Miniature ground inclinometer for slope monitoring

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ABSTRACT: A new sensor device for slope monitoring is proposed. The device, Miniature Ground Inclinometer, is a long stainless steel pipe with a small diameter, which consists of short pipe segments. Each pipe is equipped with a sensor unit inside, which contains a MEMS tilt sensor, a geomagnetic sensor, and a control circuit. Each segment is connected to other segments with flexible joints at both ends. The device moves together with the ground displacement, and the tilt sensors detect it at respective depths. The diameter of the device is the same as that of the cone for portable dynamic cone penetration test (25 mm), and therefore, it can be directly inserted into the slope ground together with the sensor units inside by using a small hammer. The real time data of the slope ground displacement is transmitted to an early warning system by a wireless sensor network developed by the authors. A trial deployment of its prototypes in a landslide site in Sichuan Province, China, is also reported.

1 INTRODUCTION

There is a long history in prevention and mitigation of rainfall and/or scouring-induced landslides. Mechanical counter measures to prevent slope failure, like retaining walls and ground anchors, have been widely used. However, they are expensive and it is not realistic to apply such mechanical measures for these slopes with potential risk, because most of landslide occurs at small scale slopes, but with a large number. Therefore, careful monitoring of slope behaviors and consequent issuing warning is reasonable as alternatives.

The authors have proposed an early warning system for slope disasters, as one of more feasible countermeasures for small-scale slope disasters (Fig. 1) (Uchimura, et. al. 2009 and 2010). The system consists of minimum number of low-cost sensors on a slope, and the data is transmitted through wireless network. Thus, the system is low-cost and simple so that the residents in risk areas can handle it to protect themselves from slope disasters. Fig. 1 also shows a sensor unit developed by the authors. It contains a MEMS (Micro Electro Mechanical Systems) tilt sensor and volumetric water contents sensor, together with micro computer, battery, SD memory, and radio communication module. The sensor unit has 8 channels of voltage convertor and 3 types of serial interfaces. An optional interface board for strain gage bridge can be also attached. So, various types of sensors can be used in this sensor network system.

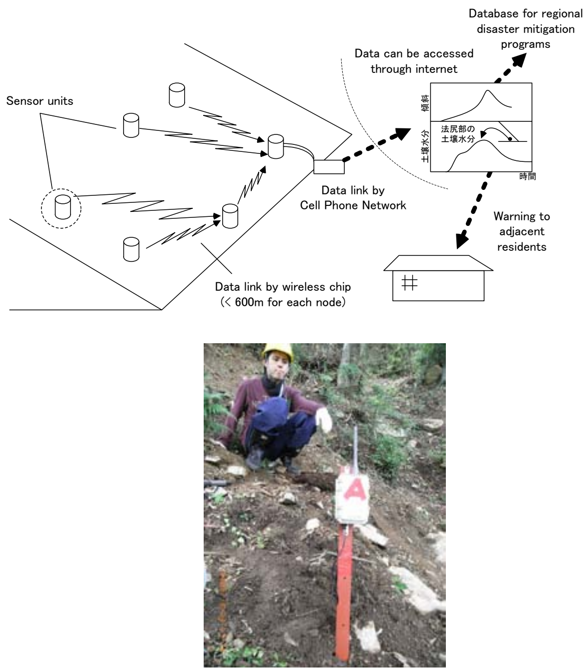

Fig. 1 Concept of wireless monitoring and early warning system for slopes and a picture of sensor unit.

The authors have developed a new sensor device named 'Miniature Ground Inclinometer'. It is a long stainless steel pipe with a small diameter, which is equipped with MEMS tilt sensors, a geomagnetic sensor, and a control circuit. By installing it into the slope ground vertically, the array of tilt sensors detects the lateral displacement of the ground. The diameter of the device is the same as that of the cone for portable dynamic cone penetration test (JGS 1433-1995), and therefore, it can be directly inserted into the slope ground together with the sensor units inside by using a small hammer. This realizes low cost and quick installation of the device in landslide sites.

