"SmART Strand" Prestressing Steel Strand with Optical Fiber for Tension Monitoring

Shinji NAKAUE*, Katsuhito OSHIMA, Masashi OIKAWA, Motonobu NISHINO, Yoshiyuki MATSUBARA, and Masato YAMADA

SmART Strand is a prestressing steel strand equipped with an optical fiber to accurately measure the tension along the entire length of the prestressing steel cable. For prestressed concrete structures and ground anchors, it is important to ensure that the required tension of prestressing steel cable is provided and maintained. In order to directly evaluate the tension of prestressing cable during the installation and use, a new measuring method using SmART Strand has been developed. SmART Strand can be used for the maintenance of prestressed concrete structures and ground anchors, as well as their prestressing management.

Keywords: prestressing steel strand, optical fiber, tension distribution measurement, monitoring

1. Introduction

To allow a prestressed concrete structure*1 to demonstrate its performance, it is essential to apply prescribed tension to prestressing steel cables, which serve as tendons, and to maintain soundness during the service life of a structure. However, the tension of a prestressing steel cable can only be managed based on the hydraulic pressure applied by tension devices (hydraulic jacks), which are installed at the end of prestressing steel cables when applying tension, and the elongation of prestressing steel cables. It is difficult to accurately identify the tension at each position of a prestressing steel cable that is arranged in a curved profile in a structure. There is no established technique to monitor tension after completion of construction over the long term.

For ground anchors*2, it is known that the remaining tension of prestressing steel cables changes due to modification of geographical features in the vicinity and weathering and deterioration of anchor bodies.[1] Excessive changes cause slippage of anchor bodies, rupture of prestressing steel cables, and a decrease in resistance against landslides. Such changes are likely to result in serious events, such as collapse of slopes or structures, or protrusion and falling of anchor heads. It is required to early detect abnormalities and deformation of prestressing steel cables and implement effective measures.[2] However, the tension distribution in the ground cannot be measured, and it is difficult to accurately estimate the change factors.

The authors have developed a technique that can solve these issues: to measure and maintain the tension distribution of prestressing steel strands using SmART Strand, a prestressing steel strand with embedded optical fibers. This measurement technique makes it possible to detect and evaluate changes in the tension at any position of prestressing steel strands, which are buried in concrete structures or in the ground, as well as abnormalities of prestressing steel strands and the scope of influence of such abnormalities. Optical fibers, which are mainly made from glass, are highly resistant to deterioration due to age, such as corrosion. Optical fibers used for measurement can be extended to a location that is easily accessible to measurers so that remeasurement can be conducted safely as needed. This measurement technique is considered to be suited for long-term monitoring to maintain structures.

This paper presents an overview of the measurement technique and SmART Strand and introduces application examples of this technique.

2. Technique to Measure Tension of Prestressing Steel Strands Using Optical Fibers

2-1 Strain measurement technique using optical fibers

This measurement technique mainly uses the Brillouin Optical Time Domain Reflectometer (BOTDR) method (Table 1). The BOTDR method uses scattered light from the incident light into an optical fiber. Specifically, the method uses scattered light that travels in the direction opposite to the incident light and returns to a measuring instrument (backscattered light, see Fig. 1). The backscattered light component, which is referred to as Brillouin scattering light, has a peak frequency that is different from the frequency of the incident light. Its shift amount depends on the strain amount and temperature at a position where the scattered light is generated (Fig. 2). The time from the entry of incident light from the end of an optical fiber to the return of backscattered light to a measuring instrument is proportional to the distance from the end of the optical fiber to the position where backscattered light is generated.

Table 1. Specifications of strain measurement using the BOTDR method

Measurement method	BOTDR
Accuracy	Approx. ±50 μ
Minimum measurement interval	Approx. 5 cm
Spatial resolution	Approx. 1 m
Measurement range	Up to several km※
Measurement time	Approx. 3 min.
Optical fiber	Single mode

※Measurement can be conducted at any point along the entire length of an optical fiber.

Strain at any position can be measured by recording the continuous backscattered light after entry of incident light, analyzing the frequency characteristics at the time of return corresponding to the length of an optical fiber to the measurement target position, and properly compensating for the frequency shift caused by the temperature dependency. Combination of strain measurement with SmART Strand enables measurement of the tension distribution of prestressing steel strands.

