Research Article

Experimental Investigation Monitoring the Saturated Line of Slope Based on Distributed Optical Fiber Temperature System

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The position of the saturated line is an important basis for evaluating the stability of the slope, and the traditional sensors cannot be monitored for a long time because of poor durability and anti-interference. A method for measuring the saturated line with distributed optical fiber temperature measurement technology was proposed, and the one-dimensional and two-dimensional model experiments of measuring the saturated line at three kinds of electron flow (5 A, 10 A, and 15 A) were conducted, and their measuring data were carefully analyzed. The results showed the three stages of the optical fiber temperature difference with time: sudden-rising, fast-rising, and slow-rising. The temperature rising rate and stable temperature difference at the position of the saturated line are between saturated soil and unsaturated soil. The fiber optic temperature increases with the increment of heating electron flow, which also demonstrates stability and repeatability.

1. Introduction

With the rapid development of society and economy, infrastructures [1–3], including roads, railways, dams, bridges, waterways, etc., are the main investment directions to support the continued prosperity of the economy and the country. However, these facilities have been placed in complex and changeable environments [4, 5] for a long time, and the failure or collapse caused by the deterioration of their structure may cause casualties and major damage [6]. For example, various geological disasters occur every year around the world, such as landslides, earthquakes, floods, etc., of which landslides account for the highest proportion [7, 8]. The landslide because of the deterioration of built infrastructure [9] has been a challenging problem worldwide, with the rising cost of infrastructure maintenance and rehabilitation [10, 11]. Slope monitoring is a basic work that must be carried out, and the saturated line is assisted to evaluate the possibility of slope failure scientifically [12, 13].

Therefore, it is very meaningful to monitor the saturated line with an effective method.

At present, piezometers, pore water pressure gauges, volumetric water contents, and other instruments are being used in the monitoring of the saturated line [14, 15]. However, they cannot meet the long-term monitoring requirements in terms of sensor durability, electromagnetic interference, chemical, and corrosion resistance [16–18]. Masaoka et al. [19] installed 59 piezometers at the soil-bedrock interface to determine the permeability coefficient and obtained data from June 18 to July 18. Kim et al. [20] installed 4 vertical displacement sensors, 4 horizontal displacement sensors, and 3 wireless volumetric water content sensors to monitor the location and location of the fault. Liu et al. [21] installed 19 sensors in an array at 10 elevations on the right bank slope for long-term monitoring, and only the monitoring data from November 2014 to November 2016 was obtained. Shi et al. [22] studied the seepage lag time of dams and set up four seepage monitoring sections in the

dam body, and four piezometers and osmometers were embedded in each monitoring section to automatically and accurately monitor the seepage pressure of the dam. Liu and Wang [23] predicted the response of the pore water pressure (PWP) in the soil to the slope stability under heavy rain, and three sets of PWP sensors were used to measure.

Many researchers focused on fiber optic sensors [24, 25] that have unique advantages, such as antielectromagnetic interference and reliable durability, to withstand extreme temperatures and corrosion. However, the use of distributed optical fiber temperature system to determine the saturated line of the slope is rarely reported. Vogt et al. [24] proposed a high-resolution vertical temperature profile method for surface water sediments to quantify the depth and time of permeation flux in detail. By fitting the data to an analytical solution of convective conduction and heat transfer in a semi-infinite, uniform, one-dimensional area with a sinusoidal surface temperature, it is converted into an apparent seepage rate. Yan et al. [7] carried out an innovative distributed temperature system (DTS) for measuring seepage rate. The experiment results showed that in the same sandy soil, the characteristic temperature and seepage rate have a good linear relationship, however, it has nothing to do with the particle size distribution. Su et al. [26, 27] used a DTS, adopted an improved optical fiber layer layout scheme, applied it in an engineering case, and proposed a real-time seepage monitoring technology based on a combination method for the full section of the embankment. Chen et al. [12] established a mathematical model to describe the heat dissipation process of a linear heat source (LHS) in porous media based on seepage mechanics and heat transfer theory. The effects of seepage velocity and seepage direction on the heat dissipation law of LHS are studied. The results show that the heat dissipation process of LHS complies with Newton's law of cooling well, and the cooling rate is positively correlated with the seepage velocity and the infiltration angle. Zheng et al. [28] developed a "Fiber Bragg grating (FBG)-based leak detection device," and according to the temperature distribution along the diaphragm wall joints and the temperature curve, location, and time generated by the use of measuring points, leakage can be determined. Cao et al. [29] allowed the measurement of soil moisture in saturated and unsaturated zones with a deviation of $0.027 \text{ m}^3/\text{m}^3$ and used the active heating optical fiber method to monitor soil moisture profiles through model experiments. Wijaya et al. [30] studied the comparison of BOTDR strain measurement methods with pretensioned and nonpretensioned fiber optic cables by field applications. The prestretched fiber optic cable obtained to reduce the differences in observations from the point and distributed sensors may be a potential solution. Cheng et al. [31] used the distributed optical fiber temperature detection to obtain data from the dam seepage heat laboratory model and used optical frequency domain reflectance (OFDR) technology to monitor temperature, which has high time and space accuracy. The results show that OFDR has high temperature detection accuracy and high spatial resolution, which can reflect the