2 MINIATURE GROUND INCLINOMETER

2.1 *Design of miniature ground inclinometer*

Fig. 2 shows the basic design concept of the miniature ground inclinometer. The device consists of stainless steel pipe segments with length of 50cm or 1m and outer diameter of 25 mm. The segments are connected to each other by a flexible connection mechanism, so that the device moves together with the ground displacement.

A sensor unit covered by a small aluminum cylindrical case is installed at the center of each segment. The sensor unit contains a MEMS tilt meter (nominal resolution = 0.04 mm/m), a geomagnetic sensor (digital compass, nominal resolution = 0.5 deg), and a temperature sensor (nominal resolution = 0.5 deg) (see also Fig. 3). Each unit also contains a microcontroller chip, which control the sensors, and transfer control commands and data to the next units by serial interfaces. When it receives a command and data from other unit, it relay them to the next unit.

There is a control and radio transmitter unit on the ground which controls all the function of the device and transfers the data to the wireless sensor network system.

A penetration cone is attached at the bottom end of device. The device can be installed directly into the slope ground by hitting with a small hammer, in the similar way to the portable dynamic cone penetration test (Fig. 4). Unlike conventional inclinometers, preliminary bore holing is not necessary. Thus, the installation work is quite easy and quick.

The segments may rotate in the ground during the installation process. Therefore, the direction of each tilt sensor in the segment is detected by the geomagnetic sensor. If the direction of the geomagnetic sensor is α, the direction of the tilt sensor is α - π /2 in X axis, and α + π for Y axis. Supposing the direction of the slope to be β from the North, the tilting in the direction of slope can be obtained as:

$$\xi = X\sin(\alpha-\beta) - Y\cos(\alpha-\beta) \qquad (1)$$

where X and Y are output of the tilt sensor in respective axis in mm/m, and ξ is the tilting in the slope direction in mm/m.

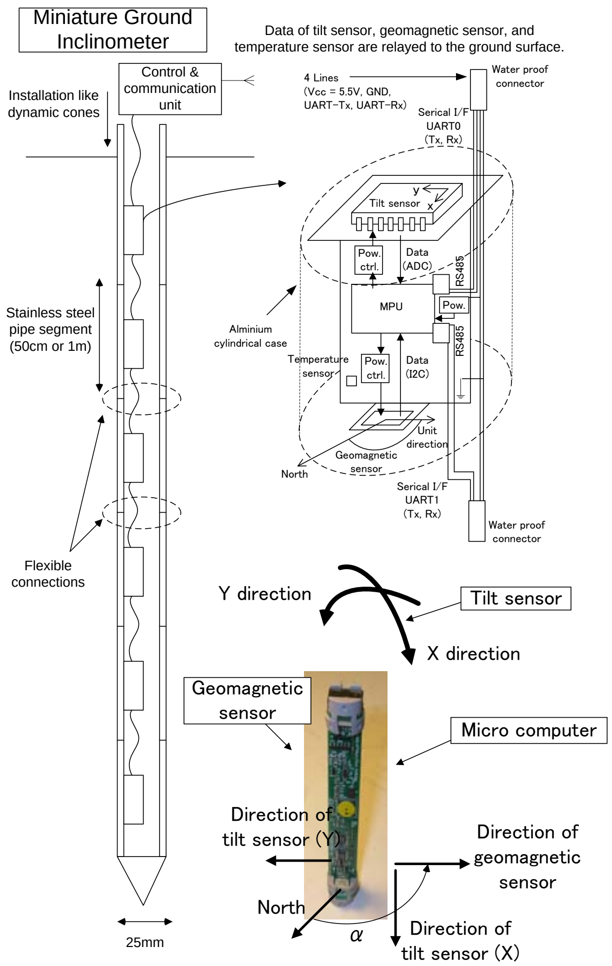

Fig. 2 Structure and functions of miniature ground inclinometer.

a) b) c)

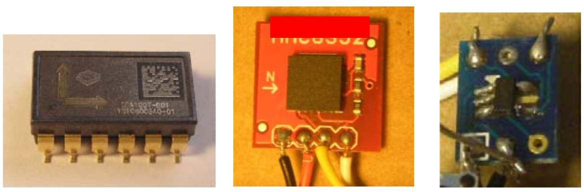

Fig. 3 a) MEMS tilt sensor; b) geomagnetic sensor; and c) temperature sensor used in the sensor unit.