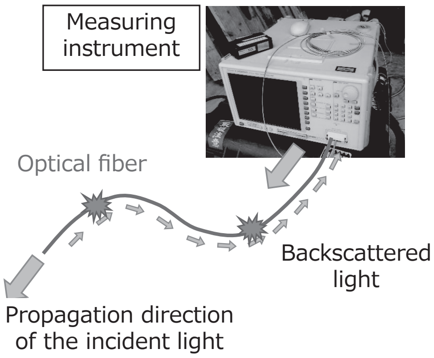

Fig. 1. Conceptual image of propagation of light in the BOTDR method

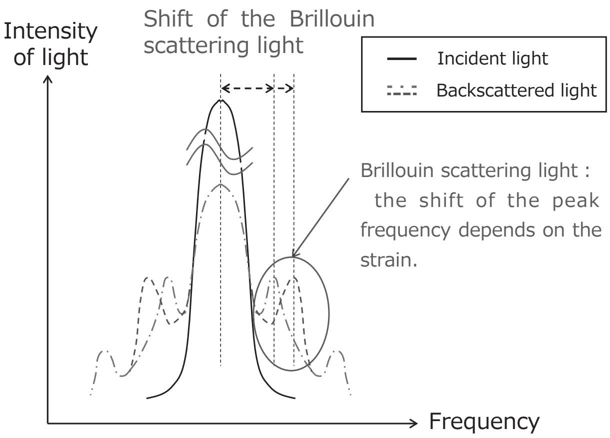

Fig. 2. Principle of strain measurement using an optical fiber

2-2 "SmART Strand" Prestressing steel strand with embedded optical fibers

(1) Overview of SmART Strand

We have developed SmART Strand to measure the tension distribution along the entire length of a prestressing steel cable (with one or more prestressing steel cables used as a single tendon) based on the strain distribution measurement technique using optical fibers. Specifically, optical fibers are embedded into prestressing steel strands that make up a prestressing steel cable.

The new epoxy coated and filled strand (ECF) type SmART Strand (Photo 1) is a prestressing steel strand with optical fibers embedded in a prestressed concrete steel stranded cable filled with epoxy resin. It can meet coating specifications for various applications, including the smooth surface type used for external cables*3 of prestressed concrete bridges, the polyethylene (PE) coating type with double corrosion-proof specifications to improve weather resistance by providing PE coating to the smooth surface type, the grit type with silica sand embedded on the surface of the epoxy resin coating to impart adhesiveness to grout and concrete, and the sheathed grit type mainly used for ground anchors to make only the tension section unbonded.

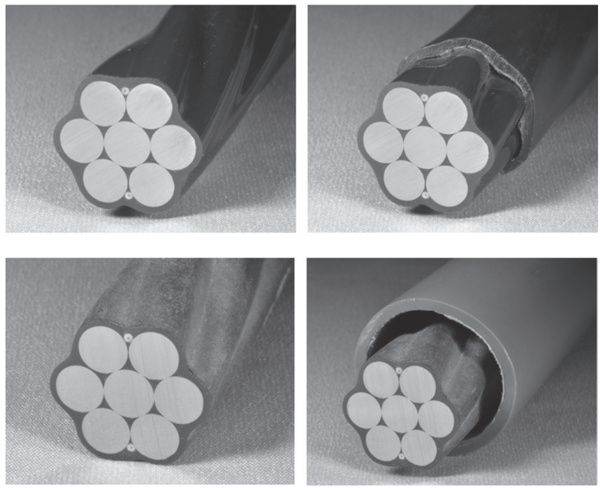

Photo 1. ECF type SmART Strand
(upper left: smooth surface type, upper right: PE coating type, lower left: grit type, lower right: PE-sheathed grit type)

In SmART Strand, optical fibers are embedded over the entire length of a prestressing steel strand along the recessed part between two side wires. Optical fibers are embedded into the resin coating to ensure adhesion and integration with the prestressing steel strand together with the coating resin (see Fig. 3). This makes sure that the optical fiber's elongation stably follows the tension elongation at each position of the prestressing steel strand. The outside diameter is the same as that of general-purpose prestressing steel strands of the same type, making it possible to simply replace general-purpose prestressing steel strands with SmART Strand. It should also be noted that optical fibers are embedded in the space of the recessed part and protected by solid epoxy resin coating. The risk of breakage and crushing of optical fibers due to contact is extremely low. Conventional work can be performed as per normal in the various processes, including

