole with minimum manpower involvement. Accordingly, the soil displacement measurement device may be configured to detect and/or measure and/or sense and/or determine the interaction force between two permanent magnets as a measure of vertical soil displacement when in use.

[00021] In various embodiments of the soil displacement measurement device, the FBG based extensometer may provide a real-time, continuous, semi-automatic soil settlement/heave monitoring system. In various embodiments of the soil displacement measurement device, the extensometer may be configured to be simple, robust and flexible for borehole applications.

Further, according to various embodiments of the soil displacement measurement device, multiple units (e.g. more than 10) may be connected together and easily installed in a deep borehole (e.g. 60m) to form a soil displacement measurement system. Thus, the number of extensometer units according to various embodiments of the soil displacement measurement system is not limited by the borehole size as is the case for the rod extensometer. In various embodiments of the soil displacement measurement device, the extensometer may be configured to give a measurement range of about 60mm-100mm with a resolution of less than 1mm. According to the various embodiments of the soil displacement measurement device, the extensometer may be configured to be flexible so as to allow an increase in the measurement range and resolution by changing the size of the magnets used in the device. According to various embodiments of the soil displacement measurement device, temperature compensation may be done by incorporating an extra FBG in the extensometer casing.

[00022] In various embodiments of the soil displacement measurement device, the extensometer may be configured to be simple and easy to fabricate. Further, according to various embodiments of the soil displacement measurement device, the FBG sensors may be enclosed in a cylindrical chamber and hence, well protected from the outside environment. Accordingly, once installed successfully, their long-term performance is envisaged. In various embodiments of the soil displacement measurement device, the adoption of magnet interaction may enlarge the measurement range as compared with the conventional rod extensometer. In various embodiments of the soil displacement measurement device, the extensometer may be configured to provide wide range automated measurement. According to various embodiments of the soil displacement system, unlike the conventional rod extensometer system, the number of units installed in the borehole may not be limited to only 3-4 units. In various embodiments of the soil displacement measurement device, the extensometer may be

configured to enable real-time continuous measurement at multiple points along a borehole with minimum manpower.

[00023] In various embodiments of the soil displacement measurement device, a FBG-based extensometer may make use of the interaction force between a ring magnet and a disc magnet which may be uniformly magnetized. The ring magnet and the disc magnets may be kept at a certain distance from each other and the magnetic force exerted on one magnet by the other depends on the distance between them. Accordingly, any relative movement between the magnets may induce an axial/radial magnetic force change between them which is realized by the FBG.

[00024] FIG. 1 shows a schematic diagram of a soil displacement measurement device 100 being configured as an inclinometer according to various embodiments. As shown in FIG. 1, in the soil displacement measurement device 100, which is configured as the inclinometer, a suspension-line 120 (for example, an optical fiber) may run through the axis of an elongate hollow housing 110 (for example, a cylindrical casing) with the help of a first partition 112 and a second partition 114 (for example, top and bottom plates). The optical fiber, which serves as the suspension-line 120, may carry a symmetrical mass body (or a suspended-body 130) at its mid-point and may have an FBG (which serves as a strain measurement element 140) written on the lower part (i.e. below the mass body) of the suspension-line 120. The FBG, being the strain measurement element 140, may be kept in the lower part of the suspension-line 120 to avoid the tensile strain being exerted in the FBG due to the weight of the hanging mass, as the FBG part of an optical fiber may be relatively weaker. According to various embodiments, a diameter and a height of the elongate hollow housing 110, which may be a poly(methyl methacrylate) (PMMA) cylinder (or cylindrical casing), may be 70mm and 400mm respectively to make it suitable for borehole installation. According to various embodiments, the top plate (which serves as the first partition 112) may rest on a supporting hollow disk (or an annular ledge) which may have an internal diameter smaller than a diameter of the top plate. According to various embodiments, the optical fiber (serving as the suspension-line 120) may be fixed in central holes of the top and bottom plates (i.e. the first partition 112 and the second partition 114) through fiber sleeves and epoxy glue. According to various embodiments, a small pre-tension may be kept in the optical fiber (serving as the suspension-line 120) while fixing the top and bottom ends of the optical fiber.

[00025] When the soil displacement measurement device 100 (which is configured as an inclinometer) is oriented vertically straight, the FBG (serving as the strain measurement element 140) may experiences a small tensile strain which starts to increase as soon as the soil

displacement measurement device 100 is tilted off vertical. Upon tilting, the suspended-body 130 may start to pull the FBG (or the strain measurement element 140) on one side and this pull may increase in consonance with the increasing angle of tilt. The more is the tilt, the more will be the pull force, and hence the strain. By knowing the strain in the FBG (or the strain measurement element 140), the angle of inclination may be calculated at a particular instant of time. Mathematical modelling may be conducted to calibrate and verify the response of the inclinometer (or the soil displacement measurement device 100). According to various embodiments, the top/bottom end of the optical fiber may be connected to a FBG interrogator to monitor the change in the strain.

[00026] The soil movement may be monitored by monitoring the movement of different soil beds through a borehole which is usually 30m-40m deep. Therefore, an in-place inclinometer system (or soil displacement measurement system) must be of this height in order to be installed in such a borehole. For a borehole as deep as 30m, at least 30 points may be required to monitor the soil profile along the entire depth. According to various embodiments, the soil displacement measurement device 100 configured as the inclinometer unit as shown in FIG. 1 may be about 40cm long. Therefore, multiple units may need to be connected to form the soil displacement measurement system. According to various embodiments, the connection between two units has to be flexible to allow the connected inclinometer units to follow the movement of the soil. Every individual unit in the soil displacement measurement system (or the inclinometer system) may actually be a measurement point. At a single point in time, the angle of inclination at all these points may be known and hence, the soil displacement profile may be drawn for that particular time.

[00027] FIG. 2(d) shows two soil displacement measurement devices connected together. FIG. 2(a) show a first soil displacement measurement device 100a with connection fixtures 250, FIG. 2(b) shows a second soil displacement measurement device 100b with connection fixtures 250, and FIG. 2(c) shows an elongate link member 260. Accordingly, a connection scheme between individual units (or individual devices) to make a full-length in-place inclinometer system (or a soil displacement measurement system) is depicted in FIG. 2(a) to FIG. 2(d). FIG. 2(a) and FIG. 2(b) show two identical soil displacement measurement devices 100a, 100b (or inclinometer units) to be connected. As shown, two connection fixtures 250 may be glued close to both ends of each soil displacement measurement device 100a, 100b (or each inclinometer unit). These connection fixtures 250 may have three grooves 252 each. According to various embodiments, the soil displacement measurement devices 100a, 100b (or the inclinometer units) may be connected with each other with elongate link members 260

(for example, in the form of curved nylon strips) as shown in FIG. 2(c). According to various embodiments, the elongate link member 260 may have a curved cross-sectional profile. Accordingly, an inner radius of the curved cross-sectional profile of the elongate link member 260 (or the curved strip) may be kept equal to an outer radius of the elongate hollow housing 110 (for example, in the form of a PMMA cylinder) to match an inner surface of the elongate link member 260 (or the curved strip) with an outer surface of the elongate hollow housing 110 (or the cylinder). A thickness of the connection fixture 250 and a thickness of the elongate link member 260 (or the strip) may be the same (for example, about 4mm). Also, a breadth of each groove 252 of each connection fixtures 250 and a breadth of the elongate link member 260 (or the strips) may be kept the same so that the elongate link member 260 (or the strips) may fit well into the respective grooves 252. According to various embodiments, three elongate link members 260 (or strips) of the same length (for example, about 50cm each) may be fixed into the three grooves 252 of the connection fixture 250 of the first soil displacement measurement device 100a (or one inclinometer unit) and another ends of the same elongate link members 260 (or strips) may be fixed into the three grooves 252 of the connection fixture 250 of the second soil displacement measurement device 100b (or another inclinometer unit) as shown in FIG. 2(d). Thus, three elongate link members 260 may join the two soil displacement measurement devices 100a, 100b (or two inclinometer units). As shown in FIG. 2(a) and FIG. 2(b), according to various embodiments, the elongate hollow housing 110 of each soil displacement measurement device 100a, 100b may have a length of about 400mm and a diameter of about 70mm. Further, each connection fixture 250 may be placed between 50mm to 100mm from respective ends of the elongate hollow housing 110. Each connection fixture 250 may have an axial length of about 50mm. According to various embodiments, the elongate link members 260 may be made of nylon. Accordingly, the elongate link members 260 may be flexible. According to various embodiments, the joint of nylon strips, serving as the elongate link members 260, may be flexible and may be able to bend according to the force applied. According to various embodiments, the connection fixtures 250 and the elongate link members (or the nylon strips) may be 3D printed (three-dimensional printed). The number of elongate link members (or connection strips) and grooves 252 in the connection fixture 250 may vary depending on applications. According to various embodiments, each soil displacement measurement device 100a, 100b (or inclinometer unit) may include one FBG and the optical fiber coming out of every unit may be spliced together in series to receive the optical signal from one optical fiber only.

[00028] According to various embodiments, the soil displacement measurement device 100 (or the inclinometer units) may be made waterproof. According to various embodiments, the soil displacement measurement system (or the full-size inclinometer), which require a number of units connected together, is supposed to be installed in the borehole which may already be
5 filled with water. Therefore, the respective soil displacement measurement device 100 (or the inclinometer) while being installed into the borehole may experience a strong buoyancy force. This buoyancy force may be reduced almost to zero by filling water in every soil displacement measurement device 100 (or inclinometer unit) before installation. Accordingly, this may make the respective units heavier thus allowing them to be easily pushed down the borehole.

10 **[00029]** Referring back to FIG. 1, according to various embodiments, there is provided a soil displacement measurement device 100. The soil displacement measurement device 100 may be configured as an inclinometer such that, when installed vertically into the ground, a measurement of a tilt in the inclinometer may be a measure of the horizontal/lateral soil displacement in the ground. As shown, the soil displacement measurement device 100 may
15 include an elongate hollow housing 110. The elongate hollow housing 110 may be of a hollow cylindrical shape. According to various embodiments, the elongate hollow housing 110 may include a rigid pipe or a rigid hollow cylinder. Accordingly, the elongate hollow housing 110 may be rigid such that horizontal/lateral displacement of the soil may tilt the elongate hollow housing 110 off vertical instead of bending the elongate hollow housing 110 as in flexible
20 housing. According to various embodiments, the elongate hollow housing 110 may have a first partition 112 and a second partition 114 defining a closed section of the elongate hollow housing 110. Accordingly, the first partition 112 may form a first closed-base and the second partition 114 may form a second closed-base in a manner such that a volume of space enclosed between the first partition 112 and the second partition 114 forms the closed section of the
25 elongate hollow housing 110.

[00030] According to various embodiments, the soil displacement measurement device 100 may include a suspended-body 130. The suspended-body 130 may be disposed within the elongate hollow housing 110. Accordingly, the suspended-body 130 may be suspended within the enclosed volume of space in the elongate hollow housing 110. According to various
30 embodiments, the suspended-body 130 may have a shape having circular symmetry about a main axis passing through the suspended-body 130 at a first surface-intersection-point 132 and a second surface-intersection-point 134. Accordingly, the suspended-body 130 may have a continuous symmetry when rotated about the main axis. According to various embodiments, the suspended-body 130 may include a cylinder, a spheroid, a cone, a double-cone, a bi-cone,

or any other suitable shapes. Further, the first surface-intersection-point 132 and the second surface-intersection-point 134 of the suspended-body 130 may be the points which the main axis intersects an exterior of the suspended-body 130. According to various embodiments, the suspended-body 130 may be suspended between the first partition 112 and the second partition 114 with the first surface-intersection-point 132 directed towards the first partition 112 and the second surface-intersection-point 134 directed towards the second partition 114. According to various embodiments, when the soil displacement measurement device 100 is in a vertical orientation, the main axis of the suspended body 130 may be aligned with a longitudinal axis of the elongate hollow housing 110.