Fig. 4 Installation of miniature ground inclinometer using hummer.

2.2 *Evaluation of geomagnetic sensor*

The geomagnetic sensors have to detect the correct direction of the sensor unit while it is installed in the aluminum case, the stainless steel pipe, and surrounded by the ground soil or rock materials. A series of tests were conducted to examine the validity of this sensor. The geomagnetic sensor was set horizontally, and slowly rotated in the air, or 1 m-deep in a loam ground installed in a pipe made of various materials (PVC, aluminum, steel, and stainless steel).

Fig. 5 summarizes the results. This sensor needs a 'calibration' procedure instructed by the manufacturer to identify a slight variation of the sensing segments in the sensor before usage. After calibration, the sensor detects correct directions with an error range of 2 degrees. The only exception is the case with steel pipe, which has strong magnetization. Thus, stainless steel and aluminum, which has less magnetization characteristics, was employed as the material for the miniature ground inclinometer.

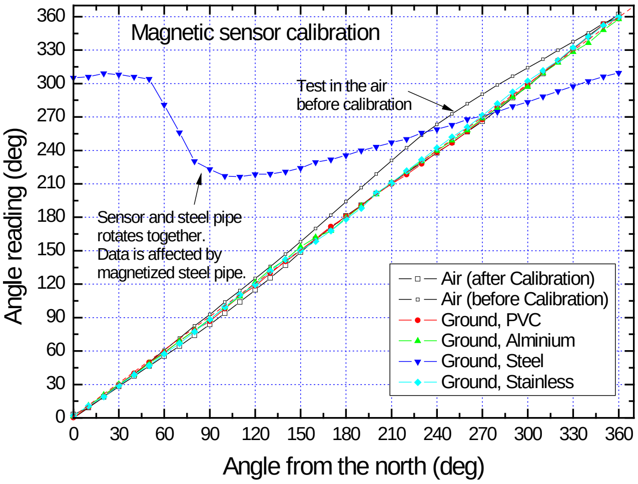

Fig. 5 Evaluation of the geomagnetic sensor.

2.3 *Evaluation of tilt sensor*

The data from the tilt sensor was evaluated together with the correction method using the geomagnetic sensor. The sensor units were installed in a model ground in a sand box, and the box was tilted (Fig. 6). As the data from the geomagnetic sensor is affected by the tilting, the direction of the tilt sensor was identified based on the data obtained at the beginning of the tilting test, when the geomagnetic sensor is in horizontal position.

Fig. 7 summarizes a result in a case with (α - β) = 127.8 degree in Eq. (1). The corrected tilting angle shows a good correspondence with the actual tilting angle, while it has some error when the angle became larger. Practically, the tilting angle in the slope before failure is very small, less than 100 mm/m in most cases. Therefore, this results shows that the corrected values of the tilting angle is good enough.

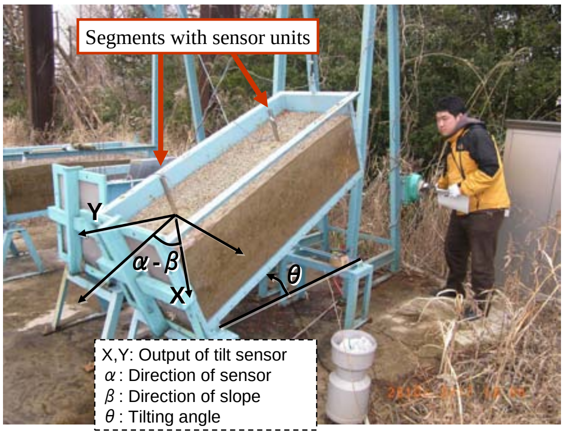

Fig. 6 Setting for evaluation of the tilt sensor.

