Bridge scour monitoring system based on active thermometry

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ABSTRACT

Scour is a very severe problem for bridge. In this paper, a bridge scour monitoring system based on active thermometry is proposed. The monitoring system fulfills scour monitoring based on the different patterns of temperature change between in liquid and in solid after heating due to their distinctive heat transfer behaviors. It utilizes a thermal cable to generate heat with a heating belt and concurrently measure temperature with DS18B20s. Several experimental tests were conducted using the system. Results confirm the methodology and substantiate the scour monitoring system.

Keywords: bridge, scour, monitoring system, active thermometry, temperature, DS18B20

1. INTRODUCTION

Scour is the erosion of sand and rock by the action of flowing water, which is one of the major causes for bridge failure. With the scour effect, the foundation material below the pier footing is being washed out. When the scour develops to a certain level, it will jeopardize the security, stability and durability of the bridge. According to the National Cooperative Highway Research Program (NCHRP) Report 396, scour accounts for 60% of bridge failures in the United States and approximately 84% of all the 575,000 bridges require scour mitigation. The same problem exists among the East-Asian countries, such as China, Japan and Korea. As failures caused by scour tend to take place suddenly and give few prior warnings or signs, scour monitoring plays an important role in decision making of bridge repairing, rehabilitating and replacing.

Several score monitoring technics and instruments have been proposed during the past few years, including sonar, radar, time domain reflectometry (TDR) and fiber Bragg grating (FBG) sensors. However, most of these available techniques have limited applications. Both sonar and radar present challenge to interpreting the results, especially for the river containing high concentration sediments, debris or rocks. And the noise caused by the turbidity of the flow makes sonar and radar applicable only after flood. The TDR technique achieves scour monitoring by generating an electromagnetic pulse and coupling it to a transmission line. It suffers problems such as loss of TDR signal and noise of the electromagnetic environment, which affect its ability to detect subtle scour changes and accuracy. Yungbin Lin, Jinchong Chen, Kuochun Chang, etc. proposed a FBG scour monitoring system, which provides real-time measurement of the process of local scour. However, the research is still at the exploring stage and needs further demonstration before application in practice.

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In this paper, we introduced a different scour monitoring methodology based on active thermometry. The monitoring system consisted in a thermal cable running parallel to the bridge piers or abutments. The thermal cable is comprised of three main components: a heating belt, DS18B20 thermometers, and packing elements. The heating belt radically released heat and the thermometers concurrently measured temperature. Since heat transfers in different ways between in solid and in liquid, the surrounding environment of each thermometer, sediment or water, could be identified by analyzing the acquired temperature time history, thus estimating the position of sediment - water interface and evaluating the structural integrity of the bridge foundation. And the system can also be used to monitoring water level, if applied through the water surface. As laboratory experiments showed in the following paragraphs, this system was feasible and efficient. It’s accurate, inexpensive, easy-to-install, and non-obstructive to the structure.

2. THEORY BACKGROUND

Modes of heat transfer in liquid and in water are convection and conduction, respectively. For heat conduction in the solid, our problem can be idealized as an infinite line source in an infinite, homogeneous, isotropic medium. By using “Transient heat method”\(^7,8\), for large value of \( t \) \(( t \gg r^2/(4\alpha) \) and \( t - t_1 \gg r^2/(4\alpha) \), respectively),

\[
\begin{align*}
\Delta T &= \frac{q}{4\pi\alpha} \ln \left( \frac{r^2}{4\alpha t} \right) - \gamma, \quad t \leq t_1 \\
\Delta T &= \frac{q}{4\pi\alpha} \ln \left( \frac{r^2}{4\alpha (t - t_1)} \right), \quad t > t_1
\end{align*}
\]

where \( \Delta T \): excess temperature; \( \Delta T = T - T_0 \), \( T_0 \) is initial temperature;

\( \gamma \): Euler’s constant (\( \gamma = 0.5772 \));

\( q \): quantity of heat released per unit length of the line source during heating, which starts at \( t = 0 \) and stops at \( t = t_1 \);

\( \alpha \): thermal diffusivity of the solid (\( \alpha = \lambda/\rho c \)); \( \lambda, \rho, c \) are the thermal conductivity, the density and the specific heat of the solid, respectively.