characteristics of the temperature field in the seepage model of the dyke.

Thus, the objective of this paper was to propose a feasible method for measuring the saturated line of the slope with DTS sensors. This study was organized as follows: firstly, the composition of the distributed optical fiber temperature measurement system is introduced, and the one-dimensional and two-dimensional model experiments of measuring the saturated line are designed. Then, the model experiments under different electron flow heating effects are carried out. Finally, 170 sets of optical fiber temperature data are acquired and analyzed.

2. DTS Technology and Experiment Design

To accomplish the saturated line monitoring by DTS, an experimental platform is designed and assembled with DTS system, seepage generating system, heating system, and physical model. Various equipment, physical model, and composition system were shown in Figures 1–3.

2.1. DTS Technology and Composition Based on Raman Scattering Principle

2.1.1. DTS System. Using the pulse light injected into the fiber by the laser, in the transmission process, the thermal vibration of the molecules in the fiber is caused, resulting in light with a longer wavelength than the source, called Stokes light, and other light with a shorter wavelength than the light source, called anti-Stokes light [13]. The intensity of the anti-Stokes light produced varies with temperature, while Stokes light does not. Using the ratio of anti-Stokes-to-Stokes light intensity, the temperature T of this point can be obtained as equation (1).

$$T = \frac{hc_0\nu}{\{k[\ln\alpha - \ln(l_{as}/l_s)]\}}, \quad (1)$$

where T is the absolute temperature value. h is Planck's coefficient. c_0 is the speed of light. ν is the Raman shift. k is the Boltzmann constant. α is the temperature correlation coefficient. l_{as} is the intensity of the anti-Stokes light. l_s is the intensity of the Stokes light.

DTS system mainly consists of distributed optical fiber main unit for temperature measurement and linear multi-mode thermal optical cables. The former part accommodates some components, such as the optical device, laser device, data processing module, etc.

- (1) Laser module: composed of a high-power pulsed semiconductor laser with tail fiber (output power $>500 \text{ mW}$) and laser drive power supply.
- (2) Optical fiber wavelength division multiplexer: it consists of a 1×3 bidirectional optical fiber coupler and wavelength division multiplexer system (multibeam interference optical filter with high isolation).
- (3) Photoelectric receiving and amplifying components: composed of optical avalanche diode with tail fiber

(a)

(b)

(c)

FIGURE 1: Continued.

(d)

FIGURE 1: DTS equipment and system composition. (a) Optical fiber temperature acquisition instrument; (b) heating system; (c) distributed fiber optic sensor; (d) measuring system.

and main amplifier with high gain, wideband, and low noise.

- (4) Signal processing system: it is composed of a double-channel, high-speed transient (50 MHz) signal acquisition, processing card, and signal processing software.

AP sensing distributed optical fiber temperature measuring host (shown in Figure 1(a)) was used. The single channel measurement was conducted with a maximum measurement length of 2 km, spatial resolution: 1m, positioning accuracy: 1m, sampling interval: 0.5 m, temperature accuracy: $\pm 1^\circ\text{C}$, and temperature resolution: $\pm 0.1^\circ\text{C}$.