5 [00031] According to various embodiments, the soil displacement measurement device 100 may include a first suspension-line-segment 122 extending from the first surface-intersection-point 132 of the suspended-body 130 towards a center 113 of the first partition 112 of the elongate hollow housing 110. According to various embodiments, one end of the first suspension-line-segment 122 may be directly connected or joined or coupled or fixed to the first surface-intersection-point 132 of the suspended-body 130 and one other end of the first suspension-line-segment 122 may be directly connected or joined or coupled or fixed to the center of the first partition 112 of the elongate hollow housing 110. According to various embodiments, the soil displacement measurement device 100 may include a second suspension-line-segment 124 extending from the second surface-intersection-point 134 of the suspended-body towards a center of the second partition 114 of the elongate hollow housing 110. According to various embodiments, one end of the second suspension-line-segment 124 may be directly connected or joined or coupled or fixed to the second surface-intersection-point 134 of the suspended-body 130 and one other end of the second suspension-line-segment 124 may be directly connected or joined or coupled or fixed to the center of the second partition 114 of the elongate hollow housing 110. According to various embodiments, the suspended-body 130 may be suspended inside the elongate hollow housing 110 across the longitudinal direction (or lengthwise) by the first suspension-line-segment 122 and the second suspension-line-segment 124. According to various embodiments, a strain measurement element 140 may be disposed along the second suspension-line-segment 122. According to various embodiments, the strain measurement element 140 may be configured to measure a strain experienced by the second suspension-line-segment 124. According to various embodiments, the strain measurement element 140 may include fibre Bragg grating (FBG).

[00032] According to various embodiments, a ratio of a length of the first suspension-line-segment 122 to a length of the second suspension-line-segment 124 may be equal or more than

1. Accordingly, the length of the first suspension-line-segment 122 may be equal or longer than the length of the second suspension-line-segment 124. In such a configuration, the soil displacement measurement device 100 may be more sensitive with better response.

5 **[00033]** According to various embodiments, the first suspension-line-segment 122 and the second suspension-line-segment 124 may be pre-tensioned. Accordingly, the first suspension-line-segment 122 and the second suspension-line-segment 124 may be preloaded with a tension so as to maintain the first suspension-line-segment 122, the second suspension-line-segment 124 and the main axis of the suspended-body 130 along a longitudinal axis of the elongate hollow housing 110.

10 **[00034]** According to various embodiments, the first suspension-line-segment 122 and the second suspension-line-segment 124 may be fixed to the respective first surface-intersection-point 132 and second surface-intersection-point 134 via adhesive. According to various embodiments, the first suspension-line-segment 122 and the second suspension-line-segment 124 may be fixed to the respective centers of the first partition 112 and the second partition 114 via adhesive. The adhesive may include glue or epoxy glue.

[00035] According to various embodiments, a protection sleeve may be provided to surround each fixing end of the first suspension-line-segment 122 and the second suspension-line-segment 124. Accordingly, a protection sleeve may be provided at an end of the first suspension-line-segment 122 that is attached or fixed or coupled or connected to the first surface-intersection point 132 of the suspended-body 130. A protection sleeve may also be provided at another end of the first suspension-line-segment 122 that is attached or fixed or coupled or connected to the center of the first partition 112. Similarly, a protection sleeve may be provided at an end of the second suspension-line-segment 124 that is attached or fixed or coupled or connected to the second surface-intersection point 134 of the suspended-body 130, and a protection sleeve may also be provided at another end of the second suspension-line-segment 124 that is attached or fixed or coupled or connected to the center of the second partition 114.

25 **[00036]** According to various embodiments, the soil displacement measurement device 100 may include a single optical fiber extending from the center of the first partition 112 of the elongate hollow housing 110 to the first surface-intersection-point 132 of the suspended-body 130, through the suspended-body 130, and from the second surface-intersection-point 134 of the suspended-body 130 to the center of the second partition 114 of the elongate hollow housing 110. Accordingly, the first suspension-line-segment 122 may be a segment of the single optical fiber between the first partition 112 of the elongate hollow housing 110 and the

first surface-intersection-point 132 of the suspended-body 130. Further, the second suspension-line-segment 124 may be a segment of the single optical fiber between the second surface-intersection-point 134 of the suspended-body 130 and the second partition 114 of the elongate hollow housing 110. According to various embodiments, the strain measurement
5 element 140 in the form of the FBG may be a part of the single optical fiber along the second suspension-line-segment 124.

[00037] According to various other embodiments, the first suspension-line-segment 122 may include a metal wire. The metal wire may include aluminium wire or steel wire. Further, the second suspension-line-segment 124 may include an optical fiber. According to various
10 embodiments, the strain measurement element 140 in the form of the FBG may be a part of the optical fiber along the second suspension-line-segment 124.

[00038] According to various embodiments, the elongate hollow housing 110 of the soil displacement measurement device 100 may be filled with a fluid medium. According to various embodiments, the fluid medium may be contained within the volume of space enclosed
15 between the first partition 112 and the second partition 114 forming the closed section of the elongate hollow housing 110. The fluid medium may include a liquid such as water. The fluid medium may reduce shaking/vibration in the first suspension-line-segment 122 and the second suspension-line-segment 124. Accordingly, when the first suspension-line-segment 122 and/or the second suspension-line-segment 124 is/are optical fiber, the fluid medium may
20 reduce the risk of the optical fiber breaking due to induced vibration or shaking from the suspended-body 130 which acts as a hanging mass. Further, the fluid medium may increase the weight of the soil displacement measurement device 100 which may allow easier installation into a borehole.

[00039] Referring to FIG. 2(a) to FIG. 2(d), according to various embodiments, the soil displacement measurement device 100 may include a first connection fixture 250a disposed
25 on an exterior of the elongate hollow housing 110 at a first end portion 116 and a second connection fixture 250b disposed on an exterior of the elongate hollow housing 110 at a second end portion 118. According to various embodiments, each of the first connection fixture 250a and the second connection fixture 250b may be configured for connecting with a flexible
30 elongate link member 260.

[00040] As shown, according to various embodiments, each of the first connection fixture 250a and the second connection fixture 250b may include three or more attachment elements 252. Each attachment element 252 may be configured to interlock with the flexible elongate link member 260. According to various embodiments, the attachment element 252 may be a

groove configured to accommodate and interlock with an end of the flexible elongate link member 260.

[00041] Referring to FIG. 2(d), according to various embodiments, a soil displacement measurement system 201 may include at least two soil displacement measurement devices 100 as described above. The at least two soil displacement measurement devices 100 may be interconnected via three or more flexible elongate link members 260. Each of the three or more flexible elongate link members 260 may have a first end interlocks with an attachment element of one of the at least two soil displacement measurement devices 100 and a second end interlocks with an attachment element of another one of the at least two soil displacement measurement devices 100. Accordingly, the soil displacement measurement system 201 may include multiple soil displacement measurement device 100 joined or connected in series one after another to form a chain of soil displacement measurement device 100 for inserting and/or installing into a borehole.

[00042] In the following, experiments/analysis conducted and results from the experiments/analysis based on the soil displacement measurement device 100 of FIG. 1 is discussed.

[00043] In an experiment to calibrate and check the performance of the soil displacement measurement device 100 of FIG. 1, a solid steel cylinder (Dia. = 39mm, height = 20mm) (serving as the suspended-body 130) was hung through an optical fiber (serving as the first suspension-line-segment 122 and the second suspension-line-segment 124). The outer and inner diameters of the inclinometer tube (PMMA), which serve as the elongate hollow housing 110, were 70mm and 66mm, respectively. The optical fiber was bonded to the top plate (i.e. the first partition 112), the bottom plate (i.e. the second partition 114) and the hanging weight (i.e. the suspended-body 130) through fiber protection sleeves. The FBG (i.e. the strain measurement element 140) was in the lower part (i.e. second suspension-line-segment 124) of the optical fiber (i.e. suspension-line 120). The inclinometer (i.e. the soil displacement measurement device 100) was initially vertical and a small tension was applied to the lower part of the optical fiber. The weight of the steel body was 1.76N. Water (i.e. fluid medium) was poured into the tube through a hole in the top plate until the tube was full. The water reduces the shaking/vibrations in the optical fiber due to the hanging weight. Extreme vibrations might break the fiber at FBG since it is relatively weaker at the FBG point. Moreover, the water makes the inclinometer unit heavier and therefore, it may be easier to push this inclinometer down the borehole into the grout. The effective weight of the steel body becomes 1.53N in water. The inclinometer unit was then inclined slowly in one direction and

the increasing strain in the FBG was recorded. The inclinometer unit was rotated by 90° and then inclined again, and the increasing strain in the FBG was recorded. The simulation data points were calculated using mathematical modelling and analysis based on tension forces in optical fiber and based on elasticity in optical fiber. The experimental and simulation results match well as can be clearly seen from FIG. 3. FIG. 3 shows a graph 390 illustrating a comparison between experimental and simulation results. It can also be observed that the effect of rotation is negligible as expected.

[00044] In another experiment, the sensitivity of the soil displacement measurement device 100 of FIG. 1 was compared with different materials used in the upper section (i.e. the first suspension-line-segment 122). According to the experiment conducted, the sensitivity of the inclinometer unit (i.e. the soil displacement measurement device 100 of FIG. 1) may be increased by increasing the weight of the steel body (i.e. suspended-body 130), but this may increase the tension in the fiber resulting in the increased possibility of breakage of the fiber due to shaking. Another way to increase the sensitivity is to use hanging wire with higher tensile strength instead of the optical fiber in the upper half (i.e. the first suspension-line-segment 122) of the inclinometer, which is from the top to the hanging steel body, while keeping the effective weight of the steel body same (1.53N). This may result in lower strain in the upper metal wire and higher strain in FBG at the lower optical fiber (i.e. the second suspension-line-segment 124). The comparison among the simulation results when materials with higher tensile strength (higher than optical fiber, 16.5 GPa) such as an aluminum wire (69 GPa), steel wire (117 GPa) are used in the upper half of the inclinometer unit, are shown in a graph 490 in FIG. 4. The diameters of all the wires are assumed the same as of optical fiber (250 μm). Hence, from the result, the inclinometer unit may be configured according to the requirement of the application.

[00045] In another experiment, the sensitivity of the soil displacement measurement device 100 of FIG. 1 was compared with different length ratio (l_1/l_2), whereby l_1 is a length of the first suspension-line-segment 122 and l_2 is a length of the second suspension-line-segment 124. From mathematical modelling and analysis based on elasticity in optical fiber, the lengths (l_1 and l_2) of the upper half and the lower half of the hanging fiber (i.e. suspension-line 120) also determine the nature of the response of the inclinometer unit (i.e. the soil displacement measurement device 100). FIG. 5 shows a graph 590 illustrating the simulated response of the inclinometer at various length ratios ($l_1 = 10$ cm, $l_2 = 25$ cm; $l_1 = 25$ cm, $l_2 = 25$ cm; $l_1 = 50$ cm, $l_2 = 25$ cm). As shown, the sensitivity of the inclinometer is better when the ratio, l_1/l_2 is more

than or equal to 1. Also, for the ratio, l_1/l_2 more than 1, the response of the inclinometer is more linear at the angles of inclination close to zero.

[00046] In further experiment, a study on the behavior of a simulated full-size borehole inclinometer (e.g. the soil displacement measurement system 201 as shown in FIG. 2(d)) is conducted. A borehole is usually of tens of meters in depth for the installation of an inclinometer. Hence, a number of such inclinometer units (e.g. the soil displacement measurement device 100 of FIG. 1) must be connected to make a full-length inclinometer (e.g. the soil displacement measurement system 201 as shown in FIG. 2(d)). As mentioned earlier, the connection between any two inclinometer units must be flexible so that full-length inclinometer can monitor the soil profile continuously.

