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On-Site Visualization as a New Strategy for Geotechnical Safety and Risk Management

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Abstract: This paper proposes a new monitoring scheme which is characterized by use of new type of instruments capable of not only processing data, but also visually outputting them for immediate recognition of measured information by vision. Therefore, time required for all workers to notice occurrence of an event could be as small as the theoretical speed limit for data transmission, namely the speed of light. The core discussion given in this paper is on how these instruments are designed and implemented, and how they could contribute to further improvement of safety and risk management for a broad range of geotechnical problems.

Keywords: On-site visualization; safety; risk; real-time risk management.

1 Introduction

It is a commonly accepted practice in monitoring schemes for geotechnical engineering projects that information gathered by monitoring devices is stored on a PC and printed later for reporting. As far as visual presentation of the measured data is concerned, it is usually performed on the PC screen. The time required for this data processing has decreased dramatically recently; however, the term “real-time” may not be used in a strict sense, since at least several seconds are required to process raw data into visible forms either on PC screen or printed materials. More importantly, one is informed with the current state of deformation and etc. not where the event is happening, but where one can look at the PC screen which could be far away from the site. In addition, technical problems associated with data gathering and transmission, or human errors in machine operation could jeopardize correct management of measured information, thus putting workers and citizens at risks as the necessary information to them is not transmitted properly.

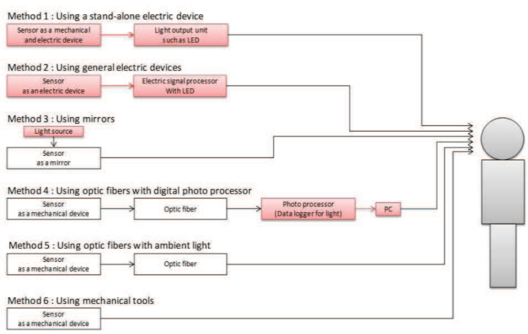

Figure 1. Various methods for monitoring and data visualization.

A totally new approach designed for infrastructure monitoring has been proposed by Akutagawa et al. (2007). This new approach is called as On-Site Visualization whereby light emitting sensors are used as the key technology for monitoring and simultaneous visual disclosure of the measured information on-site. For example, a new deformation sensor used in this approach is capable of 1) measuring displacement and 2) showing it by the designated color of light emitting diode (LED, for short) on a real-time basis. The same concept can be applied for monitoring of strain, inclination, earth pressure, water pressure, temperature, etc. Since these new devices are equipped with light emitting function or used together with the specially designed data converter with light emitting capability, the monitored data are translated in real-time into the color of light visually identifiable by workers and citizens around. In comparison with the traditional methods in which the monitored data are basically processed by data loggers or PCs, the new method using light emitting sensors could lead to an establishment of a totally new strategy for the safety and risk management in wide range of geotechnical engineering projects.

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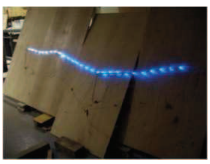
This paper introduces the basic descriptions of various methods (with special interests in Methods 1, 2 and 4) as shown in Figure 1, used for the OSV monitoring and also introduces several application examples wherein displacement, inclination, pressure, stress in concrete, etc. have been monitored and visualized during geotechnical projects to improve safety and risk management practices in a totally new manner compared to the conventional methods.

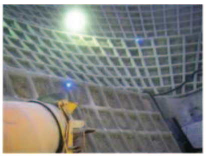
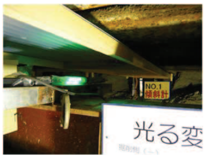
2 Visualization by Using Stand-Alone Electric Devices

The first method uses a stand-alone electric device called Light Emitting Deformation Sensor (LEDS) that can measure a relative displacement between two points by a simple mechanism and show the result by the color of LED (Akutagawa et al. 2007, 2010). LEDS can be installed between two points, A and B that are connected by a spring and a stiff wire. The spring is chosen in such a way that its stiffness is much smaller than that of the wire. Therefore, the relative displacement between A and B becomes approximately identical to the elongation of the spring. As a relative deformation occurs and the spring is elongated or contracted, the power supply needles prepared respectively for Red, Green, and Blue LED chips, slide on a specially designed panel switch, enabling arbitrary control of color depending on the magnitude of displacement.

