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A Novel Strategy for landslide displacement and its direction monitoring

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Abstract

Landslide monitoring is important in predicting the behavior of landslides, thereby ensuring environmental, life, and property safety. On the basis of our previous studies, we conducted the double shear test by using a third-generation optical fiber transducer that uses expandable polystyrene (EPS) as base material. However, the third-generation transducer has poor performance when cohesive force is present between the grout and capillary stainless steel pipe of the transducer. Thus, the fourth-generation optical fiber transducer was invented. Similar to the third-generation transducer, the fourth-generation transducer also used EPS as its base material. Single shear test was conducted on the fourth-generation transducer after being grouted with cement mortar (1 : 1 mix ratio). The micro-bend loss mechanism of the optical fiber was considered, and the optical time domain reflectometry instrument was used. The fact that the loss sequence of optical fibers subjected to loading is different at various locations is found. The relationship of the loading-point displacement VS.

optical fiber sliding distance and optical loss were measured. Results show that the maximum initial measurement precision of the newly proposed device is 1 mm, the corresponding sliding distance is 21 mm, and the dynamic range is 0–20 mm. The fourth-generation transducer can measure the movement direction of loadings, thus making this transducer applicable for landslide monitoring.

20 **1** Introduction

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There are many technologies to monitorslides, such as Global Position System (GPS) (Jibson et al., 2000), Geographic Information System (GIS) (Dhaka et al., 2000), Remote Sensing (RS) (Sun et al., 2003), digital close-range photogrammetry (Matori et al., 2003) for measuring ground surface displacement, and inclinometer (Sargand et al., 2004) and time domain reflectometry (TDR) (Dennis et al., 2006) for monitoring deep sliding surfaces. Methods employed optical fiber technologies such as OTDR





(Higuchi et al., 2007; Tang et al., 2009), Brillouin optical time domain reflectometry (BOTDR) (Ding et al., 2005; Wang et al., 2009) and Brillouin optical time domain analysis (BOTDA) (Iten and Puzrin, 2009; Zeni, 2009) were also introduced into landslide monitoring area. However, all these present methods have advantages and disadvantages (Zhu et al., 2011).

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In our previous studies (Zhu et al., 2009, 2011), we put into public a novel distributed optical fiber transducer, the first, second, and third-generation, to overcome the drawbacks. We employed the optical fiber micro-bending loss mechanism and OTDR technology, based on the spatial construction principle of reinforced beams. We used a base material, some capillary stainless steel pipes and optical fiber as the sensing element. Bending resistance tests performed on the second-generation transducer and the third-generation transducer grouted with concrete C40, and proved that such sensor has higher initial measurement precision, larger sliding distance, and dynamic range.

¹⁵ Shearing force is the most common force exerted on the sliding plane during landslide. However, no evidence exists whether transducers could achieve high initial measurement precision, large sliding distance, and good dynamic range when these transducers are embedded in a grout and are subjected to shearing force. Considering this research limitation, we conducted double shearing tests by using the third-

- 20 generation transducer grouted with cement. The third-generation transducer showed poor performance when cohesive force is present between the grout cement and the capillary stainless steel pipe, thereby compelling us to construct the fourth-generation transducer. To investigate the performance of this transducer under shearing force, shearing resistance tests were performed on two types of dimension of the fourth-
- ²⁵ generation transducer that was grouted with mortar. Laboratory results confirmed our previous assumptions and conclusions, and other significant findings, such as the determination of the moving direction, etc.





2 Double-shearing test

2.1 Third-generation transducer

After several tests, expandable polystyrene (EPS) was selected as base material of the third-generation transducer. EPS was subsequently cut into rectangular parallelepipeds, and the cross sections of the parallelepipeds were shaped into squares. Φ1 capillary stainless steel pipes (#1, #2, #3, and #4) (Fig. 1) were arranged at the midpoint of each side. EPS is an ordinary commercial material in the market. Table 1 shows the relevant parameters of the EPS (Wang and Wang, 2002). Capillary stainless steel pipes were purchased from Wenzhou BIZBAO Tube Manufacturer Co.,

Ltd. in Zhejiang Province, China. The pipes had 0.7 mm internal diameters, in which fiber optics penetrated through the pipes. The optical fiber used was a simple module (type G652B), which was purchased from Wuhan Yangtze Optical Fiber and Cable Co. Ltd, Wuhan, China. The diameter of the optical fiber was 245 μm.