[00047] In this experiment, three identical inclinometer units 600a, 600b, 600c (see FIG. 6 which shows a photograph 692 of three identical soil displacement measurement device of FIG. 1 filled with water) were prepared to study their behaviour when connected with each other on a lower scale. A full-size inclinometer is typically supposed to be installed in the borehole which is already filled with water. Therefore, the inclinometer during installation into the borehole will experience a strong buoyancy force. This buoyancy force may be reduced significantly (almost to zero) by filling water in every inclinometer unit (e.g. the soil displacement measurement device 100 of FIG. 1) before installation. This may make the individual units heavier such that they can be easily pushed down the borehole. Filling water may not change the working principle of each unit in any way except, the sensitivity of the unit may be reduced slightly. This reduction in sensitivity happens because the effective weight of the steel body (i.e. suspended-body 130), which is inside the inclinometer, may be reduced as it is immersed into the water. Therefore, in the experiment, these three units may be filled with water through a hole in the top plate and later these holes were sealed. All the dimensions were kept the same as earlier except, the weight of the steel body. In the case of all the units, the weight of the steel body was 1.45N. Since the steel bodies are immersed in water, their effective weight is 1.42N. All the three units were calibrated, and the results are shown in a graph 790 in FIG. 7. Although they are identical, their characteristics are slightly different from each other. These differences are there because these units were assembled manually in the lab. For more accuracy, the angle of inclination and strain read by FBGs were fitted linearly. The linear relationships between the angle of inclination (θ) and the strain in FBG ($\mu\epsilon$) for each inclinometer unit are also shown in the graph 790 in FIG. 7. The angle of inclination can be calculated using the value of strain in FBG (i.e. strain measurement element 140) at any time. The resolution of all these inclinometer units is more or less the same

(0.006°). To achieve this angle resolution, the FBG interrogator system must have a peak wavelength resolution of 1 pm.

[00048] A schematic diagram of the connected inclinometer units 600a, 600b, 600c forming an inclinometer 801a (i.e. a soil displacement measurement system) is shown in FIG. 8(a), all the distances are also shown in FIG. 8(a). A photograph 892 of the actual inclinometer 801b for the experiment is shown in FIG. 8(b). The connected inclinometer set-up is implanted in a container filled with soil. It was made sure that the bottom of the inclinometer was fixed and the container was not moving at all. Further, a force was applied on the top 805 of the inclinometer 801 to bend it in one direction as shown in FIG. 9(a). Since the inclinometer connections are flexible, the expected bending profile 994 of the inclinometer is shown in FIG. 9(b). The actual values of displacements at each point in a bent position were recorded. The strain values from the FBGs in all the three inclinometer units were also recorded and these strain values were used to calculate the angles of inclination (θ_1 , θ_2 and θ_3) and hence the displacements (x_1 , x_2 and x_3). The actual and experimental displacement profiles along the height of the inclinometer are shown in a graph 990 in FIG. 9(c). As shown in FIG. 9(c), there are two profiles, one corresponding to a weaker force and another corresponding to a relatively stronger force. As shown, the experimental displacement values are very close to the actual ones and the profiles match very well.

[00049] In another experiment, the inclinometer 1001 was clamped and fixed at the connection point 1003 of the lowest inclinometer unit and a force was applied on the top 1005 of the inclinometer 1001 as shown in FIG. 10(a). In this case, the lowest inclinometer unit was not supposed to move and expected bending profile 1094 is shown in FIG. 10(b). The actual and experimental displacement profiles are shown in a graph 1090 in FIG. 10(c). Again, there are two profiles corresponding to two forces (one weaker and another stronger). They also match well in this case.

[00050] According to various embodiments, the hanging mass (i.e. the suspended-body 130) may be a symmetric body (for example a sphere, a cylinder, a cone etc.) and the optical fiber may go through it along its axis of symmetry. However, in the various experiments and analysis conducted, the cylindrical body is chosen because, for the same volume of the hanging mass, the cylindrical shapes may allow the maximum angle measurement range without touching the wall of the cylindrical casing of the inclinometer unit (i.e. the soil displacement measurement device 100 of FIG. 1). According to various embodiments, the material of the hanging mass may be other metals like copper or lead.

[00051] Based on the experiments and analysis, mathematical model suggests that the strains induced in the upper (i.e. first suspension-line-segment 122) and lower half (i.e. second suspension-line-segment 124) of the optical fiber may be more or less the same, which may indicate that the sensitivity may be independent of the FBG position. However, in the various experiments and analysis conducted, the FBG is put in the lower fiber only because it avoids the unnecessary static loading of the FBG due to the hanging mass (i.e. the suspended-body 130).

[00052] According to various embodiments, the shape and the diameter of the inclinometer (i.e. the soil displacement measurement device 100 of FIG. 1) are chosen to make it suitable for borehole installation. The shape and the dimensions may be modified according to the application. As explained earlier, the sensitivity of the inclinometer may be better when the ratio, l_1/l_2 is more than or equal to 1. Also, for the ratio, l_1/l_2 more than 1, the response of the inclinometer may be more linear at the angles of inclination close to zero.

[00053] According to various embodiments, the connections between inclinometers (i.e. the soil displacement measurement device 100 of FIG. 1) may be flexible and may allow the inclinometer system (e.g. a soil displacement measurement system) to bend and take the shape of the soil profile. Any connection method, as long as it has this requirement fulfilled, maybe adopted.

[00054] According to various embodiments, while the the soil displacement measurement device 100 of FIG. 1 as depicted is used as tilt sensor or inclinometer. The soil displacement measurement device 100 of FIG. 1 can also be used as accelerometer by restricting the movement of the mass (i.e. the suspended-body 130) in the radial direction while allowing it to move in the axial direction as shown in FIG. 11. FIG. 11 shows a schematic diagram of a soil displacement measurement device 1100 being configured as an inclinometer according to various embodiments.

[00055] Various embodiments have provided a soil displacement measurement device and/or a soil displacement measurement system which are configured as a FBG based in-place inclinometer that is rotation independent and employs less manpower as compared to the conventional one. The resolution for the measurement of angle of inclination may be 0.006° which is very good for almost all the commercial applications. Heavy construction sites, tunnelling, oil drilling, geological drilling and coal mine drilling etc. may be the areas of application for the various embodiments.

[00056] FIG. 12 shows a schematic diagram of a soil displacement measurement device 1200 being configured as an extensometer according to various embodiments. As shown in FIG. 12, in the soil displacement measurement device 1200, which is configured as the extensometer, a disc magnet (which serves as an inner magnet 1230) and a ring magnet (which serves as an outer ring-magnet 1270) may be placed in parallel planes as shown in FIG. 12. Both magnets may be concentric and magnetized along a z-direction (i.e. their directions of magnetization may be either parallel or anti-parallel). Thus, in the soil displacement measurement device 1200, both magnets may be magnetized along a longitudinal direction (or along an axis) of the soil displacement measurement device 1200. According to various embodiments, the disc magnet may be suspended by a suspension arrangement 1220. For example, the disc magnet may be hanging with an optical fiber with fiber Bragg grating (FBG) (which serves as a strain measurement element 1240) as shown in FIG. 12. Since the magnets are concentric, the radial magnetic force (F_r) on the disc magnet may be zero. Thus, there may be zero or negligible resultant force acting on the disc magnet in any of the radial direction. On the other hand, the axial magnetic force (F_z) may be a function of an axial distance between the disc magnet and the ring magnet. According to various embodiments, the axial magnetic force (F_z) between the two coaxing magnets may change as an axial distance between the two magnets changes when the two magnets move relative to each other. In Fig. 12, since the disc magnet is being suspended by the optical fiber, the change in the axial magnetic force (F_z) between the two coaxing magnets may induce a change in strain in the optical fiber which may be sensed and/or measured and/or detected and/or determined by the FBG. In use, the ring magnet may be fixed or anchored with the soil outside an outer casing (for example a cylindrical hollow housing 1210) with the help of spider legs (which serves as anchors 1272) in a borehole. When the soil settles/heaves, the ring magnet may move along the outer casing accordingly while the disc magnet, which is suspended inside the outer casing, may remain stagnant together with the outer casing at its initial or original position. Accordingly, the relative movement between the two coaxing magnets due to soil movement may change the axial magnetic force (F_z) between the two magnets to induce a change in the strain in the optical fiber suspending the disc magnet, whereby the change in strain may be sensed and/or measured and/or detected and/or determined by the FBG.

[00057] FIG. 13 shows a schematic diagram of a soil displacement measurement device 1300 being configured as an extensometer according to various embodiments. As shown in FIG. 13, in the soil displacement measurement device 1300, which is configured as the

extensometer, a disc magnet (which serves as an inner magnet 1330) may be magnetized in a y-direction while the ring magnet (which serves as an outer ring-magnet 1370) may be magnetized in a z-direction (i.e. the directions of their magnetization are perpendicular to each other). Accordingly, in the soil displacement measurement device 1300, the ring magnet may

5 be magnetized along a longitudinal direction (or along an axis) of the soil displacement measurement device 1300, while the disc magnet may be magnetized in a direction perpendicular to the longitudinal direction (or the axis) of the soil displacement measurement device 1300. According to various embodiments, the disc magnet may be suspended by a suspension arrangement 1320. For example, the disc magnet may be attached to a free end of

10 an aluminum cantilever (the cantilever may be in the z-x plane) and a FBG sensing element (which serves as a strain measurement element 1340) may be bonded to a fixed end of the cantilever as shown in FIG. 13. According to various embodiments, a magnetic force between the two coaxing magnets in the y-direction (or in the direction perpendicular to the longitudinal direction of the soil displacement measurement device 1300) may be a function

15 of an axial distance between the disc magnet and the ring magnet. Accordingly, when the two coaxing magnets are moved relatively towards each other along the longitudinal direction (or along the axis) of the soil displacement measurement device 1300, the disc magnet may be pushed in the y-direction (or a direction perpendicular to the axis of the soil displacement measurement device 1300) by a stronger magnetic force between the two magnets as the two

20 magnets become closer. Hence, the disc magnet may pull the free end of the cantilever along the y-axis along with it which in turn may induce a strain in the cantilever which may be sensed and/or measured and/or detected and/or determined by the FBG sensing element. According to various embodiments, an axis of the ring magnet may be at $x = 0$, $y = 0$, and the disc magnet may be shifted and/or offset in the +y direction so as to have a stronger magnetic force in the

25 y-direction when it is required to have a higher measurement range and/or resolution. Therefore, according to various embodiments, any vertical movement in the ring magnet's (or in the soil) position along the longitudinal direction of the soil displacement measurement device 1300 may change a magnetic force between the two coaxing magnets which may induce a change in strain in the cantilever, whereby the change in strain may be sensed and/or

30 measured and/or detected and/or determined the FBG.

[00058] Referring back to FIG. 12 and FIG. 13, according to various embodiments, there is provided a soil displacement measurement device 1200, 1300. The soil displacement measurement device 1200, 1300 may be configured as an extensometer such that when installed vertically into the ground, the extensometer may measure a vertical soil displacement

in the ground. As shown, each of the soil displacement measurement device 1200, 1300 may include a cylindrical hollow housing 1210, 1310. Accordingly to various embodiments, the cylindrical hollow housing 1210, 1310 may include a rigid pipe or a rigid hollow cylinder. Accordingly, the cylindrical hollow housing 1210, 1310 may be rigid such that
5 horizontal/lateral displacement of the soil may not bend the cylindrical hollow housing 1210, 1310.

[00059] According to various embodiments, the soil displacement measurement device 1200, 1300 may include the outer ring-magnet 1270, 1370 slidably arranged on an exterior surface 1211, 1311 of the cylindrical hollow housing 1210, 1310 in a manner such that the
10 cylindrical hollow housing 1210, 1310 may be inserted through a central cavity of the outer ring-magnet 1270, 1370. Accordingly, the outer ring-magnet 1270, 1370 may be placed over the exterior surface 1211, 1311 of the cylindrical hollow housing 1210, 1310 with the cylindrical hollow housing 1210, 1310 put or pass through the central cavity of the outer ring-magnet 1270, 1370 such that the outer ring-magnet 1270, 1370 is movable relative to the
15 cylindrical hollow housing 1210, 1310 in continuous contact with the exterior surface 1211, 1311 of the cylindrical hollow housing 1210, 1310.

[00060] According to various embodiments, the soil displacement measurement device 1200, 1300 may include the inner magnet 1230, 1330 disposed within the cylindrical hollow housing 1210, 1310. According to various embodiments, the soil displacement measurement
20 device 1200, 1300 may further include the suspension arrangement 1220, 1320 holding the inner magnet 1230, 1330 with respect to the cylindrical hollow housing 1210, 1310 so as to suspend the inner magnet 1230, 1330 within an interior space of the cylindrical hollow housing 1210, 1310. Accordingly, the cylindrical hollow housing 1210 may define the interior space in which the inner magnet 1230, 1330 may be held in suspension with respect to the cylindrical
25 hollow housing 1210 by the suspension arrangement 1220, 1320. Hence, a portion of the suspension arrangement 1220, 1320 may be fixed to a portion of the cylindrical hollow housing, and a further portion of the suspension arrangement 1220, 1320 may be extended into the interior space of the cylindrical hollow housing 1210 in a manner in which the further portion of the suspension arrangement 1220, 1320 may be away from the walls of the
30 cylindrical hollow housing 1210 such that the inner magnet 1230, 1330 being attached or coupled to the further portion of the suspension arrangement 1220, 1320 may be suspended or hung away from the walls of the cylindrical hollow housing 1210. According to various embodiments, the inner magnet 1230, 1330 may be a disc magnet, a round magnet, a cylinder magnet, or a ring-shaped magnet, or any other magnet with suitable shapes.