2.1.2. Heating System. The heating system (Figure 1(b)) adopts an alternating straight heating equipment with a maximum output power of 6kW and other auxiliary equipment, with a maximum output electron flow of 20 A and a maximum output voltage of 300 V. The system can automatically select the range according to the length, electron flow, or voltage of the optical cable, and the system can heat the copper network in the optical cable while ensuring the constant output of heating power.

2.1.3. Fiber Optic Sensor. Two-core, multimode (50/125), water-blocking, armored, heating fiber optic cable

(Figure 1(c)) was used with a diameter of about 8 mm, outer sheath wall thickness >1.5 mm, and a resistance of about $20 \Omega/\text{km}$. The structure includes components, such as the outer sheath, heating copper mesh, stainless steel hose (easy to bend and loop), Kevlar fiber, oil-filled bundle tube, and two-core optical fiber.

2.2. Model Experiment Design of Measuring Saturated Line.

To explore the cable temperature change with time under the condition of stability and variation of saturated line, one-dimensional cylinder experiment was selected for single point measurement and two-dimensional rectangular groove experiment for distributed measurement. The model design is as follows:

2.2.1. One-Dimensional Cylinder Experiment Model. The one-dimensional cylinder experiment model consists of a 35 cm diameter sealing steel tube, a 25 cm diameter sealing steel tube, and a 15 cm diameter dispersed spiral surround detection cable. The 35 cm diameter steel tube sidewall bottom hole welding fine steel tube is used for the inlet and outlet. The 25 cm diameter steel pipe is perforated at the bottom, and the inner and outer layers are wrapped with geotextile to protect the saturated soil from overflow and eliminate the influence of incoming and outgoing water directly hitting the cable on the experiment. The length of

FIGURE 2: One-dimensional cylinder model and cable dispersion around design (unit: cm).

the scattered optical cable is 0.5 m/circle, and the height difference is 5 cm, as shown in Figure 2.

2.2.2. Two-Dimensional Rectangular Groove Experiment Model-Distributed Measurement. The two-dimensional experiment model was a rectangular steel trough of 300 cm × 50 cm × 100 cm (length × width × height), which was composed of the left inlet section, the middle experiment section, and the right outlet section. There were 7 groups of optical cable measuring points (J0 to J6) in the inlet section and outlet section, respectively. The experiment models are shown in Figure 3.

2.3. Experiment Conditions and Measurement Steps. Because of the difference in density and specific heat capacity of soil and water, when the heating system is heating

the copper mesh, the temperature measured by the optical fiber of saturated soil and unsaturated soil is different. According to this situation, the experiment was designed to keep the saturated line stable, heat under different heating electron flow conditions, and understand the relationship between heating electron flow and fiber temperature difference value in saturated soil and unsaturated soil. One-dimensional cylinder experiment studied the relationship among fiber temperature difference, saturated line change, and heating electron flow from point measurement angle. The horizontal saturated line and normal stable seepage saturated line were formed in the two-dimensional rectangular groove experiment. The relationships among fiber temperature difference, saturated line stability, and heating electron flow were studied from the perspective of distributed measurement. There were 6 kinds of experimental conditions in total, as seen in Table 1.

FIGURE 3: Two-dimensional rectangular model diagram and measurement process (unit: cm).

TABLE 1: Experimental conditions.

Experiment conditions	Heating electron flow			Note
	5 A	10 A	15 A	
Stabilization (130 cm)	1	2	3	One-dimensional cylinder (point)
Saturated line (35.00 cm)	4	5	6	Two-dimensional rectangular (distributed)

One-dimensional and two-dimensional experiment water level stability (working conditions 1~3, 4~6), measurement steps are as follows:

- (1) Physical connection: the experiment cable tail fiber was inserted into the distributed optical fiber temperature measurement host optical fiber measurement port. The temperature measurement host is connected to the computer, and both ends of the cable and the heating system are connected to the positive and negative poles, and they are connected to the power supply (if connected, omit this step).
- (2) Collection before heating: open the distributed optical fiber temperature measurement host and

software, set parameters, and collect the unheated optical fiber temperature data for 30 minutes.

- (3) Heating and collection: select the experiment heating electron flow, open the heating system, continue to heat the optical cable with the electron flow by the experiment for a long time (5 h). Then, collect optical fiber temperature data.
- (4) Collection after heating: turn off the heating system and continue to collect optical fiber temperature data until the optical fiber temperature returns to normal temperature. Stop the collection and close the optical fiber temperature measurement software and the host.

