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A Novel Strategy for landslide displacement and its direction monitoring

Z.-W. Zhu^{1,2}, Q.-Y. Yuan³, D.-Y. Liu^{1,2}, B. Liu⁴, J.-C. Liu⁴, and H. Luo^{1,2}

¹College of Civil Engineering of Chongqing University, Chongqing 400045, China

²Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, Chongqing 400045, China

³Department of Geriatrics, Southwest Hospital, the Third Military Medical University, Chongqing 400038, China

⁴College of Electro-optic Engineering of Chongqing University, Chongqing 400044, China

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Correspondence to: Z.-W. Zhu (zqiao999@126.com)

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(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).

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.

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-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-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.

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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

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

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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, 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

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.

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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 Mile-marker 50 of I-540 were set. Field monitoring results show that the weak grout at Mile-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 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.



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

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 third-generation 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.

Parameter	Density (kg m^{-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

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Table 2. Parameters of test models.

Test model	Dimension of the model (mm)	Cross-section of the transducer (mm)	Grouting material	Curing time
1	$\Phi 110 \times 500$	25×25	cement mortar 1 : 1	4d
2	$\Phi 110 \times 500$	25×25	cement mortar 1 : 2	14d
3	$\Phi 110 \times 500$	25×25	cement mortar 1 : 1	7d
4	$\Phi 110 \times 500$	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				2				3				4			
Number of optical fiber		1#	2#	3#	4#	1#	2#	3#	4#	1#	2#	3#	4#	1#	2#	3#	4#
Initial measurement precision	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
	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 (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	Precision of initial measurement		Max. sliding distance		Dynamic range (mm) direction	Determination of the loading (\$m ⁻¹)	unit price
	Value (mm)	Reflectometry coefficient/loss	Value (mm)	Reflectometry coefficient/loss			
TDR (Dennis et al., 2006)	5	0.005 (ρ)	25.4	0.123 (ρ)	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

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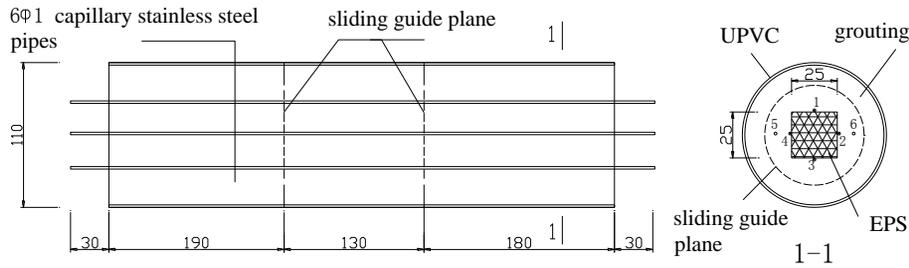


Fig. 1. Double shearing test model (unit: mm).

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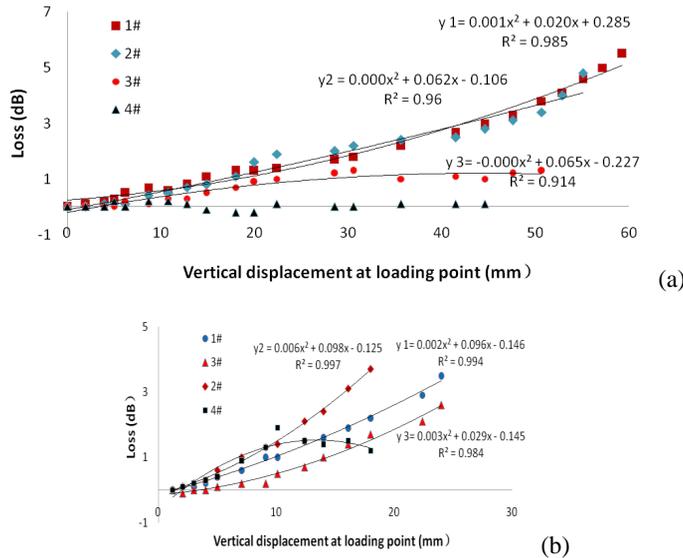


Fig. 2. Relationship between fiber optical loss and vertical displacement at loading point. **(a)** Model 1, **(b)** Model 2.