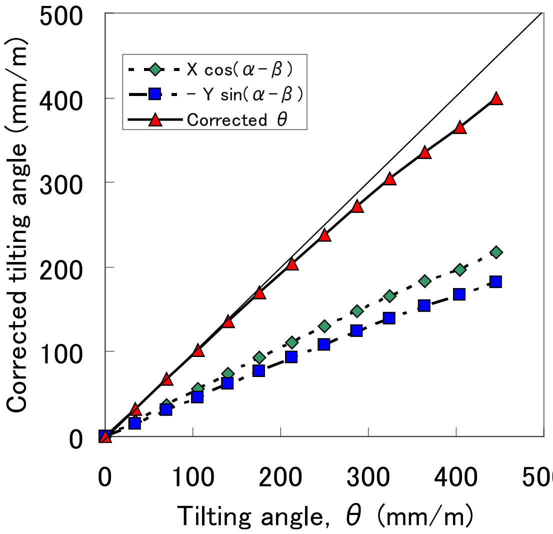

Fig. 7 Evaluation results of the tilt sensor.

3 DEPLOYMENT IN A LANDSLIDE SITE

3.1 *Site description and installation of device*

Prototypes of the miniature ground inclinometer have been installed in an unstable slope site in Taziping, Sichuan Province, China (Fig. 8). The height of the slope is around 250 m, and its average slope angle is 30 degree. According to a site investigation, there is 20 to 40 m of deposit of weathered andesite on the assumed slip surface of intact andesite layer (Fig. 9). This area was strongly shaken by the Wenchuan Earthquake in 2008. Since then, the slope slides gradually at every heavy rainfall events.

The prototypes were installed into 2 bore holes which had been left opened after previous site investigation works. Figs 8 and 9 show their positions. The boring data in Fig. 9 shows the ground profile for a depth of 30 m or more, but the bore holes had been collapsed at the depth of 12 m at the time of installation of the devices. Therefore, devices were installed for 12 m-deep only.

One meter-long stainless steel pipes were used as the segments, and each of them was equipped with a sensor unit. The connections between the segments were made flexible by using a short chip of high-pressure vinyl tube (Fig. 10). The total weight of the inclinometer is more than 30 kg, but the rupture strength of this tube is large enough to support it. The cables between sensor units were connected with waterproof coating (Fig. 11).

Fig. 8 Landslide site in Taziping, Sichuan Province.

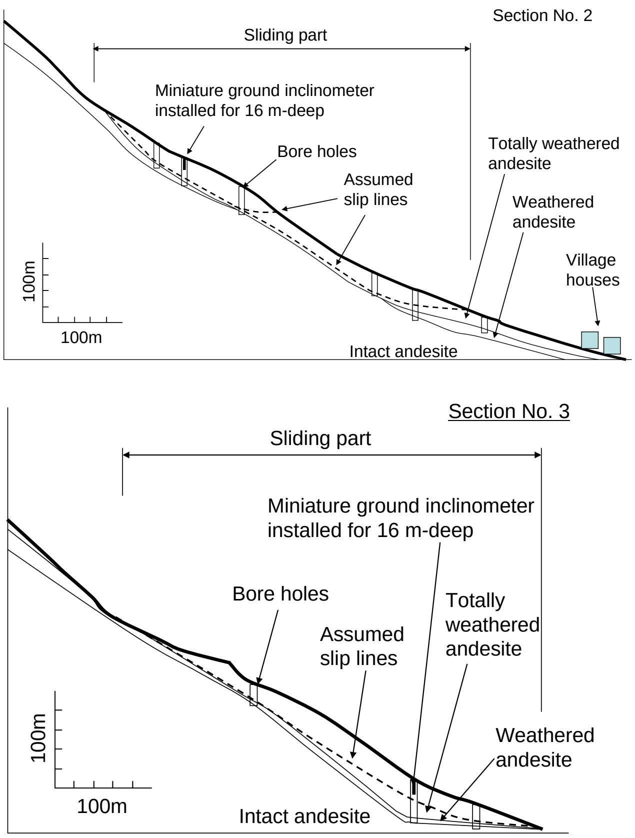

Fig. 9 Crosssections of the Taziping landslide site (Sections No. 2 and 3 shown in Fig. 8).