LEDSs were applied in several sites as shown in Table 1. Since this device can be used in a stand-alone mode with a battery box, installation is simple and visibility is satisfactory especially in underground construction sites. Similar ideas of transforming deformation into LED color can be extended for visualization of forces in rock bolts and ground anchors (Akutagawa et al. 2011; Quali 2015).

Table 1. Application examples of light emitting deformation sensor.

 **Figure 2**. Hand-made Light Emitting Deformation Sensor.	**Laboratory simulation of landslide** Three LEDSs were used to monitor a simulated landslide as shown in **Figure 2**. Four wood panels were used to represent moving blocks of the slope while three LEDSs were installed with the initial color of white. As one of the panels was moved, the induced displacements were picked up by the LEDS, and their color changed from white to blue. The very first On-Site Visualization experiment by the LEDS hand-made by students.
 **Figure 3.** Monitoring of Soil-Mixed-Wall by LEDS.	**Safety monitoring at an open cut excavation site** Safety monitoring was performed at a late stage of a construction site. The tunnel was constructed by a cut and cover method and the LEDSs were installed between the retaining wall and steel columns to monitor what-they-call "unexpected small displacement" as shown in **Figure 3**. While a worker loosened an oil-jack of one of the strut beams, the closely positioned LEDSs changed their colors showing to everyone around that the movement occurred just by a small amount within an assured safety.
 **Figure 4**. LEDS installed in a NATM tunnel.	**Monitoring tunnel convergence** LEDSs having 1m long light emitting part were used to monitor extra convergence displacement of a tunnel in which soft and squeezing ground conditions were observed occasionally. LEDSs were installed on its side wall to ensure the further displacement after extra reinforcement of shotcrete was confined to its minimum level, as shown in **Figure 4**.

 **Figure 5**. LEDS installed at a tunnel portal slope.	**<u>Monitoring of a high slope at a tunnel portal</u>** Stability of a high slope just outside of a tunnel portal was monitored by two LEDSs. To ensure additional visibility of the LEDS, optional LED unit cabled from the original sensor was hung on the side wall of the tunnel entrance, as shown in **Figure 5**.
 **Figure 6**. LEDS installed to monitor a temporary steel frame structure.	**<u>Monitoring reinforced soil wall during road tunnel construction</u>** An LEDS was installed between the reinforced soil wall and a steel column to ensure the construction works nearby did not affect the reinforced ground. As this site was right in the middle of heavily populated area with large traffic in Tokyo, the maximum care had to be taken to achieve safety throughout the construction just beneath the road, as shown in **Figure 6**.

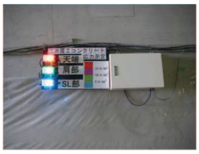
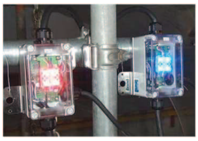
3 Visualization by Using Electronic Devices

The second method employs a general-purpose electronic device for visualization of arbitrary data. A fully integrated monitoring and visualization system may be arranged where multiple sets of sensors with visual output function are controlled and operated by a PC. It is also possible to use a laser pointer, for example, as a stand-alone device with which inclination can be visualized easily. Light Emitting Converter (LEC) is a compact data logger that is capable of 1) converting analog signal from an arbitrary sensor connected to it into digital one, 2) showing it by the color of LED based on a pre-defined color scheme and 3) storing data on an SD card. A sensor to be connected to LEC can be chosen from a family of available sensors for measurement of deformation, strain, inclination, pressure, temperature, etc (Izumi et al. 2014a). The color scheme can be defined and changed later, if necessary, for each LEC-sensor pair by the control software installed on a PC. Five colors of choice can be used to visualize the measured data of arbitrary type with respect to properly defined threshold values (Akutagawa 2010).

Acceleration sensors used in automobile industry are utilized to form a Light Emitting Inclination Sensor (LEIS). LEIS is equipped with a heater and automatic temperature control function such that the temperature inside the sensor box is kept at 50 degrees centigrade at all times to stabilize inclination reading (Izumi et al. 2014b). The LEIS has two acceleration sensors positioned at orthogonal directions and the maximum gradient computed from them is calculated and compared with pre-defined threshold values to determine the corresponding color of rotating lamps. Table 2 includes field application examples using these devices. Use of these devices with properly defined threshold values, defining relationships between measured data and color of light; helps improve safety management a great deal.

Table 2. Application examples for electric devices.