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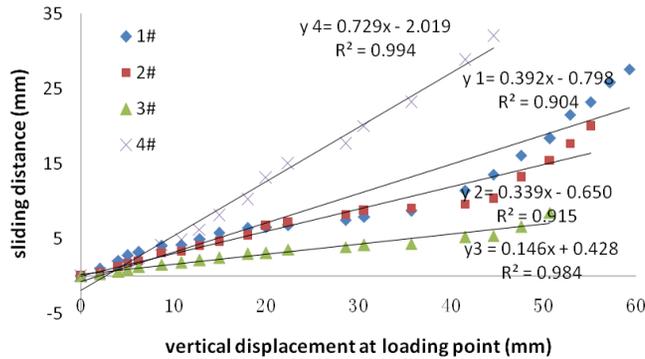
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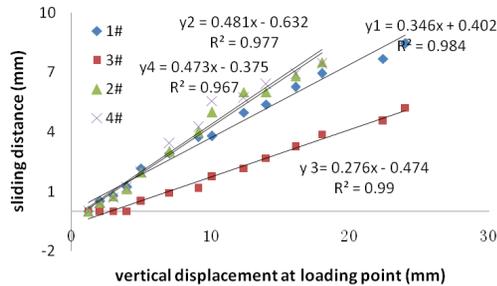
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(a)



(b)

Fig. 3. Relationship between fiber optical sliding distance and vertical displacement at loading point. **(a)** Model 1, **(b)** Model 2.

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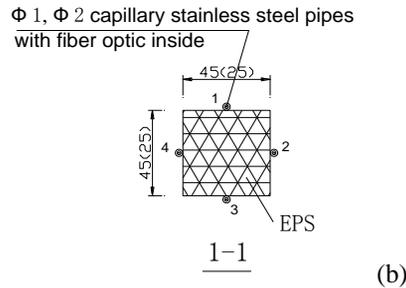
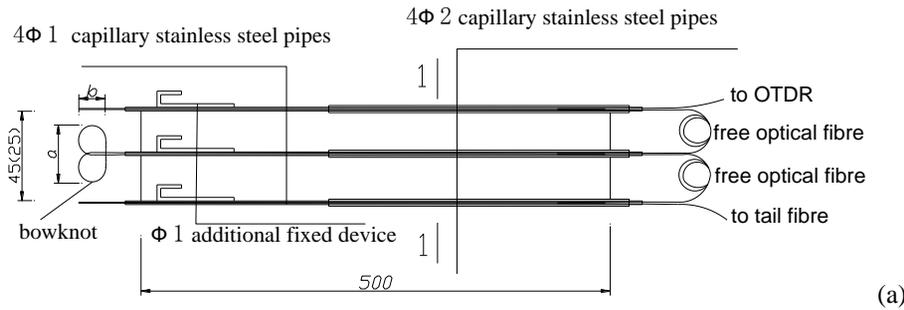


Fig. 4. Draft of the forth-generation transducer. **(a)** Elevation view of the sensor. **(b)** Cross section of the sensor (unit: mm).