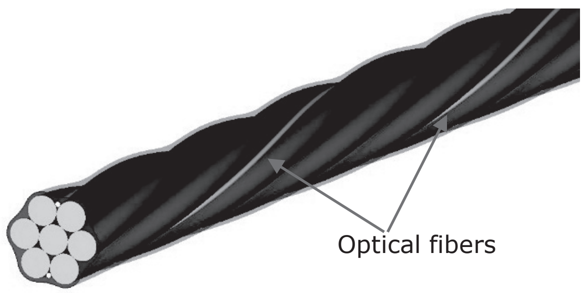

Fig. 3. Image of embedded optical fibers

binding and transport of prestressing steel cables, insertion into concrete structures, and application of tension. It was confirmed that the teeth on the inner surface of a wedge, which is provided at a location to install an anchorage (Photo 2) for holding a prestressing steel strand to a concrete structure with tension, bite the surface of a prestressing steel strand but do not affect the optical fiber or obstruct the light passing performance. It was also confirmed that, even after application of tension is completed, an optical fiber can be connected from the tip of an anchorage to a measuring instrument to conduct measurement.

Although we have developed not only ECF type but also a bare strand type, we mainly introduce the ECF type in this paper.

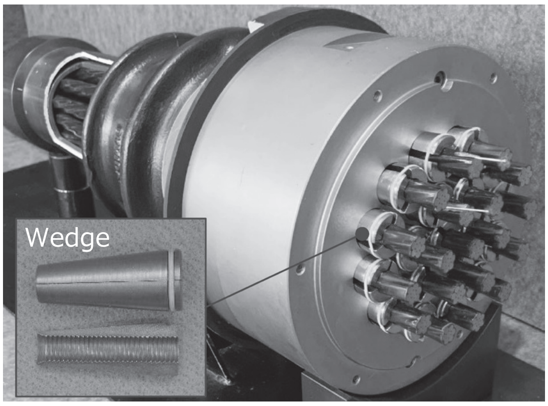

Photo 2. Example of anchorage

(2) Mechanical performance of SmART Strand

Table 2 shows the mechanical properties of SmART Strand. The ECF type is available in two nominal diameter variations (15.2 mm and 15.7 mm), while the bare wire type is available in one nominal diameter variation (15.2 mm) (as of October 2020). The ECF type (15.2 mm) conforms to the Japan Society of Civil Engineers (JSCE) standard (draft) JSCE-E 141.[3] The ECF type (15.7 mm) is a prestressing steel strand of higher strength. The strength characteristics are approximately 1.28 times higher than those of a seven-wire prestressing steel strand (SWPR7BL) specified in JIS G 3536. This is a prestressing steel strand that has been widely used in recent years, mainly for prestressed concrete bridges. The mechanical properties of the ECF type (15.7 mm) conform to the Design and Construction Guidelines for Prestressed Concrete Structures Using Ultra-High Strength Prestressing Steel Cables.[4] The mechanical properties of the bare wire type (15.2 mm) conform to SWPR7BL.

The ECF type meets all the requirements of the quality control test for confirming the corrosion-proof performance of epoxy resin coating in accordance with the JSCE standard (draft) JSCE-E141. Its corrosion-proof performance is comparable to that of ordinary ECF strands. The coating adhesiveness test results are shown in Photo 3 as an example. A coating adhesiveness test is conducted to check for cracks in coating and defects in adhesion when a steel strand is bent on a small diameter. For evaluation, a pinhole inspection device using the discharge inspection method is used for confirmation in addition to a visual check.

Table 2. Main mechanical properties of SmART Strand

Type	ECF		Bare
	High strength	Ultra-high strength	High strength
Nominal dia.	15.2 mm	15.7 mm	15.2 mm
Load against 0.2% permanent elongation	≥ 222 kN	≥ 285 kN	≥ 222 kN
Maximum Load	≥ 261 kN	≥ 335 kN	≥ 261 kN
Elongation	≥ 3.5%	≥ 3.5%	≥ 3.5%
Relaxation	≤ 2.5% ≤ 6.5%	≤6.5%	≤ 2.5%
Epoxy resin coating thickness	400 to 1200 μm※1 400 to 900 μm※2		—