- (5) Physical disconnect: disconnect the power supply, remove all physical connections, and protect all important ports and connectors.

3. Results and Analysis

According to the experiment plan, a one-dimensional cylinder and two-dimensional rectangular groove saturated line experiment under the heating action of three electron flows were carried out, and a total of 24 sets of optical fiber temperature time history data at different positions were obtained. The following is a detailed analysis of the aspects of temperature and temperature difference.

3.1. Variation of Measured Temperature and Temperature Difference under Cylindrical Experiment. The temperature data at 30 locations in the one-dimensional cylinder over time were examined. Among them, the temperature measurement data of 11 points and the temperature difference data of 7 points (102 cm to 146 cm) near the set saturated line were displayed in Figure 4. It was specified that the abscissa takes the time just heated as 0. Then, it is a negative value without heating, and a positive value after heating.

After heating, the temperature of optical fiber presents three stages: sudden-rising, fast-rising, and slow-rising. After heating for 2 min, the temperature of all optical fibers suddenly rises to a certain value. After heating for 10 minutes, the temperature difference of the fiber begins to rise rapidly and gradually slows down, and the rising rate gradually decreases. Take figure 4(a) as an example, during the 0.5 hours before heating cable, the temperature of each point is 7.5°C to 11.5°C, the average temperature is 8.3°C to 11.0°C, and the fluctuation amplitude is 1.2°C to 1.6°C. When heated by 0.5 A electron flow, the temperature of each point rises slightly and then fluctuates up and down with a certain temperature as the center over time. After being heated by 0.5 A for 4~5 hours, the temperature of each point is 8.0°C to 12.5°C. The average temperature is 9.1°C to 12.4°C, and the fluctuation amplitude is 0.8°C to 2.2°C. Similarly, in figure 4(c), the temperature of the same point is 5.5°C to 8.5°C, the average temperature is 6.2°C to 8.0°C, and the fluctuation amplitude is 0.8°C to 1.2°C. When the optical cable is heated by the electron flow of 10A, the temperature rises rapidly from 0 to 0.2 h and then slowly rises, and it basically fluctuates with a certain temperature value after 0.5 h. After being heated for 4~5 hours, the temperature is 9.5°C to 21.5°C, the average temperature is 10.8°C to 17.0°C, and the fluctuation amplitude is 0.8°C to 1.4°C. If 15 A electron flow is used, the initial temperature is 9.3°C to 12.3°C, the initial average temperature is 10.1°C to 11.3°C, and the initial fluctuation amplitude is 1.1°C to 1.7°C. The temperature is 30.0°C to 36.1°C, the average temperature is 31.2°C to 34.9°C, and the fluctuation amplitude is 1.4°C to 2.6°C after heating for 4~5 hours.

It is comprehensively found that before heating, although there is a temperature difference at each measuring

point near the 130 cm position of the infiltration point, it behaves differently because it is affected by the ambient temperature. However, the temperature difference between each point is basically equivalent to the fluctuation amplitude. As can be clearly seen from the figure after being heated by electron flow, the temperature of each point in the cylinder during the experiment changes dramatically, and they increase significantly with time at the beginning of heating and then reach a relatively stable value. Although the measured temperature value after heating has a large difference to a certain extent, it is still affected by the initial environment temperature. Therefore, the temperature difference with the initial temperature subtracted over time is shown in Figures 4(b), 4(d), and 4(f). It can be found from figure 4(b) that when heated by 5 A for 4~5 hours, the relatively stable temperature difference is 0.8°C to ~3.0°C, which is not much different from the fluctuation amplitude. When heated by 10 A or 15 A, the differentiation in temperature difference near the saturated point (130 cm) is very obvious. The temperature difference of each point is 5.3°C to 14.5°C (10 A), 20.1°C to 32.9°C (15 A), and the stable temperature difference is 6.5°C to 13.8°C (10 A), 20.8°C to 31.6°C (15 A), respectively.