2.2 Test model

¹⁵ We fabricated a cylinder test model by using an unplasticized polyvinyl chloride (UPVC) pipe as formwork. Table 2 shows the details of the cylinder test model.

Two 20 mm deep sliding guide planes, which were spaced 130 mm around the test piece, were created by using a cutting machine (Fig. 1). The distance of the two bearings of the test machine was set at 130 mm to guarantee the shearing movement

²⁰ of the test piece. To investigate the cohesive force between the mortar and the capillary stainless steel pipes, two Φ1 steel pipes (#5 and #6) that had no internal optical fibers were arranged beside the transducer.

2.3 Other experimental materials and instruments

In this study, the experimental instruments we employed were: OTDR, type TFP2A, manufactured by Tektronix in the United States. Optical fiber fusion splicer, type





AV6491E, manufactured by the 41st Institute of China Electronics Technology Group Corporation, Hefei, China. Fiber cleaver, type MAX CI-01, manufactured in South Korea. Fiber optic stripper, type Clauss CFS-2, manufactured in the United States. 0–50 submeter, and Vernier caliper. The 10KN hydraulic universal testing machine was used as loading machine for the tests.

2.4 Experimental results

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The results are shown in Figs. 2 and 3, and Tables 3 and 4.

Results show that grouting integrity worsens as grouting strength decreases. The recovery amount of the reference steel pipe was larger than the sliding distance of fiber #3. However, the recovery amount of the reference steel pipe was smaller than that of the other fibers. The reference pipe of model #1 was broken. In this study, model

- #1 had the highest strength. Cohesive force was also shown to be positively correlated to the model strength, thereby indicating that cohesive force influences the movement of steel pipes. The influence of cohesive force on steel pipes should be reduced.
- The two results have a certain initial measurement precision, sliding distance, and dynamic range, thus making this transducer capable of monitoring shear deformation.

The fitting curve of the sliding distance and the vertical displacement at the loading point is linear, whereas that of fiber optic loss is non-linear.

Fiber optic loss occurred in the following order: fiber #1, #2, #4, and #3. This indicates this cylinder test model can determine the movement direction of the loading is from fiber #1–#3, which is actually the same to the loading direction.

The maximum loss of the two models is less than $5 \, dB$, which is lower than that of the second-generation transducer. Model #2 has a maximum sliding distance of less than 8.5 mm and has a dynamic range even less than 0–7 mm. These results indicate

²⁵ the poor performance of the third-generation transducer grouted with concrete when subjected to shear load.





3 Study on the fourth-generation transducer

3.1 Fourth-generation transducer

We designed a fourth-generation fiber transducer with bowknot (Fig. 4) and established a single shearing test model to overcome the drawbacks caused by the cohesive
force that verified in the third-generation transducer double-shearing tests, to improve the performance of the transducer when subjected to shear load, and to verify its determination of the loading direction. The material and shape of the base material of the fourth-generation transducer was the same with that of the third-generation sensor. However, additional fixed devices were set in the Φ1 steel pipe fixed range, and Φ2
capillary stainless steel pipes were capped on the Φ1 and Φ2 capillary stainless steel pipes were 0.7 and 1.7 mm, respectively.

3.2 Single shearing test model

Two models (model #3 and #4) were made with the same mix ratio of cement mortar
by using base materials with different dimensions. Table 2 provides the model details.
We fabricated a cylinder test model that has UPVC pipe as formwork to ensure that the model is compatible with the field test (Fig. 5).

Monitoring becomes inaccurate because the cohesive force of cement mortar on capillary stainless steel pipes hinders the free movement of steel pipes. Therefore, the

- model shown in Fig. 5 was designed to enable the Φ1 steel pipe house a 300 mm long Φ2 steel pipe that is treated with surface painting before placing into the test model. The Φ2 steel pipe will be pulled out once cement mortar pre-hardens to ensure that the Φ1 steel pipe can move freely in the mortar. To guarantee the anchorage quality of Φ1 steel pipes in fixed range, we provided two additional fixed devices with anchor
- ²⁵ bars on each steel pipe. A reference steel pipe #5 is placed beside pipe #4 to verify the influence of cohesive force on the pipes.