\( r \): distance to line source.

\( t_1 \): time heat stops.

For heat convection in a liquid, in this study, the thermal resistance can be neglected due to the small cross-section area of the thermal cable. The lumped parameter method is adopted by assuming the inner temperature is uniform within any given cross section of the thermal cable. The problem simplifies to

\[
\begin{align*}
\rho cV \frac{\partial T}{\partial t} &= q - Ah(T - T_0), \quad t \leq t_1 \\
\rho cV \frac{\partial T}{\partial t} &= Ah(T - T_0), \quad t > t_1 \\
T &= T_0, \quad t = 0
\end{align*}
\]
where \( h \) is the convective heat transfer coefficient; \( \rho \) and \( c \) are the density and the specific heat, and \( A \) and \( V \) are the convective area and volume per unit length of the sensor, respectively. The solution is

\[
\Delta T = \begin{cases} 
\frac{\Delta t}{hA} \left( 1 - \exp\left(-\frac{t}{\tau_c}\right) \right) & t \leq t_1 \\
(T(t_1) - T_0) \cdot \exp\left(-\frac{t-t_1}{\tau_c}\right) & t > t_1 
\end{cases}
\]  

(3)

with \( \tau_c = \frac{\rho c V}{hA} \), which is called time constant.

3. EXPERIMENTAL INVESTIGATION

The scour monitoring system was comprised of a thermal cable with an external power supply, Data Acquisition Unit (DAU) and Data Processing Unit (DPU), as showed in Fig. 1.

![Fig. 1 System Overview](image-url)
The thermal cable consisted of three major components: a heating element, thermometers and packing elements (Fig. 2). A heating belt acted as the heating element. It was 1m long and had a cross section dimensions of 2mm×10mm. Six DS18B20s were glued on it and used to measure temperature. The adopted DS18B20s had a wide operating temperature range of -50°C - 125°C and a coarse but adequate accuracy of ±0.5°C. Its diameter was 5mm and its length was 30mm. Temperature was sampled nearly every 10s. Electronic transmission of the signal limited the transmitting distance to 200m. The layout scheme of DS18B20s is shown in Fig. 3. P. 1 ~ P. 6 denotes the six DS18B20 thermometers respectively. The main wire of the thermal cable consisted of three lines, two power supply lines (L1 and L2) for the heating belt and DS18B20s, respectively, and one data line (L3) for DS18B20s (Fig. 2). After all lines of the six DS18B20s were carefully connected, hot pyrocondensation pipes of a 16mm diameter were used as the packing elements. They encapsulated the heating belt and the distributed DS18B20s, as shown in Fig. 2. To properly protect the thermal cable from water, double layers of hot pyrocondensation pipes were used and epoxy resin was applied to some key locations.

Employment of DS18B20s made the DAU very simple. STA-D series of data acquisition module played the role. It was connected to data line L3 and could be directly connected to a computer, which acted as the DPU. The acquired data were converted to digital format by the acquisition module and then were transmitted to the computer to be stored and analyzed.
A cylindrical metal bucket with water and sand in was used to simulate the circumstance where bridge piers stand (Fig. 1). The bucket was 90 cm tall and had a diameter of 60 cm. The volume of sands and water was 40 cm³ and 30 cm³, respectively. The thermal cable was plugged into the sands from the center of the bucket, making sure P. 1 and P. 2 were in the sands, P. 3 and P. 4 in the water and P. 5 and P. 6 in the air. Before experiments performed, the sands should be fully saturated and temperature equilibrium should be reached within and around the bucket. After making sure L3 was in good connection to the computer through the data acquisition module, tests were conducted as follows: Firstly, turn on the computer; connect L2 to the power, the 16 DS18B20s start to record temperature, lasting for about five minutes. Then connect L1 to the power; the heating belt starts to generate heat. Lastly, after some time of heating, disconnect L1; keep DS18B20s sampling for some time, disconnect L2. Several tests were conducted with variation of heating time. Besides, some explorative tests were carried out. To simulate the actual circumstance of flowing water, some disturbance was made to the water when heating. We stirred the water around the bucket using a stick for several seconds and didn’t stir again until the flow rate deceased considerably. We did this three times for each test. And the other experimental procedures were the same. The room temperature was recorded every 30 minutes throughout all the tests.