The inclinometers were installed in the bore holes on 2010/09/09. The measurement was started immediately, but the gap between the bore holes and inclinometer pipes were left. Therefore, the data of tilt sensors are valid corresponding to the ground displacement only after 2010/10/24, when the bore holes were fill with fine sand. The data from the sensor units were collected to a radio transmitter (Fig. 12), and sent to a receiving and data logging unit installed on a roof of a residential house near the site. The logging unit also includes a cell phone module, and the data is sent to a data server placed in Chengdu City via internet.

Fig. 10 Flexible connection between pipe segments.

Fig. 11 Waterproof connection between sensor units.

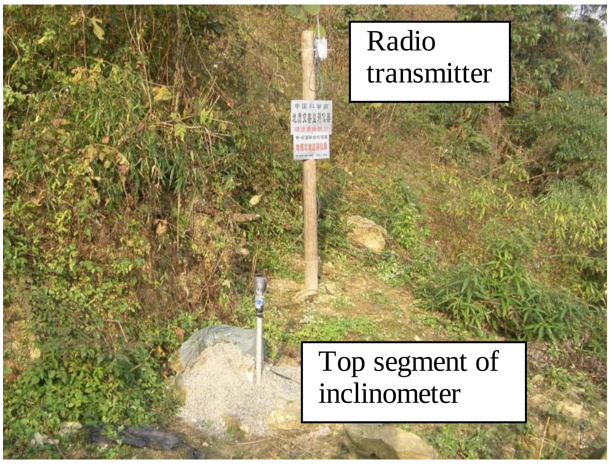

Fig. 12 Final setup of the miniature ground inclinometer placed on Section No. 3 of Fig. 9..

Fig. 13 Receiving and data logging unit.

3.2 *Obtained data*

Figs. 14 summarizes the data of the tilt sensors of each unit in X and Y directions. The increments from the values on 2010/10/25, just after filling the bore holes with sand, are shown. The units are named as Unit 1 to 12, in order from the top to bottom. For both of X and Y directions, the values of Units 1, 2, 3, 8, and 10 shows large changes and fluctuations, while those of others units are within a range of 0.5 degrees. The instability at Unit 1 may be because half of the top segment with Unit 1 is exposed in the air (Fig. 12).

The instability for Units 2, 3, 8 and 10 may be due to a technical problem in the sensor units. Fig. 16 shows the power supply voltage for the tilt sensor of each unit. The power is delivered from the control and radio transmitter unit on the ground surface through the cable, and it should be regulated into 5 V for proper function of the tilt sensors. However, the voltages for Units 2, 3, 8 and 10 are not 5 V, but decreasing with time. This makes malfunction of the tilt sensors. The reason for this abnormal voltage data is not clear, but the most possible reason is water submergence into the aluminum cases of the units. Thus, the tilt data from Units 1, 2, 3, 8, and 10 are assumed to be zero in the following calculation. Fig. 15 shows the magnified plots of the data from the normal tilt sensors.

Table 1 shows the direction of each sensor units obtained by the geomagnetic sensor, which is denoted as α in Eq. (1). The downward direction of the slope, β in Eq. (1), is 236 degrees counterclockwise from the North. Thus, the tilting angle of each unit in the slope direction can be calculated by Eq. (1), as shown in Fig. 17.