[00061] According to various embodiments, the soil displacement measurement device 1200, 1300 may include the strain measurement element 1240, 1340 provided to a region of the suspension arrangement 1220, 1320. According to various embodiments, the region of the suspension arrangement 1220, 1320 may be a region in which the suspension arrangement
5 may experience a strain that may be sensed and/or measured and/or detected and/or determined by the strain measurement element 1240, 1340. According to various embodiments, the strain measurement element 1240, 1340 may include fibre Bragg grating (FBG).

[00062] According to various embodiments, a relative movement between the outer ring-magnet 1270, 1370 and the cylindrical hollow housing 1210, 1310 along a longitudinal axis
10 of the cylindrical hollow housing 1210, 1310 may cause the outer ring-magnet 1270, 1370 to coact with the inner magnet 1230, 1330 in a manner such that a magnetic force between the outer ring-magnet 1270, 1370 and the inner magnet 1230, 1330 may change a corresponding strain at the region of the suspension arrangement 1220, 1320. For example, when the outer ring-magnet 1270, 1370 is moved along the cylindrical hollow housing 1210, 1310 towards
15 the inner magnet 1230, 1330 such that an axial distance between the outer ring-magnet 1270, 1370 and the inner magnet 1230, 1330 becomes shorter and closer or away from the inner magnet 1230, 1330 such that an axial distance between the outer ring-magnet 1270, 1370 and the inner magnet 1230, 1330 becomes longer and further, depending on the respective directions of magnetization of the respective magnets, a magnetic force (i.e. a magnetic
20 repulsion force or a magnetic attractive force) between the coacting outer ring-magnet 1270, 1370 and the inner magnet 1230, 1330 may change (i.e. increase to become stronger or decrease to become weaker). The change in the magnetic force between the outer ring-magnet 1270, 1370 and the inner magnet 1230, 1330 may introduce and/or change a resultant force (i.e. increase to become stronger or decrease to become weaker) which is exerted by the inner
25 magnet 1230, 1330 to the suspension arrangement 1220, 1320 and which has a tendency to pull and/or stretch and/or deform the region of the suspension arrangement 1220, 1320 such that the region of the suspension arrangement 1220, 1320 with the strain measurement element 1240, 1340 may experience a strain or a change in strain. Thus, the relative movement between the outer ring-magnet 1270, 1370 and the cylindrical hollow housing 1210, 1310 along the
30 longitudinal axis of the cylindrical hollow housing 1210, 1310, which may be translated to a relative movement between the outer ring-magnet 1270, 1370 and the inner magnet 1230, 1330 in the axial direction of the cylindrical hollow housing 1210, 1310, may cause the region of the suspension arrangement 1220, 1320 to experience a corresponding strain change which

may be sensed and/or measured and/or detected and/or determined by the strain measurement element 1240, 1340.

[00063] According to various embodiments, the change in the strain may be detected by the strain measurement element 1240, 1340 as a measure of the relative displacement of the outer ring-magnet 1270, 1370 along the longitudinal axis of the cylindrical hollow housing 1210, 1310. Accordingly, the strain sensed and/or measured and/or detected and/or determined by the strain measurement element 1240, 1340 may be used to convert into and/or calculate and/or determine and/or derived the displacement of the outer ring-magnet 1270, 1370 with respect to the cylindrical hollow housing 1210, 1310. The displacement of the outer ring-magnet 1270, 1370 may then be a measure of vertical soil displacement when the soil displacement measurement device 1200, 1300 is used.

[00064] According to various embodiments, the soil displacement measurement device 1200, 1300 may further include one or more anchors 1272, 1372 coupled to the outer ring-magnet 1270, 1370 in a manner such that the one or more anchors 1272, 1372 project away from the cylindrical hollow housing 1210, 1310 for anchoring the outer ring-magnet 1270, 1370 to an external medium. The external medium may be a settling layer of the soil in the ground in which the soil displacement measurement device 1200, 1300 may be installed. According to various embodiments, the one or more anchors 1272, 1372 may be distributed along a circumference of the outer ring-magnet 1270, 1370 and may be configured to anchor radially outward away from the cylindrical hollow housing 1210, 1310. The one or more anchors 1271, 1372 may be spider-legs type projections, claw type projections, jaw type projections, hook type projections, or other suitable projections that may be penetrated and/or pierced and/or sunk and/or pressed into soil.

[00065] Referring back to FIG. 12, according to various embodiments, the cylindrical hollow housing 1210 may have a first partition 1212 and a second partition 1214 defining a closed section of the cylindrical hollow housing 1210. Accordingly, the first partition 1212 may form a first closed-base and the second partition 1214 may form a second closed-base in a manner such that a volume of space enclosed between the first partition 1212 and the second partition 1214 forms the closed section of the cylindrical hollow housing 1210.

[00066] According to various embodiments, the inner magnet 1230 may be suspended with a first flat-surface 1232 of the inner magnet 1230 directed towards the first partition 1212 of the cylindrical hollow housing 1210 and a second flat-surface 1234 of the inner magnet 1230 directed towards the second partition 1214 of the cylindrical hollow housing 1210. The first flat-surface 1232 may be opposite the second flat-surface 1234. Accordingly, the inner magnet

1230 may be aligned to the cylindrical hollow housing 1210 such that the first flat-surface 1232 and the second flat-surface 1234 of the inner magnet 1230 are facing respective first partition 1212 and second partition 1214 of the cylindrical hollow housing 1210. According to various embodiments, when the soil displacement measurement device 1200 is in a vertical orientation, an axis of symmetry of the inner magnet 1230 may be aligned with a longitudinal axis of the cylindrical hollow housing 1210.

[00067] According to various embodiments, the suspension arrangement 1220 may include a first suspension-line-segment 1222 extending along the longitudinal axis of the cylindrical hollow housing 1210 between a center of the first flat-surface 1232 of the inner magnet 1230 and a center of the first partition 1212 of the cylindrical hollow housing 1210. According to various embodiments, one end of the first suspension-line-segment 1222 may be directly connected or joined or coupled or fixed to the center of the first flat-surface 1232 of the inner magnet 1230 and one other end of the first suspension-line-segment 1222 may be directly connected or joined or coupled or fixed to the center of the first partition 1212 of the cylindrical hollow housing 1210. According to various embodiments, the suspension arrangement 1220 may further include a second suspension-line-segment 1224 extending along the longitudinal axis of the cylindrical hollow housing 1210 between a center of the second flat-surface 1232 of the inner magnet 1230 and a center of the second partition 1214 of the elongate hollow housing 1210. According to various embodiments, one end of the second suspension-line-segment 1224 may be directly connected or joined or coupled or fixed to the center of the second flat-surface 1232 of the inner magnet 1230 and one other end of the second suspension-line-segment 1224 may be directly connected or joined or coupled or fixed to the center of the second partition 1214 of the cylindrical hollow housing 1210. According to various embodiments, the inner magnet 1230 may be suspended inside the cylindrical hollow housing 1210 across the longitudinal direction (or lengthwise) by the first suspension-line-segment 1222 and the second suspension-line-segment 1224. According to various embodiments, a strain measurement element 1240 may be disposed along the first suspension-line-segment 1222. According to various embodiments, the strain measurement element 1240 may be configured to measure a strain experienced by the first suspension-line-segment 1222.

[00068] According to various embodiments, the inner magnet 1230 and the outer ring-magnet 1270 may be magnetized such that respective magnetization directions are parallel or antiparallel relative to each other. Accordingly, the inner magnet 1230 and the outer ring-magnet 1270 may be magnetized in the longitudinal direction (or along the longitudinal axis) of the cylindrical hollow housing 1210. With the outer ring-magnet 1270 outside the

cylindrical hollow housing 1210 and the inner magnet 1230 inside the cylindrical hollow housing 1210, the inner magnet 1230 and the outer ring-magnet 1270 may be in a concentric arrangement. In such concentric arrangement, a radial magnetic force on the inner magnet 1230 may be zero such that there may be zero or negligible resultant force acting on the inner magnet 1230 in any of the radial direction. On the other hand, an axial magnetic force (i.e. an axial magnetic repulsion force or an axial magnetic attractive force) between the two coaxing magnets 1230, 1270 may be a function of an axial distance between the inner magnet 1230 and the outer ring-magnet 1270. According to various embodiments, the axial magnetic force between the two coaxing magnets 1230, 1270 may change as the axial distance between the two magnets 1230, 1270 changes when the two magnets 1230, 1270 move relative to each other. In Fig. 12, since the inner magnet 1230 is being suspended by the first suspension-line-segment 1222 and the second suspension-line-segment 1224, the change in the axial magnetic force between the outer ring-magnet 1270 and the inner magnet 1230 may introduce and/or change a resultant axial force (i.e. increase to become stronger or decrease to become weaker) which is exerted by the inner magnet 1230, 1330 to the first suspension-line-segment 1222 and the second suspension-line-segment 1224. According to various embodiments, the first suspension-line-segment 1222 and the second suspension-line-segment 1224 may be pre-tensioned. Accordingly, the first suspension-line-segment 1222 and the second suspension-line-segment 1224 may be pre-loaded with respective initial axial forces. Since the initial axial forces have a tendency to pull and/or stretch and/or deform the respective first suspension-line-segment 1222 and second suspension-line-segment 1224, each of the first suspension-line-segment 1222 and second suspension-line-segment 1224 may be under strain. Therefore, the resultant axial force may be a result of the change in the initial axial force (for example, by addition or subtraction) caused by the change in the axial magnetic force between the outer ring-magnet 1270 and the inner magnet 1230. The resultant axial force may change the strain experienced by the first suspension-line-segment 1222 and second suspension-line-segment 1224 accordingly. Thus, the change in the axial magnetic force between the two coaxing magnets 1230, 1270 may induce a change in strain in the respective first suspension-line-segment 1222 and the second suspension-line-segment 1224, which may be sensed and/or measured and/or detected and/or determined by the strain measurement element 1240 along the first suspension-line-segment 1222. Accordingly, the relative movement between the outer ring-magnet 1270 and the cylindrical hollow housing 1210 along the longitudinal axis of the cylindrical hollow housing 1310 may result in relative movement between the two magnets 1230, 1270, which may be translated to a relative movement between the outer ring-magnet

1270 and the inner magnet 1230 in the axial direction of the cylindrical hollow housing 1210, may changes a magnetic force between the two coaxing magnets 1230, 1270 to induce a change in the strain in the respective first suspension-line-segment 1222 and the second suspension-line-segment 1224 suspending the inner magnet 1230, whereby the change in strain may be sensed and/or measured and/or detected and/or determined by the strain measurement element 1240 along the first suspension-line-segment 1222.

[00069] According to various embodiments, the first suspension-line-segment 1222 may be an optical fiber. Accordingly, when the strain measurement element 1240 is a FBG, the FBG may be part of the optical fiber.

[00070] According to various embodiments, a protection sleeve may be provided to surround each fixing end of the first suspension-line-segment 1222 and the second suspension-line-segment 1224. Accordingly, a protection sleeve may be provided at an end of the first suspension-line-segment 1222 that is attached or fixed or coupled or connected to the first flat-surface 1232 of the inner magnet 1230. A protection sleeve may also be provided at another end of the first suspension-line-segment 1222 that is attached or fixed or coupled or connected to the center of the first partition 1212. Similarly, a protection sleeve may be provided at an end of the second suspension-line-segment 1224 that is attached or fixed or coupled or connected to the second flat-surface 1234 of the inner magnet 1230, and a protection sleeve may also be provided at another end of the second suspension-line-segment 1224 that is attached or fixed or coupled or connected to the center of the second partition 1214.