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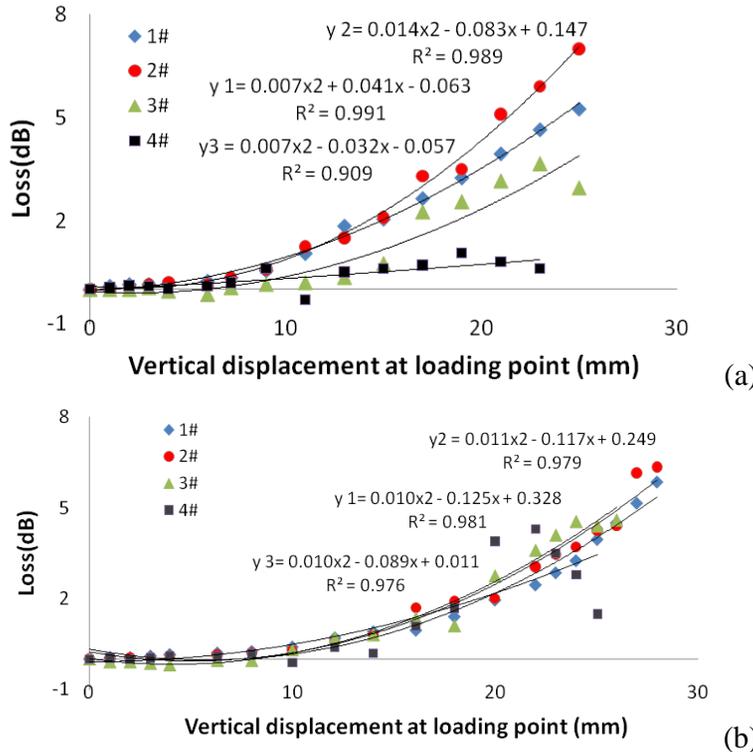


Fig. 6. Relationship between fiber optical loss and vertical displacement at loading point. (a) Model 3, (b) Model 4.

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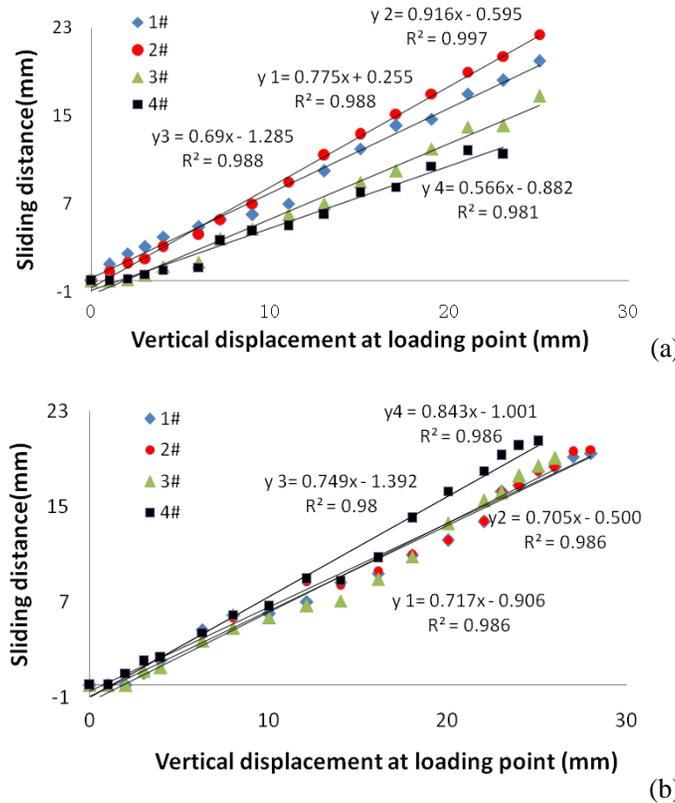


Fig. 7. Relationship between fiber optical sliding distance and vertical displacement at loading point. **(a)** Model 3, **(b)** Model 4.

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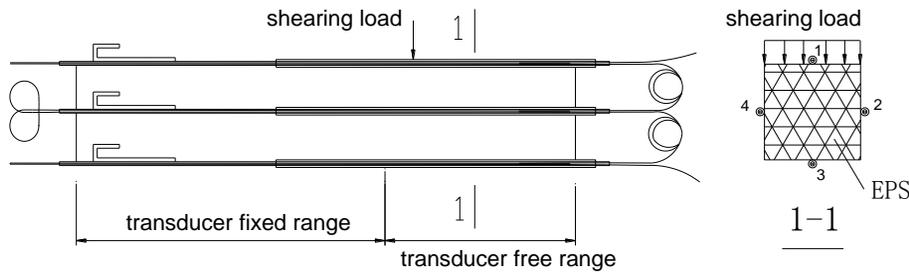


Fig. 8. Diagram of the transducer subjected to shearing load.

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