To better distinguish and determine the saturated line, when the fiber is heated by 10 A and 15 A for 4 to 5 hours, the temperature difference of three key points of the point above the saturated line in the unsaturated soil (138 cm), the point on the saturated line (130 cm), and the point below the saturated line in the saturated soil (122 cm), is plotted in Figure 5. The differentiation in temperature difference near the saturated point (130 cm) is very obvious. In the 10 A working condition, the temperature difference, the stable temperature, and the fluctuation amplitude in the unsaturated soil are 14.1°C to 15.8°C, 15.0°C, and 1.7°C, and they are 11.0°C to 13.4°C, 12.1°C, and 2.4°C on the saturated line and 7.9°C to 9.7°C, 8.9°C, and 1.8°C in the saturated soil, respectively. Similarly, in another working condition, they are 30.8°C to 32.7°C, 31.6°C, and 2.1 °C in the unsaturated soil, 26.9°C to 28.7°C, 27.5°C, and 2.0°C in the saturated line, and 21.0°C to 23.7°C, 22.5°C, and 2.7°C in the saturated soil. The temperature rise range of the characteristic point above the saturated line (unsaturated soil) is slightly larger, and the temperature rise time is slightly longer than that of the characteristic point below the saturated line (saturated soil). After heating for 10 minutes, the temperature rise rate of the fiber temperature difference values at all characteristic points tends to be stable and small. The temperature difference of the characteristic point at the position of the saturated line is between the upper and lower positions of the saturated line. Basically, it shows that unsaturated soil >the saturated line >the saturated soil. It means that it is feasible to use a relatively stable temperature difference value to determine the infiltration point.

In addition, Figure 6 shows the temperature difference data of each measuring point in the cylinder along the height at 3 different times (initial (0 s), sudden rise (2 min), and relative stable (5 h)). From the data, it is impossible to distinguish the position of the saturated line in the initial time, however the position of the saturated line can be easily

FIGURE 4: Variation of original temperature ((a) 5 A; (c) 10 A; (e) 15 A) and temperature difference ((b) 5 A; (d) 10 A; (f) 15 A) with time.

determined between the sudden-rise and the relatively stable phase. The temperature abrupt change is basically the same in all optical cables. With the temperature difference rising, the stable value of temperature difference at the position of unsaturated soil, saturated line, saturated soil decrease

gradually, and the positions of the saturated line are almost the same with DTS system and the pore water pressure measurement separately.

As shown in Table 2 and Figure 7 below, when the heating electron flow is 5 A, it is difficult to determine the position of

FIGURE 5: Variation of temperature difference under 4 to 5 hours after heating: (a) 10 A; (b) 15 A.

FIGURE 6: Distribution of temperature difference along height: (a) 10 A; (b) 15 A.

TABLE 2: Relationship between surge value, stable temperature difference, and heating electron flow.

Electron flow	sudden (°C)			Stable (°C)			Amplitude (°C)		
	5 A	10 A	15 A	5 A	10 A	15 A	5 A	10 A	15 A
unsaturated soil	1.87	8.07	17.58	2.98	13.83	31.63	0.51	0.62	2.10
saturated line	1.52	6.11	14.20	2.33	10.40	27.49	0.86	1.40	2.07
Saturated soil	1.32	4.71	10.76	1.25	7.87	22.49	1.81	1.41	2.77

FIGURE 7: Distribution of temperature difference along (a) height and (b) electron flow.

FIGURE 8: Variation with time ((a); (c); (e)) and along height ((b); (d); (f)) of temperature difference.

the saturated line because of the small difference in temperature difference between unsaturated soil and saturated soil after heating and the joint influence of optical fiber temperature

measurement fluctuation. 10 A and 15 A are easier to determine. The greater the heating electron flow, the greater the difference in temperature, and the more obvious the

FIGURE 9: Distribution of temperature difference along height in different positions: (a) 10 A; (b) 15 A.

experiment effect. The variation of temperature difference at the wetted line is always between the upper and lower regions, which is consistent with the judgment at the water surface.

3.2. Variation of Measured Temperature and Temperature Difference under Rectangular Experiment. The temperature data at 140 cm locations in the two-dimensional rectangle over time were examined. Among them, the temperature difference of 5 points near the set saturated line with time and height were displayed in Figure 8.