[00071] According to various embodiments, the soil displacement measurement device 1200 may further include an annularly shaped magnet-housing 1680 (see FIG. 16) having a cavity in the center to accommodate the inner magnet 1230, wherein an outer boundary of the annularly shaped magnet-housing 1680 may be dimensioned to fit into the cylindrical hollow housing. Accordingly, the magnet-housing 1680 may prevent the inner magnet 1230 from collapsing towards an inner wall of the cylindrical hollow housing 1210 so as to maintain the inner magnet 1230 along the axis of the cylindrical hollow housing 1210.

[00072] According to various embodiments, the cylindrical hollow housing 1210 of the soil displacement measurement device 1200 may be filled with a fluid medium. According to various embodiments, the fluid medium may be contained within the volume of space enclosed between the first partition 1212 and the second partition 1214 forming the closed section of the cylindrical hollow housing 1210. The fluid medium may include a liquid such as water. The fluid medium may reduce shaking/vibration in the first suspension-line-segment 1222 and the second suspension-line-segment 1224. Accordingly, when the first suspension-line-

segment 1222 and/or the second suspension-line-segment 1224 is/are optical fiber, the fluid medium may reduce the risk of the optical fiber breaking due to induced vibration or shaking. Further, the fluid medium may increase the weight of the soil displacement measurement device 1200 which may allow easier installation into a borehole.

5 **[00073]** Referring back to FIG. 13, according to various embodiments, the suspension arrangement 1320 of the soil displacement measurement device 1300 may include a cantilever structure 1321 which is aligned parallel to the longitudinal axis of the cylindrical hollow housing 1310 and which has a first end portion 1323 fixedly coupled to the cylindrical hollow housing and a second free-end portion 1325. According to various embodiments, the
10 cantilever structure 1321 may be aligned on the longitudinal axis of the cylindrical hollow housing 131. According to various other embodiments, the cantilever structure 1321 may be offset laterally from the longitudinal axis of the cylindrical hollow housing 1310. According to various embodiments, the first end portion 1323 of the cantilever structure 1321 which is fixedly coupled to the cylindrical hollow housing may be directed towards an end of the
15 cylindrical hollow housing. According to various embodiments, the second free-end portion 1325 of the cantilever structure 1321 may be directed into a middle section of the interior space of the cylindrical hollow housing 1310.

[00074] According to various embodiments, the inner magnet 1330 may be fixed to the second free-end portion 1325 of the cantilever structure 1321. Accordingly, a force exerted
20 by the inner magnet 1330 at the second free-end portion 1324 of the cantilever structure 1321 may cause a deflection of the cantilever structure 1321. According to various embodiments, the strain measurement element 1340 may be attached to the first end portion 1323 of the cantilever structure 1321. Accordingly, the strain measurement element 1340 may detect and/or sense and/or measure and/or determine a strain at the first end portion 1323 of the
25 cantilever structure 1321 when the cantilever structure 1321 is deflected as a result of a force acting on the second free-end portion 1324.

[00075] According to various embodiments, the suspension arrangement 1320 may further include a cantilever-structure-holder 1327 in the form of a circular panel fixedly mounted to an interior wall of the cylindrical hollow housing 1310. The cantilever-structure-holder 1327
30 may be mounted towards an end of the cylindrical hollow housing 1310. According to various embodiments, the cantilever-structure-holder 1327 may serve as a first partition of the cylindrical hollow housing 1310. According to various embodiments, the cantilever-structure-holder 1327 in the form of the circular panel may include a cavity in which the first end portion 1323 of the cantilever structure 1321 may be fixedly fitted. Accordingly, once the first end

portion 1323 of the cantilever structure 1321 is fitted into the cavity of the cantilever-structure-holder 1327, the first end portion 1323 of the cantilever structure 1321 may be rigidly coupled to the cylindrical hollow housing 1310.

[00076] According to various embodiments, the inner magnet 1330 may be fixed to the
5 second free-end portion 1323 of the cantilever structure 1321 in an orientation in which a magnetization direction of the inner magnet 1330 may be at least substantially perpendicular to the longitudinal axis of the cylindrical hollow housing 1310. Accordingly, the outer ring-magnet 1370 may be magnetized along the longitudinal direction (or along the axis) of the cylindrical hollow housing 1310 and the inner magnet 1330 may be magnetized in a direction
10 perpendicular to magnetization direction of the outer ring-magnet 1370. According to various embodiments, the inner magnet 1330 may be suspended by the cantilever structure 1321. According to various embodiments, a magnetic force (i.e. a magnetic repulsion force or a magnetic attractive force) between the two coaxing magnets 1330, 1370 in the magnetization direction of the inner magnet 1330 (or in the direction perpendicular to the longitudinal
15 direction of the cylindrical hollow housing 1310) may be a function of an axial distance between the inner magnet 1330 and the outer ring-magnet 1370. Accordingly, when the two magnets 1330, 1370 are moved relatively towards each other or away from each other along the longitudinal direction (or along the axis) of the cylindrical hollow housing 1310, the magnetic force between the two coaxing magnets 1330, 1370 may change (i.e. increase to
20 become stronger or decrease to become weaker). For example, the inner magnet 1330 may be pushed in the magnetization direction of the inner magnet 1330, which may be perpendicular to the cantilever structure 1321, by a stronger magnetic force between the two coaxing magnets 1330, 1370 as the two magnets 1330, 1370 become closer. Hence, the inner magnet 1330 may apply a perpendicular force on the second free-end portion 1324 so as to pull/push
25 the second free-end portion 1324 of the cantilever structure 1321 causing a deflection of the cantilever structure 1321 which in turn may induce a strain or a change in strain at the first end portion 1323 of the cantilever structure 1321. The strain or the change in strain at the first end portion 1323 of the cantilever structure 1321 may be sensed and/or measured and/or detected and/or determined by the strain measurement element 1340 at the first end portion 1323 of the
30 cantilever structure 1321. Therefore, according to various embodiments, relative movement between the outer ring-magnet 1370 and the cylindrical hollow housing 1310 along the longitudinal axis of the cylindrical hollow housing 1310, which may be translated to a relative movement between the outer ring-magnet 1370 and the inner magnet 1330 in the axial direction of the cylindrical hollow housing 1310, may changes a magnetic force between the

two coaxing magnets 1330, 1370 to cause the cantilever structure 1321 to experience a corresponding strain change which may be detected and/or measured and/or sensed and/or determined by the strain measurement element 1340.

[00077] According to various embodiments, the cylindrical hollow housing 1310 may include a second partition (not shown) at another end of the cylindrical hollow housing 1310 opposite the first partition 1312 (or another end opposite the end of the cylindrical hollow housing 1310 having the cantilever-structure-holder 1327). Accordingly, the first partition 1312 may form a first closed-base and the second partition may form a second closed-base in a manner such that a volume of space enclosed between the first partition 1312 and the second partition forms the closed section of the elongate hollow housing 1310. According to various embodiments, the cylindrical hollow housing 1310 of the soil displacement measurement device 1300 may be filled with a fluid medium. According to various embodiments, the fluid medium may be contained within the volume of space enclosed between the first partition 1312 and the second partition forming the closed section of the cylindrical hollow housing 1310. The fluid medium may include a liquid such as water. The fluid medium may increase the weight of the soil displacement measurement device 1300 which may allow easier installation into a borehole.

[00078] In the following, experiments/analysis conducted and results from the experiments/analysis based on the soil displacement measurement device 1200 of FIG. 12 and the soil displacement measurement device 1300 of FIG. 13 is discussed.

[00079] In an experiment, performance of the soil displacement measurement device 1200 of FIG. 12 (which is configured as an extensometer) was evaluated using different radii/thickness of the disc magnet (i.e. which serves as the inner magnet 1230). According to various embodiments, the soil displacement measurement device 1200 of FIG. 12 as the extensometer, works on the principle that the axial magnetic force (F_z) changes according to the distance (z) between the ring magnet (i.e. the outer ring-magnet 1270) and the disc magnet (i.e. the inner magnet 1230). In the experiment, the ring magnet and the disc magnet are magnetized in parallel ($\varepsilon = 1$) direction, therefore, the axial magnetic force (F_z) is stronger in z -direction as shown in FIG. 14. The axial magnetic force (F_z) on the disc magnet induces tensile/compressive strain in the FBG (i.e. strain measurement element 1240) (refer FIG. 12) along the optical fiber (i.e. suspension arrangement 1220). The strain induced in the FBG versus the distance between the ring magnet and the disc magnet (z) is plotted in a graph 1490 in FIG. 14. The distance is measured from the center of disc magnet to the center of the ring magnet. The magnetic force is linear in certain range of axial distance (z) which is considered

as the measurement range of the extensometer. The size of the ring magnet and the size of the disc magnet may affect the measurement range and measurement resolution of the extensometer as F_z depends on magnets' sizes. In borehole applications, the ring magnet is permanently installed into the soil outside the borehole. Hence, it cannot be changed once installed. However, the disc magnet may be easily replaced to change the measurement range and measurement resolution of the extensometer. For a given thickness ($2d_I$) and different radii (R_I) of the disc magnet, the strain induced in the FBG versus the distance (z) between the magnets is given in the graph 1490 in FIG. 14. Further, for a given radius (R_I) and different thicknesses ($2d_I$) of the disc magnet, the strain induced in the FBG versus the distance (z) between the magnets is given in a graph 1590 in FIG. 15. Also, the simulation is conducted using 'Magnetic Fields, No Currents (mfnc)' model in COMSOL Multiphysics. The magnetizations $\mathbf{M}_1 = 883.310\hat{z} \text{ (KA/m)}$, $\mathbf{M}_2 = 883.310\hat{z} \text{ (KA/m)}$ are used for the disc magnet and the ring magnet, respectively. The simulation data points are also shown in FIG. 8 and FIG. 9, respectively. The measurement range of the soil displacement measurement device 1200 of FIG. 12 shown in FIG. 14 is about 60mm (from $z = 5\text{cm}$ to $z = 11\text{cm}$) and the measurement resolution is 0.33mm. As shown, for borehole application, the results indicated that the measurement range and resolution of the soil displacement measurement device 1200 of FIG. 12 as the extensometer may be improved by changing the radius (R_I) and thickness ($2d_I$) of the disc magnet.

[00080] In another experiment, actual experimental results are compared with simulation and analytical results for the soil displacement measurement device 1200 of FIG. 12. The experimental setup of the soil displacement measurement device 1200 of FIG. 12 is shown in a photograph 1692 in FIG. 16. The ring magnet (outer dia. = 76 mm, inner dia. = 42 mm, thickness = 12 mm) (i.e. outer ring-magnet 1270) and the disc magnet (dia. = 10mm, thickness = 5mm) (i.e. inner magnet 1230) used in this experiment are magnetized along their thickness. The ring magnet is outside the outer casing (acrylic tube with outer dia. = 40mm, inner dia. = 34mm) (i.e. cylindrical hollow housing 1310). Since a hole cannot be drilled through the disc magnet, a special arrangement consisting of two cylindrical fiber-sleeve housings 1684 which have the same diameter as of the disc magnet is made to suspend the magnet through the fiber. The fiber-sleeve housings 1684 are glued to both sides (top and bottom) of the disc magnet and each of them has a hole at its center to house the fiber sleeve 1686. The FBG (i.e. strain measurement element 1240) is in the upper side of the fiber. Additionally, the disc magnet is housed in a magnet housing 1680. The diameter of the magnet housing 1680 is equal to the

inner diameter of the outer casing and it has a hole at its center to accommodate the disc magnet. This magnet housing 1680 prevents the disc magnet from collapsing to the inner wall of the outer casing due to the strong magnetic force between the coacting ring and disc magnets especially when they are close to each other. Thus, the disc magnet hangs through the fiber
 5 along the axis of the system and the ring magnet which is kept outside the outer casing is free to move along the z-axis. The ring magnet is mounted on a height adjustable platform to conduct the experiment.

[00081] Both the magnets are neodymium magnets and the magnetizations M_1 and M_2 are the same (883.310 KA/m). The strain induced in the FBG as the ring magnet moves
 10 downwards (closer to the disc magnet) verse the axial distance (z) between the magnets is shown in a graph 1790 in FIG. 17. The axial distance is measured from the center of ring magnet to the center of disc magnet. The analytical results and the simulation results are also shown along with the experimental results. As shown, the experimental data matches well with the analytical and simulation data.