3.3 Experiment

The simple shear model was adopted in the experiment. Once the test piece prehardens (after three days), a sliding guide plane that is 3 mm wide and 20 mm deep was cut perpendicularly in the axial direction by using a cutting machine (Fig. 5). The

- ⁵ fixed end of the test piece was placed on the testing machine. The capillary stainless steel pipes were numbered in sequence (#1–#4), each steel pipe was penetrated with optical fibers. A bowknot was formed at the free end of the test piece. The size of the bowknot was then adjusted, as shown in our previous studies (Zhu et al., 2011). Optical fibers were glued at the fixed end of the test piece by using 502-branded glue. A free
- optical fiber was set aside among each bowknot to ensure monitoring capabilities. The locations of the bowknot (left) and the Φ1 capillary stainless steel pipe (10 cm to the right) were marked to measure the distance traveled by the optical fibers. The universal tester was adjusted in the crown face of the test piece, and a dial indicator was installed to record the vertical displacement at the loading point. The optical fiber penetration test
- ¹⁵ was performed prior to loading to guarantee optical fiber integrity and joint reliability. The length of the light waves in the experiment was 1310 nm.

3.4 Experimental results

Experimental results are shown in Figs. 6 and 7, and Tables 3 and 4.

At the end of the experiments, the test pieces were shown to be integral, and the ²⁰ reference pipes were not broken. The recovery amount of the reference steel pipe was close to the vertical displacement at loading point of both models. This result indicates that the influence of cohesive force between the steel pipes and mortar was reduced. The following indexes denote that the performance of the fourth-generation transducer with grouting is better than that of the third-generation transducer subjected to shearing ²⁵ force, thereby indicating the success of the design of the fourth-generation transducer.

Compared with model #4, model #3 had a higher initial measurement precision. When all the optical fibers of model #3 reached 0.1 dB, the corresponding relevant





vertical displacements at the loading point were smaller than those of model #4. The highest initial measurement precision of model #3 reached 1 mm, which is smaller than that of the TDR technology (Dennis et al., 2006). The corresponding maximum sliding distance was 21 mm, which is higher than that of a single optical fiber (Tang et al.,

⁵ 2009). The fiber in the model was also not broken. The maximum sliding distance of model #3 could be further increased. However, the test was interrupted because of the loss data in fibers #3 and #4, which were found to be saturated. The dynamic range of fibers #1 and #2 of model #3 reached 0–20 and 0–21.6 mm, respectively.

The sliding distances of the optical fiber around the transducer were smaller than the vertical displacement at the loading point. The difference of the sliding distances and the vertical displacement for fibers #1 and #3 were respectively greater than 20% and 30% because of the influence of the soft base material.

The fiber optical losses for both models occurred in the following sequence: fiber #1, #2, #4, and #3. This result is similar to the results of the double shearing test. Thus, this model determined the loading direction is also from fiber #1–#3.

The linear and nonlinear fitting curves of the fiber optical sliding distance and the loss and vertical displacements at loading point were similar to that of the double shearing test.

The performances of these two models were different. Therefore, model #3, which was grouted with a small-dimension transducer, was found to have good performance. Thus, model #3 is the better choice if the measurement range of the model is allowed.

4 Theoretical analysis of determination of loading direction

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Assume that the loading direction is from pipe #1–#3 and that the steel pipes of the fourth-generation transducer are arranged such that the steel pipe #1 is at the near end adjacent to the detector, next is #2 and #3 pipe, and finally out from the #4 pipe. The shear failure mode of the beam should be used, then shear stress, accompanied by tensile stress, will be produced first in steel pipe #1.Then the pipes #2 and #4 will





also be under shear stress. Because the EPS material is too soft, thus delay pipe #3 in transferring a part of shear force. So, among the pipes, pipe #3 was under the least stress and was the last pipe to be subjected to stress.