※1 Crown of a cross section
※2 Mean value of all crowns of a cross section (six crowns)

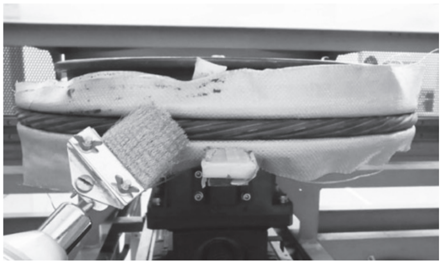

Photo 3. Pinhole inspection during a bending test (ECF type)

(3) Integrity of optical fibers with prestressing steel strands

To confirm the integrity of optical fibers with prestressing steel strands, tension was applied stepwise to SmART Strand using a tensile tester to measure the strain at each step. Figure 4 shows the results. The sample length is approximately 1.2 m. The strain value near the center of the length was extracted and plotted. A strain gauge was

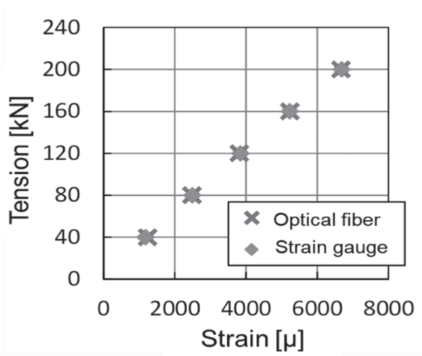

Fig. 4. Example of strain measurement results (ECF type 15.2 mm)

attached near the center of a sample, and the results were compared with the measured strain values. The results well matched the measurement results of SmART Strand. It was confirmed that the optical fibers behaved integrally same as the prestressing steel strands.

(4) Method of conversion to tension distribution

The optical fibers are used to measure the strain distribution. Thus, it is necessary to convert the measured strain into the tension of the prestressing steel strands. It was confirmed that the axial strain amount of the side wires is different from that of the steel strands because the side wires of a seven-wire strand are spirally arranged. In this measurement technique, the equivalent elastic modulus is evaluated in advance, and the results are converted into tension. Regarding tension distribution measurement using this conversion method, tension measurement tests were conducted for straight and curved arrangements, and its validity was confirmed.(5)

3. Application to Actual Structures

3-1 Application to construction of a Prestressed concrete bridge superstructure

To verify the applicability of this measurement technique to actual prestressed concrete structures, SmART Strand was applied to various prestressing steel cables used for construction of the superstructure of prestressed concrete bridges, and measurement was conducted. As one example, the measurement results of the internal cable*3 for the Pier 1 (P1) capital (Figs. 5 and 6) and the external cable between Pier 2 (P2) and Pier 4 (P4) (Figs. 7 and 8) are presented. Anchorages and hydraulic jacks were installed in the same procedure for construction of ordinary cables, and tension was applied. The 15.2 mm bare wire type SmART Strand was used as the internal cable for the P1 capital, and the 15.2 mm ECF type SmART Strand (smooth surface type) was used as the external cable between P2 and P4. Photo 4 shows application of tension and measurement of the internal cable for the P1 capital as an example. For both types of cables, the tension distribution over the entire length was measured. The influence of tension loss due to friction and due to reduction of elongation of a prestressing steel cable caused by the biting of a wedge for anchorage was also measured. It was confirmed that the results exceeded the tension required in the design over the entire length. Measurement was conducted again 26 months and 19 months later, respectively. It was confirmed that it was possible to conduct remeasurement properly.

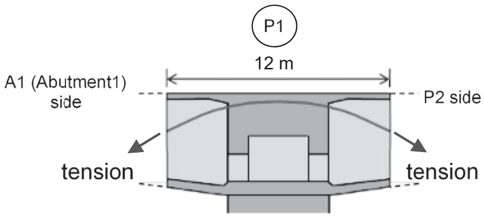

Fig. 5. Arrangement of a cable subject to measurement (internal cable of the Pier 1 capital)