[00082] In an experiment, performance of the soil displacement measurement device 1300
 of FIG. 13 (which is configured as an extensometer) was evaluated using different radii/thickness of the disc magnet (i.e. which serves as the inner magnet 1330). According to various embodiments, the soil displacement measurement device 1300 of FIG. 13 employs two magnets (a ring magnet (i.e. the outer ring-magnet 1370) and a disc magnet (i.e. the inner
 20 magnet 1330)) which are magnetized in perpendicular directions as shown in FIG. 13. The disc magnet is magnetized in +y direction ($\epsilon_d = -1$) and the ring magnet is magnetized in +z ($\epsilon_r = +1$) direction. In this configuration, the magnetic force, F_y (in y-direction) on the disc magnet causes the disc magnet to pull/push the free end of the cantilever (i.e. suspension arrangement 1320) in y-direction and the tensile/compressive strain is induced in the FBG (i.e.
 25 strain measurement element 1340) as shown in FIG. 13. The magnetic force (F_y) changes according to the axial distance (z) between the ring magnet and the disc magnet, which are coacting. In this case, a deliberate attempt is made to make the axis of the ring magnet and the axis of disc magnet non-coinciding to realize greater F_y in y-direction. The axis of the ring magnet is at $x = 0, y=0$ while, the axis of the disc magnet is at $x = 0, y > 0$. The strain in the
 30 FBG verses the axial distance (z) between the ring magnet and the disc magnet is plotted in FIG. 18. The axial distance (z) is measured from the center of disc magnet to the center of ring magnet. For a given thickness ($2d_1$) and different radii (R_1) of the disc magnet, the strain verses the axial distance (z) between the magnets is shown in a graph 1890 in FIG. 18. Further,

for a given radius (R_I) and different thicknesses ($2d_I$) of the disc magnet, the strain verses the distance between the magnets is shown in a graph 1990 in FIG. 19. The simulation data points are also shown. For the analytical and simulation results shown in FIG. 18 and FIG. 19, the axis of the disc magnet is at $x = 0$, $y = 3\text{mm}$. As shown, the measurement range and resolution
 5 may be improved by changing the size of the disc magnet.

[00083] In another experiment, actual experimental results are compared with simulation and analytical results for the soil displacement measurement device 1300 of FIG. 13. The experimental setup 2000 of the soil displacement measurement device 1300 of FIG. 13 is shown in a photograph 2092 in FIG. 20. The ring magnet (outer dia. = 76 mm, inner dia. = 42
 10 mm, thickness = 12 mm) (i.e. the outer ring-magnet 1370) is magnetized in +z direction. Instead of using a disc magnet magnetized along its diameter and putting it in the x-y plane, a disc magnet (dia. = 25 mm, thickness = 6 mm) (i.e. inner magnet 1330) magnetized along its thickness is used and it is put in the z-x plane. Thus, the magnetic fields both the magnets are perpendicular to each other (the ring magnet in +z direction ($\epsilon_r = +1$), the disc magnet in +y
 15 direction ($\epsilon_r = -1$). This arrangement is easier and allows more space for the free end of the cantilever (i.e. suspension arrangement 1320) to move in the y-direction. The size of the cantilever used in this experiment is $190 \times 20 \times 2\text{mm}^3$. The other end of the cantilever is fixed in a solid cylindrical cantilever holder (i.e. cantilever-structure-holder 1327) which has a rectangular hole to accommodate the cantilever. The cantilever holder is made of acrylic and
 20 its diameter is equal to the inner diameter of the outer casing. The strain in the FBG verses the distance (z) between the ring magnet and the disc magnet is shown in a graph 2190 in FIG. 21. The simulation data shown in FIG. 21 match well with the experimental data. The linear range of extensometer measurement is about 80mm (from $z = 50\text{mm}$ to $z = 130\text{mm}$) and the measurement resolution is about 0.65mm. According to various embodiments, a longer
 25 cantilever may also improve the measurement range and resolution.

[00084] In yet another experiment, repeatability of the soil displacement measurement device 1300 of FIG. 13 (which is configured as an extensometer) was evaluated. According to various embodiments, multiple units of extensometer must be installed in a bore to monitor the soil movement at various depths. In this experiment, three extensometer units are
 30 connected in series to form an extensometer system 2201 (i.e. a soil displacement measurement system) at different depths as shown in a photograph 2292 in FIG. 22. The responses of all the units are shown in a graph 2390 in FIG. 23. The size of magnets and the size of cantilevers in all the three units are identical and they are the same as used in FIG. 20. As shown, the

responses of all the units are more or less the same which confirms the repeatability of the soil displacement measurement device 1300 of FIG. 13.

[00085] According to various embodiments, the soil displacement measurement device 1200 of FIG. 12 (which is configured as an extensometer) and the soil displacement measurement device 1300 of FIG. 13 (which is configured as an extensometer) may be simple and easy to fabricate.

[00086] According to various embodiments, the soil displacement measurement device 1200 of FIG. 12 (which is configured as an extensometer) may be suitable when the requirements for measurement range and resolution are low to moderate. A high requirement for measurement range and measurement resolution would demand a larger disc magnet hanging through the FBG fiber the soil displacement measurement device 1200 of FIG. 12. In this case, the axial force (F_z) on the disc magnet would be very high (especially, when the disc magnet is very close to the ring magnet), which might break the fiber.

[00087] On the other hand, according to various embodiment, in the soil displacement measurement device 1300 of FIG. 13 (which is configured as an extensometer), the FBG is bonded to an aluminum cantilever, which makes this design more robust. The movement of the free end of the cantilever is limited by the outer casing wall. Therefore, even a very high magnetic force (F_y) (when the disc magnet is very close to the ring magnet) cannot bend the cantilever beyond its elastic limit. A larger disc magnet can be easily used for a higher measurement range and resolution requirement without the fear of fiber breakage. Also, the size of the cantilever can be altered to have higher measurement range and resolution. Thus, according to various embodiment, the soil displacement measurement device 1300 of FIG. 13 may be more robust and flexible.

[00088] FIG. 24 shows a schematic diagram of a single soil displacement measurement device 2400 which may be made up of the soil displacement measurement device 100 of FIG. 1 (which is configured as an inclinometer) being joined together with the soil displacement measurement device 1300 of FIG. 13 (which is configured as an extensometer). As shown, the optical fibers from both units may be spliced together. The joint may also be a rigid joint such that the housing from both units form an integrated and integral housing for the combined device. While FIG. 24 illustrates the soil displacement measurement device 100 of FIG. 1 (which is configured as an inclinometer) being joined together with the soil displacement measurement device 1300 of FIG. 13 (which is configured as an extensometer), it is understood that the soil displacement measurement device 100 of FIG. 1 (which is configured as an inclinometer) may also be joined together with the soil displacement measurement device

1200 of FIG. 12 (which is configured as an extensometer) to form a single soil displacement measurement device.

[00089] FIG. 25 shows a schematic diagram of the single soil displacement measurement device 2400 of FIG. 24 (which is configured as an inclinometer and an extensometer) being
5 connected with the soil displacement measurement device 100 of FIG. 1 (which is configured as an inclinometer) via link members 260 forming flexible joints to form a soil displacement measurement system 2501. Conventionally, the inclinometer units may be installed closer to each other than the extensometer units to have a more accurate soil deformation profile. Typically, the inclinometers are installed 1 m apart from each other while the extensometers
10 are installed at 5 m apart from each other in a bore hole. According to various embodiments, the single soil displacement measurement device 2400 of FIG. 24 (i.e. the combined unit) may be sandwiched between the soil displacement measurement devices 100 of FIG. 1 (i.e. the inclinometer units) at desired depths through flexible joints (such as nylon strips previously described). The distances and the sizes of the single soil displacement measurement device
15 2400 of FIG. 24 (i.e. the combined unit) and the soil displacement measurement devices 100 of FIG. 1 (i.e. the inclinometer units) may be altered according to the installation site requirements.

[00090] The following examples pertain to various embodiments.

[00091] Example 1 is a soil displacement measurement device including:

- 20 a cylindrical hollow housing;
- an outer ring-magnet slidably arranged on an exterior surface of the cylindrical hollow housing in a manner such that the cylindrical hollow housing is inserted through a central cavity of the outer ring-magnet;
- an inner magnet disposed within the cylindrical hollow housing;
- 25 a suspension arrangement holding the inner magnet with respect to the cylindrical hollow housing so as to suspend the inner magnet within an interior space of the cylindrical hollow housing; and
- a strain measurement element provided to a region of the suspension arrangement,
- 30 wherein relative movement between the outer ring-magnet and the cylindrical hollow housing along a longitudinal axis of the cylindrical hollow housing causes the outer ring-magnet to coact with the inner magnet in a manner such that a magnetic force between the outer ring-magnet and the inner magnet changes a corresponding strain at the region of the suspension arrangement, and

wherein the change in the strain is detected by the strain measurement element as a measure of the relative displacement of the outer ring-magnet along the longitudinal axis of the cylindrical hollow housing.

5 [00092] In Example 2, the subject matter of Example 1 may optionally include one or more anchors coupled to the outer ring-magnet in a manner such that the one or more anchors may project away from the cylindrical hollow housing for anchoring the outer ring-magnet to an external medium.

[00093] In Example 3, the subject matter of Example 1 or 2 may optionally include that the strain measurement element may include fibre Bragg grating (FBG).

10 [00094] In Example 4, the subject matter of any one of Examples 1 to 3 may optionally include that the inner magnet may include a disc magnet, or a round magnet, a cylinder magnet, or a ring-shaped magnet.

[00095] In Example 5, the subject matter of any one of Examples 1 to 4 may optionally include that the cylindrical hollow housing is filled with a fluid medium.

15 [00096] In Example 6, the subject matter of any one of Examples 1 to 5 may optionally include that

wherein the cylindrical hollow housing may have a first partition and a second partition defining a closed section of the cylindrical hollow housing,

20 wherein the inner magnet may be suspended with a first flat-surface of the inner magnet directed towards the first partition of the cylindrical hollow housing and a second flat-surface of the inner magnet directed towards the second partition of the cylindrical hollow housing, the first flat-surface being opposite the second flat-surface,

wherein the suspension arrangement may include

25 a first suspension-line-segment extending along the longitudinal axis of the cylindrical hollow housing between a center of the first flat-surface of the inner magnet and a center of the first partition of the cylindrical hollow housing, and

30 a second suspension-line-segment extending along the longitudinal axis of the cylindrical hollow housing between a center of the second flat-surface of the inner magnet and a center of the second partition of the cylindrical hollow housing,

wherein the strain measurement element may be disposed along the first suspension-line-segment.

[00097] In Example 7, the subject matter of Example 6 may optionally include that the inner magnet and the outer ring-magnet may be magnetized such that respective magnetization directions are parallel or antiparallel relative to each other.

5 [00098] In Example 8, the subject matter of Example 6 or 7 may optionally include that the first suspension-line-segment may include an optical fiber.

[00099] In Example 9, the subject matter of any one of Examples 6 to 8 may optionally include that a first suspension-line-segment-connector may be fixed to the first flat-surface of the inner magnet, and a second suspension-line-segment-connector may be fixed to the second flat-surface of the inner magnet.

10 [000100] In Example 10, the subject matter of Example 9 may optionally include that a protection sleeve may be provided to surround each fixing end of the first suspension-line-segment and the second suspension-line-segment.

[000101] In Example 11, the subject matter of Example 6 to 10 may optionally include an annularly shaped magnet-housing having a cavity in the center to accommodate the inner magnet, wherein an outer boundary of the annularly shaped magnet-housing may be dimensioned to fit into the cylindrical hollow housing.

[000102] In Example 12, the subject matter of any one of Examples 1 to 5 may optionally include that

20 wherein the suspension arrangement comprises a cantilever structure which is aligned parallel to the longitudinal axis of the cylindrical hollow housing and which has a first end portion fixedly coupled to the cylindrical hollow housing and a second free-end portion,

wherein the inner magnet is fixed to the second free-end portion of the cantilever structure, and

25 wherein the strain measurement element is attached to the first end portion of the cantilever structure.

[000103] In Example 13, the subject matter of Example 12 may optionally include that the suspension arrangement may further include a cantilever-structure-holder in the form of a circular panel fixedly mounted to an interior wall of the cylindrical hollow housing, wherein the circular panel may include a cavity in which the first end portion of the cantilever structure is fixedly fitted.