 **Figure 7**. LEC installed to monitor tunnel convergence.	**<u>Visualizing safety during tunneling under special condition</u>** A NATM tunnel had to be constructed with an overburden of only 30cm due to the constraints of the project. After the top thin layer was completed as a reinforced concrete structure sitting on reinforced ground, the tunnel was driven while allowing daily traffic above. Three displacement sensors were used with LECs to make sure that the traffic load during tunnel construction was within the expected range and the tunnel structure remained safe, as shown in **Figure 7**.

 **Figure 8.** LECs installed to visualize strains in tunnel lining.	**<u>Visualizing stresses in tunnel lining</u>** LECs were connected to stress sensors embedded in secondary concrete lining. This type of operation may be of benefit if continuing pressure on the lining is expected in squeezing ground, as shown in **Figure 8**.
 **Figure 9**. LECs installed to visualize curing environment.	**<u>Visualizing temperature and moisture</u>** Temperature and moisture were visualized during concrete curing process. To optimize moisture and temperature during concrete aging process, LECs were used together with moisture and temperature sensors. Workers were able to use visualized information to control their work, as shown in **Figure 9**.
 **Figure 10**. LEC installed to monitor water quality.	**<u>Visualizing acid content in underground water</u>** Water quality can also be monitored by OSV. Injection for soil reinforcement uses materials with various chemical ingredients. A pH sensor can be connected to LEC to monitor and present hydrogen ion exponent which is an index for acid content of underground water, as shown in **Figure 10**.
 **Figure 11**. LECs and red laser pointers installed at an open excavation site.	**<u>Visualizing safety at Delhi metro construction site</u>** An open cut site with 10m depth was monitored by using LECs and laser pointers. Inclination of retaining walls, boundary walls, forces in strut beams, etc. were monitored for visualization of safety to workers and citizens nearby (Nakamura *et al*., 2010, Izumi *et al*., 2014a), as shown in **Figure 11**.

4 Visualization by Using Plastic Optic Fibers

A unique method described in this chapter offers an eye for geotechnical engineers who sometimes need to see behind concrete wall or within soil to make sure that things are in order. For this purpose, plastic optic fibers are used where a special attention is paid to how light travels, bounces, and gets reflected or refracted in soils with highly complex 3D geometry that is sensitive to deformation of granular materials and to alteration of any quantity affecting paths of light (Akutagawa et al. 2014b, 2017).

To perform the task at a given point, two plastic optical fibers having diameter of 1mm are used. Fiber-1 is used to supply light to the point of observation. Fiber-2 collects light reflected back from surfaces of nearby particles and so on, and carries it back to a photo sensor. Therefore, the area of observation at the tip of fibers is in the order of mm. In a natural geo-environment, a monitored zone ahead of the fibers would be crowded with soil particles of varying sizes, liquid containing arbitrary substances in it, and possibly air of arbitrary contents. Exact geometry of these solid particles, liquid and air is extremely complex since they are also affected by meniscus force of water. If absolutely none of these factors changes over time, the intensity (=brightness) or color of reflected light remains constant. If, on the other hand, any single or more factors change, the properties of the reflected light are changed declaring that "something is happening over here". In the terminology of On-Site Visualization, the local zone ahead of fibers is “On-Site” and visualized information is available there. However, it is impossible to see it by human eyes, and therefore the information must be sent to an “Off-Site” location, namely the other end of fibers, where the returned light can be observed by naked eyes or digitally processed by photo sensors. As far as geometrical arrangement of fibers at an observation point, arbitrarily arrangements may be chosen depending on the nature of a problem as shown in Table 4. This method therefore is characterized by the use of optic fiber as one-pixel camera, and is fundamentally different from the other methods in which grated fibers are used (for example, Meltz, G. et al., 1989; Hill et al. 1978).

Table 3. Three types for optic fiber sensors.

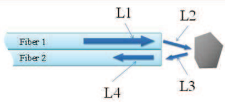


Figure 12. Profile of a twin fiber sensor.

Twin fiber sensor

Light once out of the 1st fiber, hits surfaces of nearby particles and gets scattered. Part of the scattered light gets into the 2nd fiber which is digitally recorded. The properties of the returning light L4 (intensity and color) are affected by many factors telling the story of what is happening at the tip of the fibers, as shown in **Figure 12**.

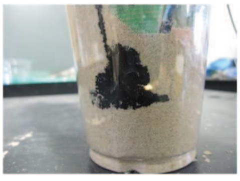


Figure 13. Black ink injected in a cup of sands.