Figure 8(a), 8(c), and 8(e) show that the temperature of optical fiber with time presents three stages: sudden rise, fast rise, and slow rise after heating, which is the same as the results of the one-dimensional cylinder test. After 2 min, the temperature of all optical fibers suddenly rises to a certain value. After heating for 10 minutes, the temperature difference of the fiber begins to rise rapidly and gradually slows down, and the rising rate gradually decreases. Take the second group of fibers (J1) in Figure 8(a) as an example. 0.5 hours before heating, the temperature difference of each point is -0.4°C to 0.9°C . The average temperature difference is -0.1°C to 0.2°C , and the fluctuation amplitude is 0.6°C to 1.3°C . When heated by 10 A electron flow, the temperature of each point rises slightly and then fluctuates up and down with a certain temperature as the center over time. After being heated for 4–5 hours, the temperature difference of each point is 3.5°C to 9.6°C , the average temperature difference is 4.4°C to 8.3°C , and the fluctuation amplitude is 1.3°C to 1.7°C . Similarly, the temperature difference of the fourth group of fibers (J3) in Figure 8(c) is -0.4°C to 1.8°C , the average temperature difference is -0.1°C to 0.2°C , and the fluctuation amplitude is 1.1°C to 2.4°C . After being heated for 4–5 hours, the temperature difference is 3.2°C to 9.7°C , the average temperature difference is 4.9°C to 9.4°C , and the fluctuation amplitude is 0.3°C to 1.1°C . If 15 A electron flow is used as shown in 8e, the temperature difference is -0.7°C to 1.2°C , the average temperature difference is 0.0°C to 0.3°C , and the fluctuation amplitude is 1.3°C to 2.0°C . The

temperature difference is 9.1°C to 16.9°C , the average temperature difference is 10.3°C to 16.7°C , and the fluctuation amplitude is 0.1°C to 1.2°C after heating for 4–5 hours.

Figures 8(b), 8(d), 8(f) show the temperature difference data of measuring points in the two-dimensional rectangular model at 3 different times (initial (0 s), sudden rise (2 min), relative stable (5 h)). Similar to a one-dimensional cylinder test, it is impossible to distinguish the position of the saturated line in the initial time; however, the position of the saturated line can be easily determined between the sudden-rise and the relatively-stable phase. The temperature abrupt change is basically the same in all optical cables. With the temperature difference rising, the stable value of temperature difference at the position of unsaturated soil, saturated line, saturated soil decrease gradually, and the position of the saturated line with DTS sensors is consistent with the result of pore water pressure measurement. The relative stable temperature difference of the 7 groups of optical fibers in the two-dimensional rectangular test heated by two electric flows are plotted in Figure 9 along the height distribution diagram. By the above determination method, the position of the saturated line of each point can be easily determined so that it can be plotted as the saturated line of the entire slope.

According to the analysis of the heating experiment chart, the temperature difference of the optical fiber at the position of the saturated line is between saturated soil and unsaturated soil. Hence, it is convenient and quick to visually check the position of water level. When the heating electron flow is low, it is difficult to determine the position of the infiltrating line. As the heating electron flow increases, the difference becomes more obvious, and it is easier to determine the position of water surface. Therefore, it is recommended to use the electron flow of 10 A and above for experimenting. Through fitting analysis, it can be concluded that the sudden rise and stability of fiber temperature have a certain function relation with heating electron flow. By the above judgment method, optical fiber can be used in water conservancy, hydropower

engineering, environment, agriculture, and other fields for groundwater level measurement.

4. Conclusions

The position of the saturated line is an important basis for evaluating the stability of the slope. Traditional sensors cannot be monitored for a long time because of poor durability and anti-interference. In view of the above shortcomings, a method for measuring the saturated line with distributed optical fiber temperature measurement technology was proposed, and the two model tests were designed, and temperature with time at 170 locations was obtained. The main findings of this study were summarized as follows:

- (1) Although in the same geotechnical material and water level, the temperatures of the cable are basically the same when the cable is not heated, which are not convenient to determine the position of saturated line .
- (2) When the cable is heated at a stable water level, the temperature difference shows three stages of rising, namely sudden-rising, fast-rising, and slow-rising. The temperature rising rate and stable value of temperature difference above the water level are higher than those below the water level, and the value at water level is between unsaturated soil and saturated soil. The position of saturated line can be judged obviously.
- (3) Under the same conditions, the temperature difference of the cable increases with the increase of heating electron flow. Heating cable with a higher current intensity is helpful for measurement and judgment of saturated line.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships.

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