The profile of horizontal displacement at each depth in the ground relative to the bottom segment can be obtained by accumulating the values in Fig. 17 multiplied by the length of the segment pipes (1 m), as shown Fig. 18. A trend of displacement at a depth of 2 to 4 m is observed, while some more displacements are also possible for Units 1, 2, 3, 8, and 10. This is a continuous sliding with average rate of 10 mm/month, which should be carefully observed.

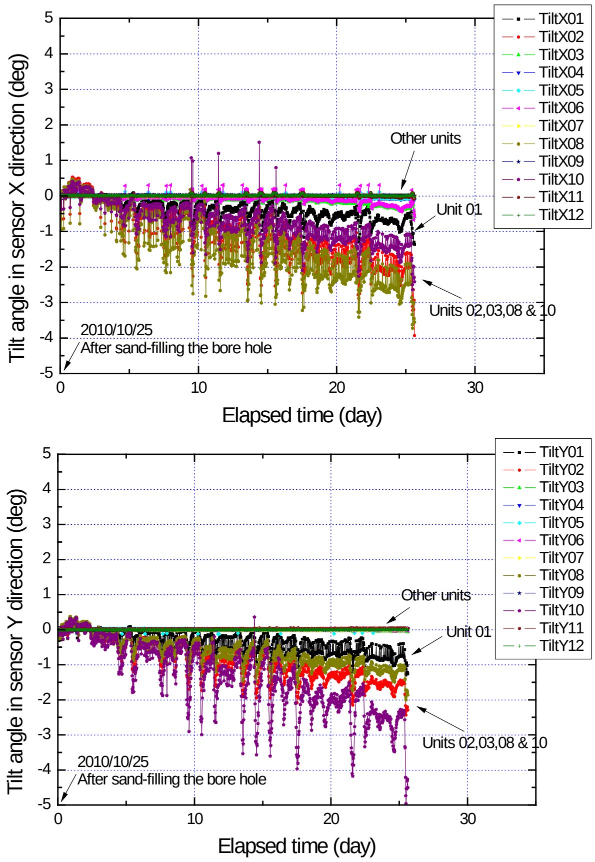

Fig. 14 Data of tilt sensors in X & Y directions.

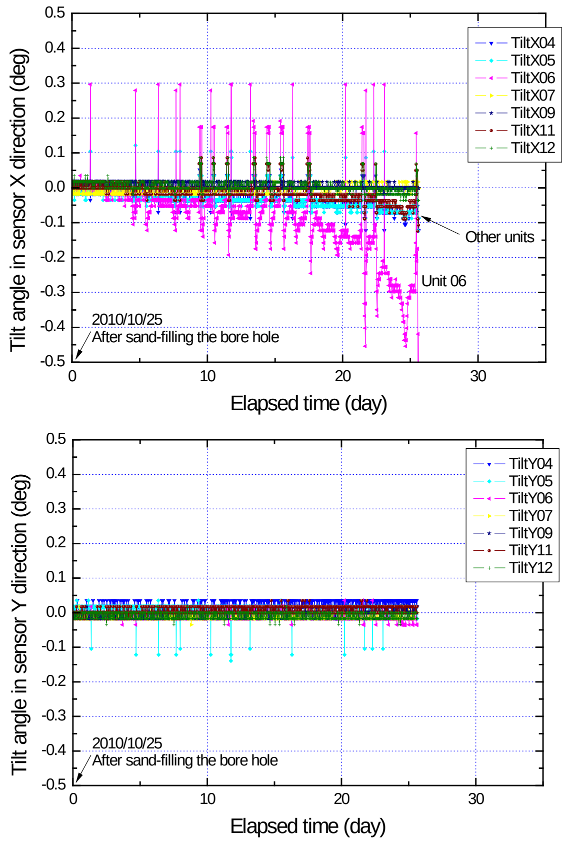

Fig. 15 Data of tilt sensors in X & Y directions. (Normal sensors only.)