When the loading direction of the subjected transducer is the same as that shown in Fig. 8, the force applied on the transducer will cause sliding of steel pipes at the free end. As optical fibers are penetrated through the pipes, the stress on the pipes will be transferred to the optical fibers, and the pipes movement will lead to the sliding of optical fibers. The size of the bowknot at the free end of the optical fibers will decrease, and the optical fiber curvature will increase. These changes in the curvature will result in microbend loss, which will be captured by using the OTDR instrument. Therefore,

In microbend loss, which will be captured by using the OTDR instrument. Therefore, the movement direction of loadings can be determined according to the sequence of occurrence of optical fiber loss. This result indicates that the movement direction starts from pipe #1 and ends at pipe #3, which is similar to the experimental results.

5 Discussion

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The fiber optical transducer we invented is used for field monitoring of slope stability. The monitored slopes have different characteristic parameters (e.g., strength and friction angle). To guarantee successful monitoring, the transducer we invented is to be adopted these parameters of the appointed slope. That is, the selected slope corresponded to the matched transducer base material, as well as its dimension, and grouting strength. We discussed these in the following subsections.

5.1 Influence of grouting strength

The experimental results showed that the integrity of model #1 is better than that of model #2 because the grout strength of model #1 is stronger than that of model #2. However, one reference pipe of model #1 was broken. The positive correlation of cohesive force with grout strength leads to the reference pipe being broken.





Dennis (Dennis et al., 2006) had carried out field monitoring on the slopes beside the Arkansas State highway designated as Interstate 540 (I-540) which connected Ft. Smith to Fayetteville, USA. Two field monitoring sites, Mile-marker 46 and Milemarker 50 of I-540 were set. Field monitoring results show that the weak grout at Mile-⁵ marker 50 did not cause TDR cable deformation. However, the grout was too strong to split the surrounding soil at Mile-marker 46. Therefore, the influence of grout strength should be fully considered.

5.2 Influence of base material

The transducer we invented did not confine the type and dimension of the base ¹⁰ material of the transducer. We have studied the performance of the transducer that has EPS and polyvinyl chloride as base material, and various dimensions of the third-generation transducer were also employed. However, shearing tests were not conducted. Experimental results of this paper indicate that the performance of model #3 is better than that of model #4. The cement mortar ratio of the two models is the same. The sliding guide planes decrease much influence of curing time on mortar strength. The only difference found between the two models is their cross-section dimension of the two transducers. Thus, the performance of the transducer using various base materials and dimensions should be further studied.

5.3 Influence of experimental instruments

According to the experimental results of the third-generation and fourth-generation transducers, the loss data of optical fibre is too discrete and is extremely inconsistent with the displacement variations because fiber #4 is located at the end of the entire sensing line and far from the OTDR. Thus, the number of survey points connected to the OTDR must not exceed three. Further studies on a new OTDR instrument to improve this drawback are urgent.





5.4 Influence of test piece preparation

As for the slope stability borehole based field monitoring, the grouting of the transducer was integrated before sliding occurred. However, to grantee the shearing loading subjected better to the test piece in our test, we annularly cut a sliding guide plane in

the test piece by using the cutting machine. This process follows the method mentioned in the study of Dennis (Dennis et al., 2006). Nevertheless, the process used in Dennis' paper is not exactly the same to the actual. While this sliding guide plane may change some characteristics of the test piece. Therefore, further study on the test piece without a sliding guide plane is necessary.

10 5.5 Comparison with other photoelectric monitoring technologies

As previously mentioned, we compared the features of the fourth-generation transducer with those of the other transducers in terms of initial measurement precision, sliding distance, dynamic range, unit price, and determination of load direction (Table 5).

Table 5 shows that the fourth-generation transducer is the most effective among all transducer versions because this method has a higher initial measurement precision, a larger sliding distance, good dynamic range. The unit price of the fourth-generation transducer is also very low. Unlike the other listed methods, the fourth-generation transducer can also judge the loading direction, which is a significant progress compared with the other electro-optic monitoring methods.

20 5.6 Further enhance the performance of the optical fiber transducer

As shown in Table 5, the fourth-generation transducer does not have the largest maximum sliding distance and dynamic range. Therefore, the below enhancements are needed to improve the performance of the newly proposed transducer.