[000104] In Example 14, the subject matter of Example 12 or 13 may optionally include that the inner magnet may be fixed to the second free-end portion of the cantilever structure in an

orientation in which a magnetization direction of the inner magnet is at least substantially perpendicular to the longitudinal axis of the cylindrical hollow housing.

[000105] In Example 15, the subject matter of any one of Examples 1 to 14 may optionally include that the soil displacement measurement device include a first soil displacement measurement sub-device along a first length portion of the cylindrical hollow housing and a second soil displacement measurement sub-device along a second length portion of the cylindrical hollow housing,

wherein the first soil displacement measurement sub-device is configured according to any one of claims 1 to 14,

wherein the second soil displacement measurement sub-device includes

a first partition and a second partition along the second length portion of the cylindrical hollow housing to define a closed section of the second length portion of the cylindrical hollow housing,

a suspended-body of the second soil displacement measurement sub-device being held in suspension within the second length portion of the cylindrical hollow housing with a first suspension-line segment of the second soil displacement measurement sub-device extending from the suspended-body towards a center of the first partition of the second length portion of the cylindrical hollow housing and a second suspension-line segment of the second soil displacement measurement sub-device extending from the suspended-body towards a center of the second partition of the second length portion of the cylindrical hollow housing, and

a strain measurement element of the second soil displacement measurement sub-device disposed along the second suspension-line segment of the second soil displacement measurement sub-device in a manner such that a change in tilt angle of the cylindrical hollow housing causes a change in a strain of the second suspension-line segment of the second soil displacement measurement sub-device which is detected by the strain measurement element of the second soil displacement measurement sub-device.

[000106] In Example 16, the subject matter of Example 15 may optionally include that the first length portion of the cylindrical hollow housing may include a first pipe and the second length portion of the cylindrical hollow housing may include a second pipe, and wherein the first pipe is fixedly joined to the second pipe to form the cylindrical hollow housing as a single rigid unitary part.

[000107] In Example 17, the subject matter of Example 15 or 16 may optionally include that the strain measurement element of the second soil displacement measurement sub-device may include fibre Bragg grating (FBG).

5 [000108] In Example 18, the subject matter of Example 17 may optionally include that an optical fiber for the FBG of the strain measurement element of the first soil displacement measurement sub-device and another optical fiber for the FBG of the strain measurement element of the second soil displacement measurement sub-device may be spliced together in a manner such that measurements from both the strain measurement elements may be transmitted via a single spliced optical fiber.

10 [000109] In Example 19, the subject matter of any one of Examples 15 to 18 may optionally include that the suspended-body of the second soil displacement measurement sub-device may have a shape having circular symmetry about a main axis passing through the suspended-body between a first surface-intersection-point and a second surface-intersection-point, and the suspended-body may be disposed within the second length portion of the cylindrical hollow housing and may be suspended between the first partition of second length portion of the cylindrical hollow housing and the second partition of second length portion of the cylindrical hollow housing with the first surface-intersection-point directed towards the first partition of second length portion of the cylindrical hollow housing and the second surface-intersection-point directed towards the second partition of second length portion of the cylindrical hollow housing.

20 [000110] In Example 20, the subject matter of Example 19 may optionally include that the first suspension-line-segment of the second soil displacement measurement sub-device may extend from the first surface-intersection-point of the suspended-body towards a center of the first partition of second length portion of the cylindrical hollow housing, and wherein the second suspension-line-segment of the second soil displacement measurement sub-device may extend from the second surface-intersection-point of the suspended-body towards a center of the second partition of second length portion of the cylindrical hollow housing.

25 [000111] In Example 21, the subject matter of any one of Examples 15 to 20 may optionally include that a ratio of a length of the first suspension-line-segment of the second soil displacement measurement sub-device to a length of the second suspension-line-segment of the second soil displacement measurement sub-device is equal or more than 1.

30 [000112] In Example 22, the subject matter of any one of Examples 15 to 21 may optionally include that the shape of the suspended-body of the second soil displacement measurement sub-device comprises a cylinder, a spheroid, a cone, a double-cone, or a bi-cone.

[000113] In Example 23, the subject matter of any one of Examples 15 to 22 may optionally include that the first suspension-line-segment of the second soil displacement measurement sub-device and the second suspension-line-segment of the second soil displacement measurement sub-device may be pre-tensioned.

5 **[000114]** In Example 24, the subject matter of any one of Examples 15 to 23 may optionally include that the first suspension-line-segment of the second soil displacement measurement sub-device and the second suspension-line-segment of the second soil displacement measurement sub-device may be fixed to the suspended-body of the second soil displacement measurement sub-device via adhesive.

10 **[000115]** In Example 25, the subject matter of any one of Examples 15 to 24 may optionally include that the first suspension-line-segment of the second soil displacement measurement sub-device and the second suspension-line-segment of the second soil displacement measurement sub-device are fixed to the respective centers of the first partition of the second length portion of the cylindrical hollow housing and the second partition of the second length
15 portion of the cylindrical hollow housing via adhesive.

[000116] In Example 26, the subject matter of any one of Examples 15 to 25 may optionally include that a protection sleeve is provided to surround each fixing end of the first suspension-line-segment of the second soil displacement measurement sub-device and the second suspension-line-segment of the second soil displacement measurement sub-device.

20 **[000117]** In Example 27, the subject matter of any one of Examples 15 to 26 may optionally include that a single optical fiber may extend from the center of the first partition of the second length portion of the cylindrical hollow housing to the suspended-body of the second soil displacement measurement sub-device, through the suspended-body of the second soil displacement measurement sub-device, and from the the suspended-body of the second soil
25 displacement measurement sub-device to the center of the second partition of the second length portion of the cylindrical hollow housing, wherein the first suspension-line-segment of the second soil displacement measurement sub-device may be a segment of the single optical fiber between the first partition of the second length portion of the cylindrical hollow housing and the suspended-body of the second soil displacement measurement sub-device, and wherein the
30 second suspension-line-segment of the second soil displacement measurement sub-device may be a segment of the single optical fiber between the suspended-body of the second soil displacement measurement sub-device and the second partition of the second length portion of the cylindrical hollow housing.

[000118] In Example 28, the subject matter of any one of Examples 15 to 26 may optionally include that the first suspension-line-segment of the second soil displacement measurement sub-device comprises a metal wire and the second suspension-line-segment of the second soil displacement measurement sub-device comprise an optical fiber.

5 **[000119]** In Example 29, the subject matter of any one of Examples 15 to 28 may optionally include that the closed section of the second length portion of the cylindrical hollow housing is filled with a fluid medium.

[000120] In Example 30, the subject matter of any one of Examples 1 to 29 may optionally include a first connection fixture disposed on an exterior of the cylindrical hollow housing at
10 a first end portion and a second connection fixture disposed on the exterior of the cylindrical hollow housing at a second end portion.

[000121] In Example 31, the subject matter of Example 30 may optionally include that each of the first connection fixture and the second connection fixture comprises three or more attachment elements, each attachment element being configured to interlock with a flexible
15 elongate link member.

[000122] Example 32 is a soil displacement measurement system including at least two soil displacement measurement devices according to any one of Examples 1 to 14 arranged in a series one after another.

[000123] Example 33 is a soil displacement measurement system including at least two soil
20 displacement measurement devices according to Example 32, wherein the at least two soil displacement measurement devices may be interconnected via three or more flexible elongate link members, wherein each of the three or more flexible elongate link members may have a first end interlocks with an attachment element of one of the at least two soil displacement measurement devices and a second end interlocks with an attachment element of another one
25 of the at least two soil displacement measurement devices.

[000124] Example 34 is a soil displacement measurement device including

an elongate hollow housing having a first partition and a second partition defining a closed section of the cylindrical hollow housing;

a suspended-body which has a shape having circular symmetry about a main
30 axis passing through the suspended-body between a first surface-intersection-point and a second surface-intersection-point, and which is disposed within the elongate hollow housing and suspended between the first partition and the second partition with the first surface-intersection-point directed towards the first partition and the second surface-intersection-point directed towards the second partition;

a first suspension-line-segment extending from the first surface-intersection-point of the suspended-body towards a center of the first partition of the elongate hollow housing;

5 a second suspension-line-segment extending from the second surface-intersection-point of the suspended-body towards a center of the second partition of the elongate hollow housing; and

a strain measurement element disposed along the second suspension-line-segment,

10 wherein a ratio of a length of the first suspension-line-segment to a length of the second suspension-line-segment is equal or more than 1.

[000125] In Example 35, the subject matter of Example 34 may optionally include that the elongate hollow housing may include a rigid pipe or a rigid hollow cylinder.

15 **[000126]** In Example 36, the subject matter of Example 34 or 35 may optionally include that the shape of the suspended-body may include a cylinder, a spheroid, a cone, a double-cone, or a bi-cone.

[000127] In Example 37, the subject matter of any one of Examples 34 to 36 may optionally include that the first suspension-line-segment and the second suspension-line-segment may be pre-tensioned.

20 **[000128]** In Example 38, the subject matter of any one of Examples 34 to 37 may optionally include that the first suspension-line-segment and the second suspension-line-segment are fixed to the respective first surface-intersection-point and second surface-intersection-point via adhesive.

25 **[000129]** In Example 39, the subject matter of any one of Examples 34 to 38 may optionally include that the first suspension-line-segment and the second suspension-line-segment may be fixed to the respective centers of the first partition and the second partition via adhesive.

[000130] In Example 40, the subject matter of any one of Examples 34 to 39 may optionally include that a protection sleeve is provided to surround each fixing end of the first suspension-line-segment and the second suspension-line-segment.

30 **[000131]** In Example 41, the subject matter of any one of Examples 34 to 40 may optionally include a single optical fiber extending from the center of the first partition of the elongate hollow housing to the first surface-intersection-point of the suspended-body, through the suspended-body, and from the second surface-intersection-point of the suspended-body to the center of the second partition of the elongate hollow housing, wherein the first suspension-line-segment may be a segment of the single optical fiber between the first partition of the

elongate hollow housing and the first surface-intersection-point of the suspended-body, and wherein the second suspension-line-segment may be a segment of the single optical fiber between the second surface-intersection-point of the suspended-body and the second partition of the elongate hollow housing.

- 5 **[000132]** In Example 42, the subject matter of any one of Examples 34 to 40 may optionally include that the first suspension-line-segment may include a metal wire and the second suspension-line-segment may include an optical fiber.

[000133] In Example 43, the subject matter of any one of Examples 34 to 42 may optionally include that the strain measurement element comprises fibre Bragg grating (FBG).

- 10 **[000134]** In Example 44, the subject matter of any one of Examples 34 to 43 may optionally include that the elongate hollow housing is filled with a fluid medium.

- [000135]** In Example 45, the subject matter of any one of Examples 34 to 44 may optionally include a first connection fixture disposed on an exterior of the elongate hollow housing at a first end portion and a second connection fixture disposed on an exterior of the elongate hollow housing at a second end portion.

[000136] In Example 46, the subject matter of Example 45 may optionally include that each of the first connection fixture and the second connection fixture may include three or more attachment elements, each attachment element being configured to interlock with a flexible elongate link member.

- 20 **[000137]** In Example 47, the subject matter of any one of Examples 34 to 46 may optionally be fixedly joined to a soil displacement measurement device according to any one of Examples 1 to 13.

- [000138]** Example 48 is a soil displacement measurement system including at least two soil displacement measurement devices according to Example 46, wherein the at least two soil displacement measurement devices may be interconnected via three or more flexible elongate link members, wherein each of the three or more flexible elongate link members may have a first end interlocks with an attachment element of one of the at least two soil displacement measurement devices and a second end interlocks with an attachment element of another one of the at least two soil displacement measurement devices.

- 30 **[000139]** Example 49 is a soil displacement measurement system including at least one soil displacement measurement devices according to Example 31 interconnected via three or more flexible elongate link member with at least one soil displacement measurement devices according to Example 46, wherein each of the three or more elongate link members may have a first end interlocks with an attachment element of the at least one soil displacement

measurement devices as claimed in claim 31 and a second end interlocks with an attachment element of the at least one soil displacement measurement devices according to Example 46.

[000140] Example 50 is a soil displacement measurement device including a first soil displacement measurement sub-device along a first length portion of a cylindrical hollow housing and a second soil displacement measurement sub-device along a second length portion of the cylindrical hollow housing, wherein the first soil displacement measurement sub-device is configured as an inclinometer and the second soil displacement measurement sub-device is configured as an extensometer.