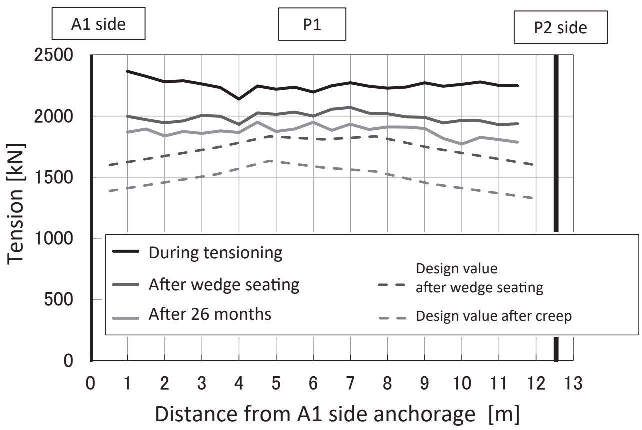

Fig. 6. Measurement results (internal cable of the Pier 1 capital)

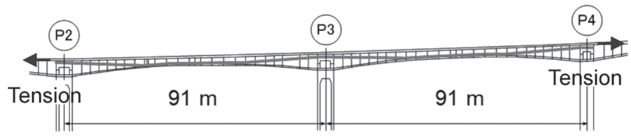

Fig. 7. Arrangement of cable subject to measurement (external cables from Pier 2 to Pier 4)

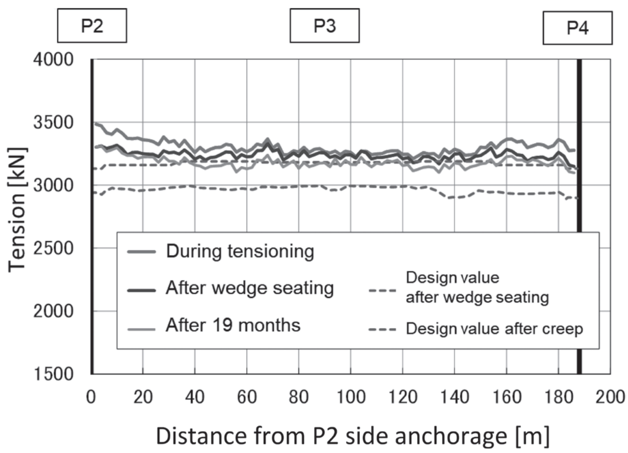

Fig. 8. Measurement results (external cable from Pier 2 to Pier 4)

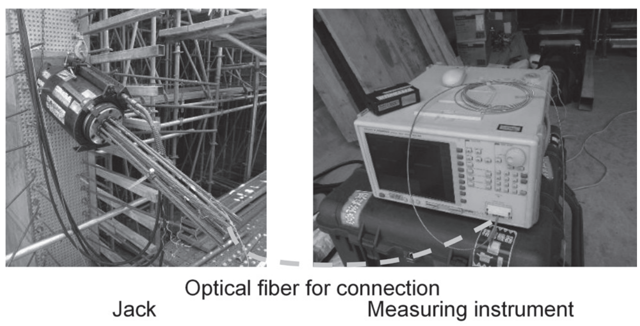

Photo 4. Example of measurement for internal cable

3-2 Application to ground anchors

To verify the applicability of this measurement technique to construction of ground anchors, the technique was applied to construction of ground anchors for slope reinforcement, and measurement was conducted (Photo 5). The 15.2-mm ECF type SmART Strand (PE-sheathed grit type) was used for the construction. Part of the results is shown in Fig. 9. It was confirmed that the 2 m part (12 to 14 m) on the free length side of an anchor body supported the tension and that tension was not transmitted to the end. It was also confirmed that tension was almost constant for the free length part, which transmits tension to an anchor body, and that the tension distribution was as expected in the design.

