A macrobending-based optical fiber inclinometer to measure the ground tilt in the depth which forms a positive and negative angle to the gravity axis

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Abstract. This paper discusses an optical fiber inclinometer to measure ground tilt in soil depth, which forms an angle between vertical axis to the gravity axis. The macrobending based-inclinometer consists of a laser source system, fiber cable, geotechnical cylinder; rolling wheels and pressing levers each sitting on top and bottom support; stainless steel rope, cylinder loads, light detection and output data. The stabilized laser was split into four by an optical coupler into ports of sensor fiber 1, sensor fiber 2, reference fiber and one backup port, then entering into a geotechnical cylinder housed in a standard geotechnical pipe. If there is instability of the soil condition resulting in a tilting of the soil surface, the geotechnical cylinder changes its position to form an angle to the gravity axis, furthermore the active pressure lever will suppress the optical fiber sensor. At this stage, the optical fiber will undergo a macro bending resulting in a change of its output. This intensity change output will correspond to the change of the angle for each tilting direction (left and right). The fiber inclinometer has a measurement range of 10° for both direction with accuracy of 0.5°.

1. Introduction

The inclinometer is an instrument to measure the angle of an object relative to the gravitational axis. Inclinometers measure topographic slope, usually using units of degrees or percent units. The inclinometer is one of the geotechnical structural instruments and is used to evaluate the movement of the soil, especially changes in the angle of the soil. These tools are widely utilized to monitor soil deformation in natural slope stabilization studies and to estimate the earth activity, road structures, building structures, bridges and other infrastructure facilities; besides it can also be used to determine the condition of rock structure deep within the earth crust by identifying the shift of the topographic slope of the soil. In the operation, the inclinometer is attached to the structure to be studied. For observation of slope conditions in the soil, the sensor is placed in a hole/borehole at the depth of soil to be studied.

Borehole inclinometer commonly uses copper wire as electrical sensor. This sensor is highly susceptible to short circuit if exposed to water or lightning. The optical fiber inclinometers proposed
here use optical fibers as sensors to detect the magnitude of the slope of the ground. This glass-based fiber-optic sensor in its application is not disturbed by circumstance of wet or damp soils. Other advantages of this optical fiber-based sensor device are more resistant to changes in surrounding weather conditions, uninterrupted by electromagnetic fields (low noise), usable in tandem (multiplexing) systems, very low transmission losses (can transmit up to several hundred kilometers) [1, 2] so that it can be used on objects in locations where there is no electricity.

Many works on optical fiber inclinometer have been reported and most of them use fiber Bragg grating (FBG) technique [3-5]. Although FBG offers high resolution but this technique needs complex system and reading technique. Other methods are Michelson interferometer [6], long period fiber grating [7] and macrobending [8, 9]. Macrobending technique is simpler and low cost although sometimes its output is unstable but it can be normalized with reference technique and a good data processing system.

In this paper, we report the development of the macrobending loss based - optical fiber inclinometer using single mode SMF 28 as the sensor, laser diode at wavelength 1.3 μm, and optical power meter which is capable of detecting two-way ground slope, i.e., the direction that forms a positive angle or negative angle to the vertical axis of the soil or the gravity axis. The inclinometer has been registered as Indonesian Patent No. P00201708582 [10]

2. Theory

Light transmitting into the optical fiber will be distorted if the fiber is bent because its refractive index is altered due to bending. If \( P(0) \) is the optical power before the fiber is bent, the output power when the fiber is bent at radius \( R \) is [11]:

\[
P(L) = P(0)e^{-\gamma L}
\]  

(1)

Generally, bending loss is written in decibel (dB) and stated as [12, 13]:

\[
\text{Bending Loss} = -\log \left( \frac{P(L)}{P(0)} \right) = -10 \log e^{-\gamma L} = 4.34\gamma L
\]  

(2)

while \( \gamma \) states the bending loss coefficient for step index - single mode fiber which value can be calculated using the following equation [11]:

\[
\gamma = \left( \frac{\pi \rho}{R} \right)^{\frac{1}{2}} V^\frac{1}{3} W^\frac{1}{3} \left( 2.405 \Delta^2 \right) \exp \left( -\frac{R}{\rho} \right)
\]  

(3)

with \( \rho \) is core radius, \( R \) is bend radius, \( \Delta \) is relative refractive index difference between fiber core and cladding, \( U, V, \) and \( W \) is optical fiber parameters which depend on core radius, core and cladding refractive index. Optical fiber is single mode at certain wavelength if the \( V \) value is smaller or equal to 2.405. It can be seen from Equation 3 that the bending loss will decrease exponentially if the bending radius is larger (or increase exponentially if bending radius is smaller).

In reality, for the light transmitting in a fiber optic at a certain wavelength, the detected bending loss does not follow Equation 3 because of whispering gallery mode (WGM) effect which causes the light goes out of the fiber core, reenter to the fiber cladding and back to the fiber core [12, 14]. In this case, the empirical equation which relates bending loss \( L \) (in dB) with bending radius \( R \) (in mm) of the standard optical fiber ITU G.652.c with core diameter 9 μm and cladding diameter 125 μm, for light at wavelength 1550 nm, is [14]:

\[
L = 5F_1 \left( 5F_2 + F_3 \right)
\]  

(4)

with

\[
F_1 = c \exp \left( -\frac{R_{\text{Eff}}}{3} \right)
\]  

(5)
The laser is slope, keep consists wheels, to used. The J intensity bottom laser that into and a forwarded at commercial to right sensor of value and ideal each output end output levers axis fiber-optic wheel more rolling two pressure equipped acts output medium, and out optical fibers in a phenomenon, power the sensor of optical its to or fiber press l a radius. current. power optical ground, fiber the or optical to light (see set-up which the and spring steel that first as inclinometer will the Optical resulting hole, cylinder is wavelength system sensor while transmission curve direction) fiber are fiber the fiber for the applying observing shows optical top optical for zero the ground, negative minimi levers used cylinder and The change pressure pressure a the static pressure pressure as the inclinometer as in Equation 4 and 6 resulting in oscillatory (non-monotonic) exponential relation between bending loss with bending radius. In its application for intensity based – sensor using bending loss phenomenon, the WGM effect should be avoided or minimized.