Black ink was injected into a cup filled with Toyoura sand as shown in **Figure 13**. As the ink got closer to the fiber tip, the light intensity dropped rapidly, since the new alien material that arrived was the black ink. The similar process of injection (such as cement grouting) could be easily monitored in the same manner, as shown in **Figure 14**.

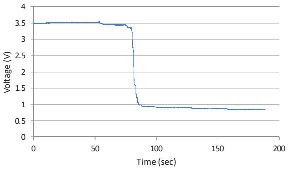


Figure 14. Voltage(brightness of light) recorded in this experiment.

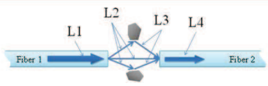


Figure 15. Profile of a gap sensor.

Gap sensor

By aligning the 2nd fiber in the line of the 1st fiber, a slightly different type of fiber sensor can be created. The Gap sensor is conveniently used to identify existence and properties of arbitrary materials between the two fibers, as shown in **Figure 15**.

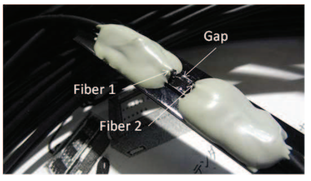


Figure 16. A gap sensor prepared to monitor concrete casting process.

Gap sensors shown in **Figure 16** were installed on the upper side of the space for casting concrete for the tunnel lining in a steel form. As concrete is pumped into this space, the concrete fills the space from bottom to top. As it is well known, the space has to be 100% filled by concrete leaving no space for quality assurance. The gap sensors installed on the ceiling of this space awaits arrival of fresh concrete filling their gap spaces, thus make sure that the concrete casting process can be properly conducted.

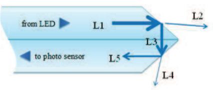


Figure 17. Profile of an RR sensor.

Reflection and Refraction sensor

Figure 17 shows a profile of RR sensor. Light is firstly sent into Fiber 1, part of which is refracted as L2 leaving Fiber 1 and the rest is reflected as L3. Then, L3 reaches the side face of Fiber 1 while some of which gets reflected, and the rest goes out of Fiber 1. The light which has just got out of Fiber 1 immediately reaches the side face of Fiber 2 as some of it gets reflected and the rest finally goes into Fiber 2 as L3'. L3', again, reaches the inclined face of Fiber 2 and what has happened before on the inclined face of Fiber 1, occurs again in the same manner. L5 which finally comes back to photo sensor depends on the type of material surrounding the fiber tip. This sensor is suited for detecting water, for example.

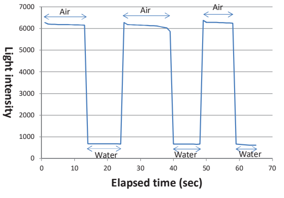


Figure 18. Light intensity recorded by the RR sensor.

This RR sensor was put in and out of water in a cup repeatedly. As expected, the light flux recorded changed alternately indicating whether the sensing point was in water or in air, as shown in **Figure 18**.

Plastic optical fibers used in this investigation are thin (diameter=1mm). Even if coated fibers were used, a pair of twin fibers (Fiber-1 to send light and Fiber-2 to receive reflected light) to conduct measurement at one point can be braced in the cross-sectional space of approximately 10mm^2. This is an immense advantage that these fiber sensors could be installed at arbitrary positions within a geo-structure (man-made or natural) without disturbing its inherent structural performances.

To execute this type of monitoring using light, one needs a set of photo sensors, a light source and optical fibers. Electricity-dependent parts (photo sensors and light source) can be placed in a secured place. The other parts for sending light, sensing and carrying reflected light are all electricity-independent, lightning protected, hard-to-break-down, and low in cost.

5 Conclusions

The experiences and lessons learnt so far in the projects in Japan, India, Indonesia and Vietnam helped identify practical requirements for organizing, planning, executing OSV monitoring projects as part of the safety management practices in all types of construction projects. As obvious, the OSV is a general scheme that can be applied to any type of construction projects, maintenance of aging infrastructures and natural disaster prevention, etc. The more wide-spread the OSV application becomes, the higher the safety management practice level will be, and eventually the safer each work place or monitored locations will be. This could be a start point of a new paradigm for field measurement and real-time information disclosure particularly useful for tunneling engineering.

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