First, the cross-section dimension of the transducer could be enlarged. In our previous study, we theoretically proved that the larger the cross-section dimension is,





the larger the sliding distance becomes. Further experiments should be made to verify this theory.

Second, the OTDR should be improved. As mentioned in Sect. 5.3, improving the OTDR will enhance the performance of the optical fiber transducer. Further studies are needed to verify this correlation.

6 Conclusions

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Double and single shearing tests were performed in this study, and a new type of optical fiber transducer was invented to overcome the drawbacks that occurred when the thirdgeneration transducer underwent double shearing tests. The results of two shearing tests show that the fourth-generation transducer has good initial measurement precision, a certain sliding distance, and good dynamic range, which indicate that this transducer can monitor shearing deformation. The fourth-generation transducer can determine the loading direction and can overcome numerous deficiencies of other existing photoelectric sensing and monitoring technologies, such as single optical fiber, optical grating, and coaxial cable. These findings indicate that the newly proposed fourth-generation transducer can be used for slope stability monitoring.

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Table 1.	Relevant parameters of EPS material.
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Parameter	Density (kgm ⁻³)	Initial elastic modulus (MPa)	Initial Poisson's ratio	Compressive strength (KPa)	Bending strength (KPa)	Tensile strength (KPa)
Value	16	4.8	0.05	90	300	350





Table 2.	Parameters	of test	models.
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Test model	Dimension of the model (mm)	Cross-section of the transducer (mm)	Grouting material	Curing time
1	Ф110 × 500	25 × 25	cement mortar 1 : 1	4d
2	Ф110 × 500	25 × 25	cement mortar 1 : 2	14d
3	Ф110 × 500	25 × 25	cement mortar 1 : 1	7d
4	Ф110 × 500	45 × 45	cement mortar 1 : 1	21d

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Table 3. Catalogue of fiber optical maximum sliding distance and vertical displacement at loading point of each model.

Test model	Fiber optical max. sliding distance (mm)				Sliding value of reference pipe (mm)	Max. vertical displacement at loading point (mm)
	1#	2#	3#	4#		
1	27.56	19.98	8.46	31.98	16.56	59.3
2	8.44	7.5	5.22	7.42	6.16	24
3	21	23.6	16.8	11.5	25.08	26
4	20.9	22.76	19.1	20.5	28.32	29.1

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Table 4. Catalogue of initial measurement precision and dynamic range of each model.

Test model 1				0			0										
				2			3					4					
Number of opti	cal fiber	1#	2#	3#	4#	1#	2#	3#	4#	1#	2#	3#	4#	1#	2#	3#	4#
Initial measurement	Relevant loss (dB)	2	4	6.25	5	2.05	2.05	5	2.05	1	2.5	9	2.5	3	3.95	10	3.95
precision	Value (mm)	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.12	0.35	0.11	0.1	0.1	0.3	0.1
Dynamic range	e (mm)	0-25.56	0–15.98	0–2.21	0-26.98	0-6.39	0-5.45	0-0.22	0-5.37	0–20	0-21.1	0-7.8	0–9	0-18.9	0-18.81	0–9.1	0–16.55

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 Table 5. Comparison of the present model with other monitoring models.

Testing method	P initial	Precision of measurement	N	lax. sliding distance	Dynamic range (mm)	Determination of the loading	unit price
	Value (mm)	Reflectometry coefficient/loss	Value (mm)	Reflectometry coefficient/loss	direction	(\$m ⁻¹)	
TDR (Dennis et al., 2006)	5	0.005 (<i>p</i>)	25.4	0.123 (<i>p</i>)	0–20.4	Can not	13.5
Single optical fiber (Tang et al., 2009)	0.3	0.5 (dB)	3.6	54 (dB)	0–3.3	Can not	0.03
Method in our previous study (Zhu et al., 2011)	2.3	0.11 (dB)	26.5	9.1 (dB)	0–23.2	Can not	0.15
The forth-generation transducer	1	0.1 (dB)	21	5.95 (dB)	0–20	Can	0.2







Fig. 2. Relationship between fiber optical loss and vertical displacement at loading point. (a) Model 1, (b) Model 2.











Fig. 4. Draft of the forth-generation transducer. (a) Elevation view of the sensor. (b) Cross section of the sensor (unit: mm).

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