[000141] In Example 51, the subject matter of Example 50 may optionally that the first soil displacement measurement sub-device is configured as a FBG based inclinometer and the second soil displacement measurement sub-device is configured as a FBG based extensometer.

[000142] In Example 52, the subject matter of Example 51 may optionally that an optical fiber for the FBG of the first soil displacement measurement sub-device and another optical fiber for the FBG of the second soil displacement measurement sub-device may be spliced together in a manner such that measurements from both the first soil displacement measurement sub-device and the second soil displacement measurement sub-device may be transmitted via a single integrated optical fiber.

[000143] In Example 53, the subject matter of any one of Examples 50 to 52 may optionally that the first length portion may include a first pipe and the second length portion may include a second pipe, and wherein the first pipe may be fixedly joined (or rigidly coupled) to the second pipe to form the cylindrical hollow housing as a single unitary part.

[000144] In Example 54, the subject matter of any one of Examples 50 to 53 may optionally include that the first soil displacement measurement sub-device along the first length portion of the cylindrical hollow housing may include

a first partition and a second partition defining a closed section of the first length portion of the cylindrical hollow housing,

a suspended-body being held in suspension within the first length portion of the cylindrical hollow housing with a first suspension-line segment extending from the suspended-body towards a center of the first partition and a second suspension-line segment extending from the suspended-body towards a center of the second partition, and

a first strain measurement element disposed along the second suspension-line segment in a manner such that a change in tilt angle of the cylindrical hollow housing

causes a change in a strain in the second suspension-line segment which is detectable by the first strain measurement element.

[000145] In Example 55, the subject matter of any one of Examples 50 to 54 may optionally include that the second soil displacement measurement sub-device along the second length portion of the cylindrical hollow housing may include that the second length portion of the cylindrical hollow housing may include

an outer ring-magnet slidably arranged on an exterior surface of the cylindrical hollow housing in a manner such that the cylindrical hollow housing is inserted through a central cavity of the outer ring-magnet;

an inner magnet which is suspended within the cylindrical hollow housing via a suspension arrangement; and

a second strain measurement element provided to a region of the suspension arrangement,

wherein relative movement between the outer ring-magnet and the cylindrical hollow housing along a longitudinal axis of the cylindrical hollow housing causes the outer ring-magnet to coact with the inner magnet in a manner such that a magnetic force between the outer ring-magnet and the inner magnet changes a corresponding strain at the region of the suspension arrangement which is detectable by the second strain measurement element.

[000146] In Example 56, the subject matter of any one of Examples 50 to 54 may optionally include that the first soil displacement measurement sub-device may be configured according to any one of Examples 34 to 44.

[000147] In Example 57, the subject matter of any one of Examples 50 to 56 may optionally include that the second soil displacement measurement sub-device may be configured according to any one of Examples 1 to 14.

[000148] In Example 58, the subject matter of any one of Examples 50 to 57 may optionally include a first connection fixture disposed on an exterior of the cylindrical hollow housing at a first end portion and a second connection fixture disposed on an exterior of the cylindrical hollow housing at a second end portion.

[000149] In Example 59, the subject matter of any one of Examples 50 to 58 may optionally include that each of the first connection fixture and the second connection fixture may include three or more attachment elements, each attachment element being configured to interlock with a flexible elongate link member.

[000150] Example 60 is a soil displacement measurement system including at least one soil displacement measurement devices according to one of Examples 50 to 59 interconnected with at least one other soil displacement measurement device according to any one of the Examples 1 to 31, 34 to 47, and 50 to 59.

- 5 **[000151]** Various embodiments have provided a soil displacement measurement device and/or a soil displacement measurement system which are simple and easy to implement for borehole application to measure horizontal/lateral and/or vertical soil displacement.

- 10 **[000152]** While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes, modification, variation in form and detail may be made therein without departing from the scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

Claims

1. A soil displacement measurement device comprising:
 - a cylindrical hollow housing;
 - an outer ring-magnet slidably arranged on an exterior surface of the cylindrical hollow housing in a manner such that the cylindrical hollow housing is inserted through a central cavity of the outer ring-magnet;
 - an inner magnet disposed within the cylindrical hollow housing;
 - a suspension arrangement holding the inner magnet with respect to the cylindrical hollow housing so as to suspend the inner magnet within an interior space of the cylindrical hollow housing, wherein a portion of the suspension arrangement is fixed to a portion of the cylindrical hollow housing and a further portion of the suspension arrangement is extended into the interior space of the cylindrical hollow housing and the inner magnet is attached to the further portion of the suspension arrangement so as to be suspended;
 - and
 - a strain measurement element provided to a region of the suspension arrangement,
 - wherein relative movement between the outer ring-magnet and the cylindrical hollow housing along a longitudinal axis of the cylindrical hollow housing causes the outer ring-magnet to coact with the inner magnet in a manner such that a magnetic force between the outer ring-magnet and the inner magnet changes a corresponding strain at the region of the suspension arrangement, and
 - wherein the change in the strain is detected by the strain measurement element as a measure of the relative displacement of the outer ring-magnet along the longitudinal axis of the cylindrical hollow housing.
2. The device as claimed in claim 1, wherein the strain measurement element comprises fibre Bragg grating (FBG).
3. The device as claimed in claim 1 or 2, wherein the cylindrical hollow housing is filled with a fluid medium.
4. The device as claimed in any one of claims 1 to 3,
 - wherein the cylindrical hollow housing has a first partition and a second partition defining a closed section of the cylindrical hollow housing,

wherein the inner magnet is suspended with a first flat-surface of the inner magnet directed towards the first partition of the cylindrical hollow housing and a second flat-surface of the inner magnet directed towards the second partition of the cylindrical hollow housing, the first flat-surface being opposite the second flat-surface,

wherein the suspension arrangement comprises

a first suspension-line-segment extending along the longitudinal axis of the cylindrical hollow housing between a center of the first flat-surface of the inner magnet and a center of the first partition of the cylindrical hollow housing, and

a second suspension-line-segment extending along the longitudinal axis of the cylindrical hollow housing between a center of the second flat-surface of the inner magnet and a center of the second partition of the cylindrical hollow housing,

wherein the strain measurement element is disposed along the first suspension-line-segment.

5. The device as claimed in claim 4, wherein the first suspension-line-segment comprises an optical fiber.

6. The device as claimed in claim 4 or 5, further comprising an annularly shaped magnet-housing having a cavity in the center to accommodate the inner magnet, wherein an outer boundary of the annularly shaped magnet-housing is dimensioned to fit into the cylindrical hollow housing.

7. The device as claimed in any one of claims 1 to 3,
wherein the suspension arrangement comprises a cantilever structure which is aligned parallel to the longitudinal axis of the cylindrical hollow housing and which has a first end portion fixedly coupled to the cylindrical hollow housing and a second free-end portion,
wherein the inner magnet is fixed to the second free-end portion of the cantilever structure, and
wherein the strain measurement element is attached to the first end portion of the cantilever structure.

8. The device as claimed in claim 7, wherein the suspension arrangement further comprises a cantilever-structure-holder in the form of a circular panel fixedly mounted to an

interior wall of the cylindrical hollow housing, wherein the circular panel comprises a cavity in which the first end portion of the cantilever structure is fixedly fitted.

9. The soil displacement measurement device as claimed in any one of claims 1 to 8, wherein the soil displacement measurement device comprises a first soil displacement measurement sub-device along a first length portion of the cylindrical hollow housing and a second soil displacement measurement sub-device along a second length portion of the cylindrical hollow housing,

wherein the first soil displacement measurement sub-device is configured according to any one of claims 1 to 8,

wherein the second soil displacement measurement sub-device comprises a first partition and a second partition along the second length portion of the cylindrical hollow housing to define a closed section of the second length portion of the cylindrical hollow housing,

a suspended-body of the second soil displacement measurement sub-device being held in suspension within the second length portion of the cylindrical hollow housing with a first suspension-line segment of the second soil displacement measurement sub-device extending from the suspended-body towards a center of the first partition of the second length portion of the cylindrical hollow housing and a second suspension-line segment of the second soil displacement measurement sub-device extending from the suspended-body towards a center of the second partition of the second length portion of the cylindrical hollow housing, and

a strain measurement element of the second soil displacement measurement sub-device disposed along the second suspension-line segment of the second soil displacement measurement sub-device in a manner such that a change in tilt angle of the cylindrical hollow housing causes a change in a strain of the second suspension-line segment of the second soil displacement measurement sub-device which is detected by the strain measurement element of the second soil displacement measurement sub-device.

10. The device as claimed in claim 9, wherein the strain measurement element of the second soil displacement measurement sub-device comprise fibre Bragg grating (FBG).

11. The device as claimed in claim 10, wherein an optical fiber for the FBG of the strain measurement element of the first soil displacement measurement sub-device and another

optical fiber for the FBG of the strain measurement element of the second soil displacement measurement sub-device are spliced together in a manner such that measurements from both the strain measurement elements may be transmitted via a single spliced optical fiber.

12. The device as claimed in any one of claims 9 to 11, wherein the suspended-body of the second soil displacement measurement sub-device has a shape having circular symmetry about a main axis passing through the suspended-body between a first surface-intersection-point and a second surface-intersection-point, and the suspended-body is disposed within the second length portion of the cylindrical hollow housing and suspended between the first partition of second length portion of the cylindrical hollow housing and the second partition of second length portion of the cylindrical hollow housing with the first surface-intersection-point directed towards the first partition of second length portion of the cylindrical hollow housing and the second surface-intersection-point directed towards the second partition of second length portion of the cylindrical hollow housing.

13. The device as claimed in claim 12, wherein the first suspension-line-segment of the second soil displacement measurement sub-device extend from the first surface-intersection-point of the suspended-body towards a center of the first partition of second length portion of the cylindrical hollow housing, and wherein the second suspension-line-segment of the second soil displacement measurement sub-device extend from the second surface-intersection-point of the suspended-body towards a center of the second partition of second length portion of the cylindrical hollow housing.

14. The device as claimed in any one of claims 9 to 13, wherein a ratio of a length of the first suspension-line-segment of the second soil displacement measurement sub-device to a length of the second suspension-line-segment of the second soil displacement measurement sub-device is equal or more than 1.

15. The device as claimed in any one of claims 9 to 14, wherein a single optical fiber extends from the center of the first partition of the second length portion of the cylindrical hollow housing to the suspended-body of the second soil displacement measurement sub-device, through the suspended-body of the second soil displacement measurement sub-device, and from the suspended-body of the second soil displacement measurement sub-device to the center of the second partition of the second length portion of the cylindrical

hollow housing, wherein the first suspension-line-segment of the second soil displacement measurement sub-device is a segment of the single optical fiber between the first partition of the second length portion of the cylindrical hollow housing and the suspended-body of the second soil displacement measurement sub-device, and wherein the second suspension-line-segment of the second soil displacement measurement sub-device is a segment of the single optical fiber between the suspended-body of the second soil displacement measurement sub-device and the second partition of the second length portion of the cylindrical hollow housing.

16. The device as claimed in any one of claims 9 to 15, wherein the first suspension-line-segment of the second soil displacement measurement sub-device comprises a metal wire and the second suspension-line-segment of the second soil displacement measurement sub-device comprise an optical fiber.

17. The device as claimed in any one of claims 9 to 16, wherein the closed section of the second length portion of the cylindrical hollow housing is filled with a fluid medium.

18. The device as claimed in any one of claims 1 to 17, further comprising a first connection fixture disposed on an exterior of the cylindrical hollow housing at a first end portion and a second connection fixture disposed on the exterior of the cylindrical hollow housing at a second end portion, wherein each of the first connection fixture and the second connection fixture comprises three or more attachment elements, each attachment element being configured to interlock with a flexible elongate link member.

19. A soil displacement measurement system comprising at least two soil displacement measurement devices as claimed in any one of claims 1 to 8 arranged in a series one after another.

20. A soil displacement measurement system comprising at least two soil displacement measurement devices as claimed in claim 18, wherein the at least two soil displacement measurement devices are interconnected via three or more of the flexible elongate link members, wherein each flexible elongate link member has a first end interlocks with an attachment element of one of the at least two soil displacement measurement devices and a

second end interlocks with an attachment element of another one of the at least two soil displacement measurement devices.