3. Optical fiber inclinometer

The optical fiber inclinometer consists of a light source, a housing of a standard geotechnical pipe containing a fiber-optic strand that acts as a sensor as well as a laser light-emitting medium, a 1x4 optical fiber coupler, four rolling wheels (using commercial bearings); with four pressure levers and support system, optical fiber input / output hole, light detector, stainless steel strap and pendulum circuit (see figure 1). Four rolling wheels, two at the top and two at the bottom of the cylinder body, serve to keep the cylinder body position in the standard geotechnical pipeline. Two pressure levers located at the top of the top wheel act as static levers to help the wheel function. The two levers on the bottom of the slip wheel act as active levers and are equipped with a spring that serves as a means of inflicting the curvature effect on the sensor fibers through pressure on the ground slope. If there is a slope of the ground, one of the levers at the bottom will press the optical fiber of the sensor, depending on the direction of the slope, resulting in macrobending of the sensor which will change the output through fiber optics. The change in the intensity will correspond to the detected slope angle change; i.e. the positive or negative directions to the vertical axis of the soil.

The stabilized laser light used for the inclinometer sensor system is launched into one 1x4 fiber coupler arm (1x4 fiber coupler) to be forwarded to the positive X-axis sensor fiber (for slope in left direction), to the negative X-axis sensor fiber (for slope in right direction) and one reference fiber while one other fiber port is not used. The optical signals coming out of the coupler outputat the end of the inclinometer are each received by the detectors and converted into electric current. Two knob switches are provided so that the slope angle reading panel shows the zero value before output reading.

4. Experimental methods

The evaluation for the optical fiber inclinometer performance was examined by measuring its laser source stability, examining the linearity of the output fiber sensor and observing the hysteresis curve of the optical fiber inclinometer. The laser stability measurement was conducted by detecting the output power transmission along the fiber for 5 hours by assuming that the temporarily measurement takes time no more than 5 hours.

The examination of the sensor linearity was conducted by launching of the laser at wavelength 1310 nm along the optical fiber and measure its output using power meter while applying pressure at the middle part (see figure 2). One end of the fiber was tied to a spring wire and the other end was left in straight and tight condition. This set up is figured an ideal condition for the optical fiber inclinometer.

The next experiment to evaluate the optical fiber inclinometer was the measurement of the hysteresis curve for left and right direction of inclination using set-up in figure 1. The sensor was tilted gradually from zero to 8 degree with gradual inclination angle per 0.5 degree and measured its output power using optical power meter.
5. Results and Discussion

Figure 3 shows the result of the stability examination of the laser source used for the fiber inclinometer for 5 hours by assuming that the temporarily measurement will not exceed 5 hours. The linearity measurement was conducted by measuring the output of the fiber underwent macrobending and is shown in figure 4.

In figure 3, it can be seen that at 18.00 (x-axis = 240 minute), the output increased because the temperature decreased. The significant drop at about 20th minute was caused by electrical shutdown at the central office. If we omit the temperature effect or accepted data only until 18.00 the output variation was 4.4%. If we include the temperature effect the error output was 7.1%. Examination of the linearity of the sensor showed quite good result with the R square value of 0.9655 with intercept at 36.8165 (see figure 4). The choice of the range is determined by the limit space inside the glass pipe which can only be moved around 10 degree or around 7 mm pressure. The hysteresis curve in figure 5 (left and right) shows quite good result for left direction of tilt; while for right tilt shows a wider error caused by the mechanical aspect for example the stainless steel bearings which moved less smooth.

![Figure 1. Optical fiber inclinometer.](image1)

![Figure 2. The principle work of optical fiber inclinometer.](image2)

![Figure 3. The plot of variation output power for 300 minutes to examine the stability of the laser source. The measurement started at 14.00 and ended at 19.00.](image3)

![Figure 4. The linearity curve for fiber inclinometer.](image4)
than the right bearings. Teflon bearing may be resulted in a smoother move. Meanwhile, a detail
calculation for the error of optical fiber inclinometer will be discussed in another report.

Some errors here probably were caused by two reasons; firstly, it was conducted using a glass
replica of geotechnical pipe as the housing for the body sensor to make a clearer or transparent view of
the pipe. This affects the results quite significantly. Secondly, the reference signal is not yet used or
functioned in this experiment because of the difficulty technical reason. In the next research, besides
improving the sensor structures, metal – standard geotechnical and reference fiber port will be used in
the experiment.

6. Conclusions
The development of an optical fiber inclinometer has been discussed. The performance of the optical
fiber inclinometer was evaluated by examining the light source stability, the linearity and the stability
of fiber sensor structure. Some recommendations for better sensor improvement for future work is the
use of the fiber optic reference port in the inclinometer, modification of some mechanical components
such as bearing wheel and metal pendulum and also the use of the real geotechnical pipe or not using
glass pipe for testing the sensor.

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