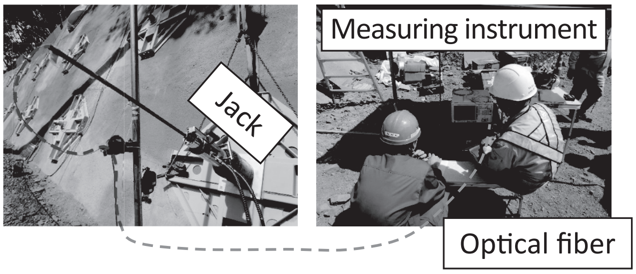

Photo 5. Tension measurement during construction of a ground anchor

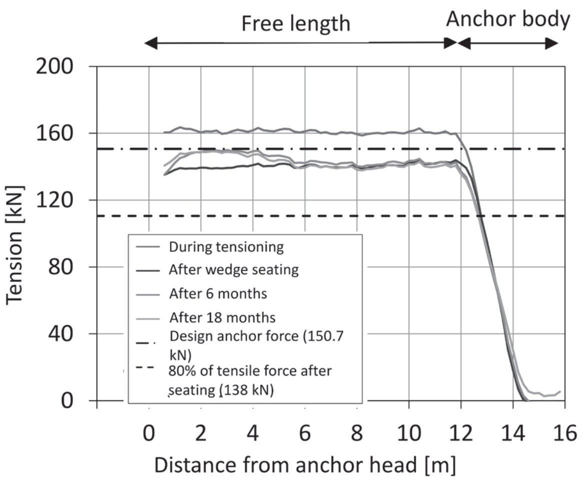

Fig. 9. Example of measurement results (ground anchor)

Measurement was conducted 6 months and 18 months after applied tension, and it was confirmed that soundness was maintained. For application to ground anchors, deformation model experiments, such as slippage of anchor bodies and landslides, were conducted separately.[6] A study is being conducted on the possibility of conducting cause analysis based on the tension distribution profile.

4. Establishment of a Study Group

Recently, the SmART Strand Tension Sensor Technology Study Group was established to work on this measurement technique. As of October 2020, 28 companies, many of which are construction companies, participated in the study group. Sumitomo Electric Industries, Ltd. serves as the secretariat of this study group. The study group has been working on activities to spread and advance the technologies to construct and maintain prestressing steel cables using this measurement technique.

5. Conclusion

We developed a tension distribution measurement technique for prestressing steel strands using SmART Strand. The technique was applied to prestressed concrete bridges and ground anchors, and its effectiveness was confirmed.

This measurement technique makes it possible to confirm the prestressing steel cable tension at any position, in concrete structures or in the ground, which was previously difficult. It also makes it possible to select and design the countermeasure construction properly depending on the amount of deformation, which is estimated based on the measurement results. Thus, the technique is expected to contribute to advancement of maintenance operations.

6. Acknowledgements

We received tremendous cooperation from KAJIMA CORPORATION, Hien Electric Industries, Ltd., and SE Corporation in developing and applying SmART Strand and this measurement technique. We hereby express our deepest appreciation.

Technical Terms

*1 Prestressed concrete structure: Prestressed concrete structure refers to a concrete structure designed to reduce the generation and width of cracks by prestressing concrete with tension using prestressing steel cables as tendons. It is widely used for road bridges, railway bridges, cylindrical tanks, and architectural structures.

*2 Ground anchor: This is a system for stabilizing prestressing steel cables on stable ground with tension and transmitting the prestress to the surface layer. It is used for various applications, including stabilization of slopes (including artificial ones), prevention of landslides, stabilization of bracing walls, and prevention of floating of underground structures.

*3 External cable and internal cable: Of Prestressing steel cables used for prestressed concrete bridges, those arranged in concrete structures are referred to as internal cables, and those arranged outside concrete structures (e.g., internal space of hollow concrete structures) are referred to as external cables.

References

(1) Japanese Geotechnical Society, "Design and construction standards and commentary for ground anchor" (2020)

(2) Public Works Research Institute and Japan Anchor Association, "Maintenance Manual for Ground Anchor" (2008)

(3) Japan Society of Civil Engineers, "Recommendations for Design and Construction of Prestressed Concrete Structures Using Advanced Prestressing Steel Coated with Epoxy Resin (Draft)" (2010)

(4) Japan Prestressed Concrete Engineering Association, "Guidelines for Design and Construction of Prestressed Structures Using High-Strength Prestressing Steel" (2011)

(5) K. Okubo, M. Imai, N. Sogabe, S. Nakaue, K. Chikiri, and J. Niwa, "Development of the Measuring Method for PC-Tensile Force Distribution by Oprical Fiber Applicable to Control of Prestressing and Maintenance of PC Structure," Journal of JSCE E2, Vol. 76, No. 1, pp. 41-54 (2020)

(6) K. Okubo, M. Imai, N. Sogabe, H. Tobe, S.w Nakaue, M. Hayakawa, and J. Niwa, "Application of the Measuring Method for Tensile Force Distribution by Optical Fiber to Ground Anchor," Journal of JSCE A2, Vol. 76, No. 1, pp. 126-138 (2020)

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