4. RESULTS AND DISCUSSION

Fig. 4 shows the excess temperature time histories of the six DS18B20 thermometers throughout the experiment. The excess temperature is \[ \Delta T = T - T_o \], in which \( T_o \) was obtained through the experimental data before heating began. The
curves of P. 1 ~ P. 6 correspond to the six DS18B20 thermometers as showed in Fig. 3: P. 1 and P. 2 were in the sands; P. 3
and P. 4 were in the water; and P. 5 and P. 6 were in the air. As showed in fig. 4, these three groups present distinctive curve
patterns, which in turn offer a clear indication of the surrounding scenarios around the responding sensors. To monitor
scour is to detect the water – sediments interface, which is not a problem if the surrounding scenarios of all the sensors have
been figured out. The interface is at the location between the sensor in water and in sands. In addition, the water level can
be easily detected as between P. 4 and P. 5, given P. 5 and P. 6 is quickly identified as in the air for the distinguished relative
high excess temperatures.

The different heat dissipation mechanisms between in water and in sands result in the distinctive curve patterns of
temperature histories. Generally speaking, heat dissipates more easily through convection via water than conduction via
sand. While it dissipates gradually through conduction in sand, heat can be directly carried away by water flow or nature
flow. Excess temperature in water and in sand has an exponential and logarithmic relationship with time, respectively (Eq.
(1), Eq. (3)). In water it exponentially rises up to a plateau \( q/hA \) when heat starts, and exponentially drops down back to
a flat (zero) when heat stops (Eq. (3)). In sand, it climbs according to formulas \( \ln t + \ln 4\alpha/r^2 - \gamma \cdot q/(4\pi\lambda) \) and
\( \ln (t/t - t_i) \cdot q/(4\pi\lambda) \) (Eq. (1)) during heating and cooling period. As illustrated in Fig. 4, curve P. 1 and P. 2 climbs up and
down, both at a decreasing rate, and curve P. 3 and P. 4 rocket up to a plateau stay stable and then fall down to zero suddenly
when heat stops. Therefore, it is suggested that P. 1 and P. 2 are in water and P. 3 and P. 4 are in sands.

To quantify the difference of curve patterns of excess temperature histories between in water and in sands, a curve fitting
analysis was performed. By comparing the fitting residues, we identified all the surrounding scenarios of the thermometers.
Considering the experimental temperature curve patterns, the theoretical formulas and readiness of application, the fitting
functions were generalized theoretical formulas introduced some undetermined coefficients, showed as follows.

\[
\begin{align*}
\text{in sand} & \quad \begin{cases} 
\Delta T = A(\ln t + B) & t \leq t_i \\
\Delta T = C \ln \frac{t}{t - t_i} + D & t > t_i
\end{cases} \\
\text{in water} & \quad \begin{cases} 
\Delta T = E[1 - \exp\left(-\frac{t}{F}\right)] & t \leq t_i \\
\Delta T = G \cdot \exp\left(-\frac{t - t_i}{H}\right) + I & t > t_i
\end{cases}
\end{align*}
\]

(4) \hspace{1cm} (5)

The relative fitting residuals are calculated as follows:

\[
R_{i,w} = \sqrt{\frac{\sum (T_{i,w} - T_{i,w})^2}{\sum T_{i,w}^2}} \quad R_{i,s} = \sqrt{\frac{\sum (T_{i,s} - T_{i,s})^2}{\sum T_{i,s}^2}}
\]

(6)
where $T'_e$ is the acquired excess temperature of the $i$th DS18b20 thermometer. $T_{a,w}$ and $T_{a,s}$, $R_{i,w}$ and $R_{i,s}$ are the fitted analytical values and relative fitting residuals of the $i$th DS18b20 thermometer, for water (Eq. (4)) and sand (Eq. (5)) respectively. $RIW_i$ is called the Reliability Index of the $i$th DS18b20 thermometer being in Water ($RIW$), which is the proportion of sand residuals to the sum of water and sand residuals. In some way, it denotes the possibility of the $i$th DS18b20 thermometer being in water. If it is larger than 0.5, the thermometer is in water; otherwise it is in sand.