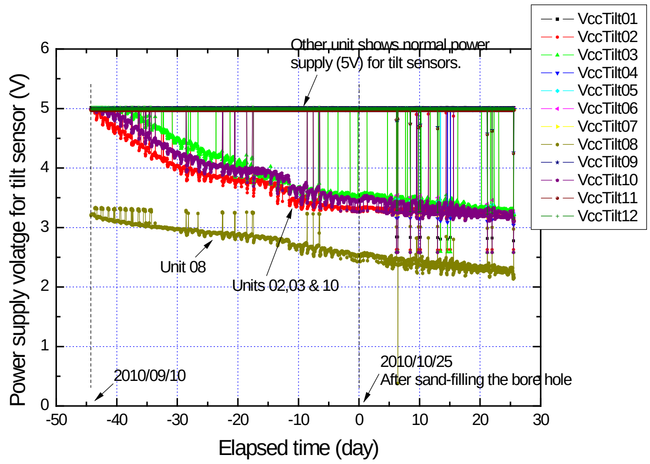

Fig. 16 Power supply voltages for tilt sensors.

Table 1 Directions of geomagnetic sensor units.

Unit	1	2	3	4	5	6
Angle	133	121	123	303	324	324

Unit	7	8	9	10	11	12
Angle	325	347	346	341	345	352

(Counterclockwise from the North, in degree)

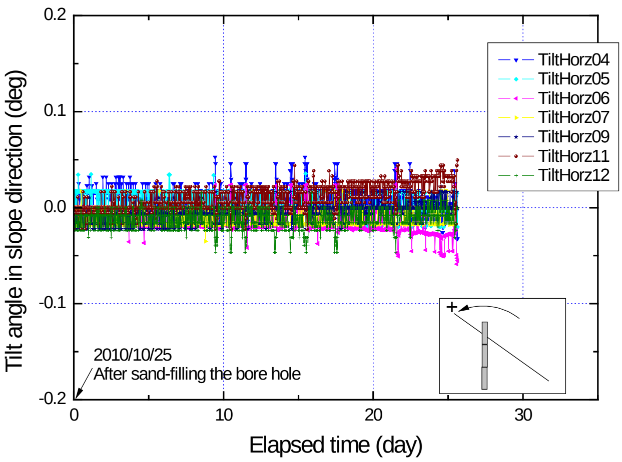

Fig. 17 Tilt angles in the slope direction.

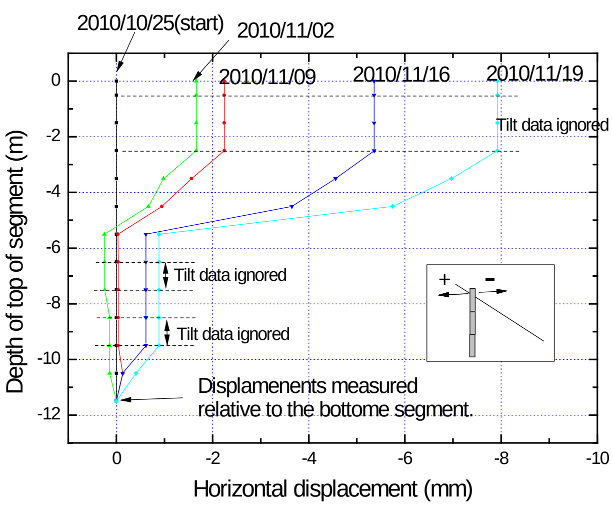

Fig. 18 Profile of horizontal displacements in the slope direction.

4 CONCLUSION

A new sensor device for slope monitoring, Miniature Ground Inclinometer, is proposed, and its prototype was developed. The device detects the displacement in the slope ground by a tilt sensor at each depth, with data correction according to the direction of the sensor units obtained by a geomagnetic sensor. The small diameter of the device allows quick installation. The real time data of the slope ground displacement is monitored by a wireless sensor network system developed by the authors, and it is used for early warning.

A trial deployment of its prototypes was conducted in a landslide site in Sichuan Province, China. The device was installed on the slope ground for a depth of 12 m. Although some technical problems were found, the device detected a systematic displacement of the slope ground.

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