Fig. 5 Curve Fitting Analysis of P. 1 ~ P. 6.
Table 1 Fitting results of Point 1

<table>
<thead>
<tr>
<th>Residue</th>
<th>P. 1</th>
<th>P. 2</th>
<th>P. 3</th>
<th>P. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>For Water</td>
<td>0.0586</td>
<td>0.0531</td>
<td>0.0090</td>
<td>0.0100</td>
</tr>
<tr>
<td>For Sand</td>
<td>0.0286</td>
<td>0.0341</td>
<td>0.0590</td>
<td>0.0605</td>
</tr>
<tr>
<td>$C_i$</td>
<td>0.328</td>
<td>0.391</td>
<td>0.867</td>
<td>0.858</td>
</tr>
</tbody>
</table>

Fig. 5 shows the results of curve fitting analysis of P.1 ~ P.4, each with one experimental temperature curve and two analytical fitted curves. The corresponding residuals and $R_{IW}$'s are shown in Table 1. As illustrated in Fig. 6, P.1 and P.2 are in sand and P.3 and P.4 are in water, which agree with the experimental setup. Therefore, conclusion can be made that the water – sediment interface is somewhere between P. 2 and P. 3.

In addition, the three disturbances for making flow add new ingredient to the heat dissipation via water and bring out potential new feature to differentiate water from sand. All the three disturbances can be quickly detected through the sudden change of the excess temperature time histories, showed in Fig. 7. What’s more, the temperature curves of the thermometers in water tend to be more fluctuant after disturbance, while those in sand stay untouched. The flow rate plays an important role in convective heat transfer. Very little changes of the flow cause noticeable abnormality of temperature curves. Given the practical monitoring system is applied in the circumstance of fickle flowing water; the temperature fluctuation is a promising index for scour monitoring.
To sum up, considering the entire course of heat dissipating including heating and cooling period, the scour monitoring technic turned out to be feasible and reliable. The reliability index of being in water was easy to be calculated, has a physical meaning and provides a good index for scour monitoring. The DS18B20 thermometers used in this monitoring system was inexpensive, easy to install and hence suitable for wide application. Even though their precision was ±0.5°C, still they were proved adequate. The precision of the scour monitoring system identifying scour depth was 7.5cm, half the spacing of the thermometers. Better precision could be achieved by reducing DS18B20s spacing without much more cost. Furthermore, the monitoring system could work with the thermal cable placed in the vicinity of bridge piers or abutments, making construction of the system flexible and uncomplicated.

After all, this is just a preliminary study of the proposed scour monitoring system. The experimental setup was simple and crude. As an applicable index of scour monitoring, temperature fluctuation requires more careful work and further demonstration. Several issues such as sensors failure, noise impact and system optimization calls for further study. And field experiments are also essential before actual application of the scour monitoring system.
5. CONCLUSION

In this study, we proposed a scour monitoring technic based on active thermometry and experimentally tested an illustrative scour monitoring system in the laboratory. The monitoring system consisted in a thermal cable running parallel to bridge piers measuring temperatures, as well as generating heat. Owing to the distinct heat transfer mechanisms via solids and liquids, the patterns of acquired temperature change was different between in water and in sediments, which provided a feasible index for detecting the sediments – water interface. By fitting the acquired excess temperature curves to the generalized theoretical functions of liquid and solid, respectively, and comparing the relative fitting residues, an index called $RIW$ can be obtained to quantify the possibility of all the thermometers being in water. Another promising index, the temperature fluctuation, was briefly explained upon a simple exploratory test. Actually the device used in this scour monitoring system is very like the thermal probe widely used in geology and engineering heat transfer. It can also be adapted and used as a monitoring technic in many other fields of engineering.

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