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Scour Monitoring of Railway Bridge Piers via Inclination Detection

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Scour Monitoring of Railway Bridge Piers via Inclination Detection

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ABSTRACT

Protection of bridge piers against scour is a crucial requisite for safe train locomotion. It is necessary to issue an alert to block the bridge when its piers are endangered by scour. As it is difficult for a human inspector to observe the bridge pier scouring during a flood directly by naked eyes, authors developed the clinometric type of scour monitoring device. These devices have installed since 2000 in East Japan Railway Company area. This device gives the alarm to the train operation room and train operation is suspended, when the inclination of the bridge pier exceeds the threshold value. Moreover, authors developed numeric models for inclination forecast to detect the inclination of a pier before it is in a critical condition due to scour.

THE RULE TO AVOID TRAIN ACCIDENTS CAUSED BY SCOUR HAZARD

East Japan Railway Company (JR East) has a network of 7,538km of track in eastern Honshu in Japan(Fig.1). There are approximately 800 bridges that are prone to of scour damage among about 2,500 bridges over water in JR East and several of them have suffered severe scour damage during the last decade.

Major characteristics of rivers in Japan are their short and steep riverbed. In a flume, stream becomes super-critical flow and water level hardly rises during a flood. Moreover lowering of riverbed progresses at many rivers at present, due to dam construction in the upper and middle reach of rivers

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JR East takes two types of measures for this purpose; first, constructing protective facilities around the bridge pier to prevent scour; second, setting a train suspension rule to suspend a train operation before scour develops. In this rule, a scour depth around a bridge pier is estimated by the empirical relationship between a scour depth, water level and width of the bridge pier because it has been difficult to measure the depth of scour directly. When water level grows up and reaches the threshold value during flood, train operation is ordered to suspend. This rule has two major drawbacks, however. The first is that this rule causes many unnecessary train cancellations, and the second is that this rule cannot suspend a train operation before a scour hazard occurs.

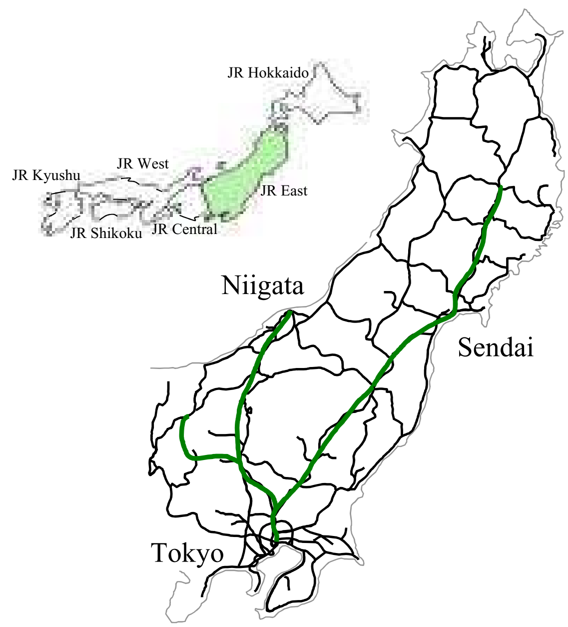

Fig.1 The networks of JR East

To cope with these problems, it is necessary to measure a depth of a scour or a stability of the bridge pier directly. Authors developed four scour monitoring devices that can monitor the riverbed level or stability of the bridge pier[1], The first is floating switch type, the second electrode type, the third accelerometer type, and the fourth clinometric type. JR East currently installs the clinometric type of scour monitoring device to monitor stability of bridge piers among these devices.

THE RULE FOR REGULATION OF TRAIN OPERATION USING THE WATER LEVEL GAGE

Water level gages have been used to give alarms in case of the threat by scour at bridge piers. JR East has approximately 600 on-line water level gages on bridge piers and water level is measured individually on real time. Scour depth is estimated by means of the empirical relationship among scour depth, water level and bridge pier width. When the estimated scour depth at the spread-footing base of the bridge pier of interest reaches to certain threshold value,

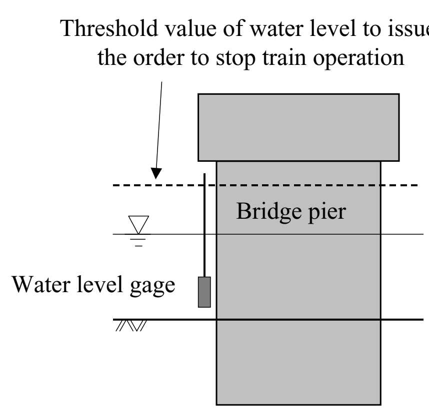

Fig.2 Outline of regulation of train operation during high water

orders to suspend train operation are to be transmitted to the train operators. Fig.2 shows outline of regulation of train operation during high water.

However, this rule causes many unnecessary train cancellations because the estimation is determined considering worst-case scenarios and the threshold value is added unclear safety margin.

Furthermore, this rule dose not ensure to suspend train operation before scour develops in some kind of site-situation, such as in a flume with steep riverbed, where stream becomes super-critical flow and water level hardly rises during flood. Thus, in this kind of site-situation, it is difficult to find the occurrence of a scour with measurement of a water level.

THE PRINCIPLE OF THE CLINOMETERIC TYPE SCOUR MONITORING DEVICE

The clinometric type scour monitoring device is fixed on the top of bridge pier, and monitors the inclination of bridge pier caused by scouring the foundation of bridge

i) The device on the top of the pier　　ii) Inside of the device

Fig.3　The clinometric type of scour monitoring device

pier(Fig.3). This device can measures inclination of the pier in the same principle of a bubble tube type level. Inclination can be measured with the accuracy of 0.001° in the range of ±0.5°per with a frequency more than once per second.

Fig.4 shows time series of the inclination of a certain bridge pier. This figure shows that the bridge

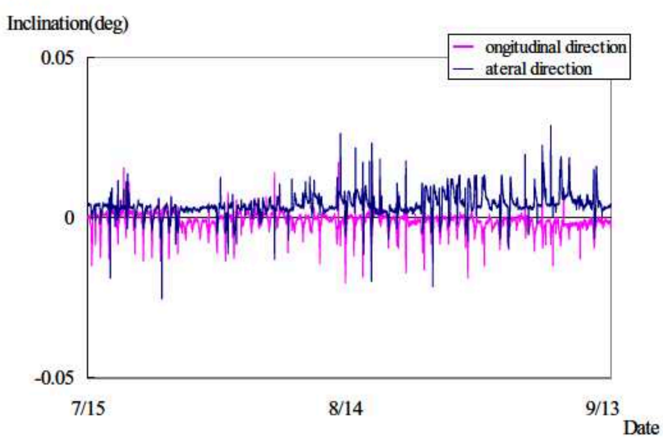

Fig.4　Time series of the inclinations of a certain bridge pier

pier inclination fluctuates within a small range in a day cycle, and it is considered the influence of the movement of the bridge caused by the cycle of a temperature. In Fig.4, a jump of the data shows that a train passed over the bridge. Fig.5 shows scattered diagram of the daily inclination of same bridge and the plotted inclination was observed every thirty minutes during a half year.

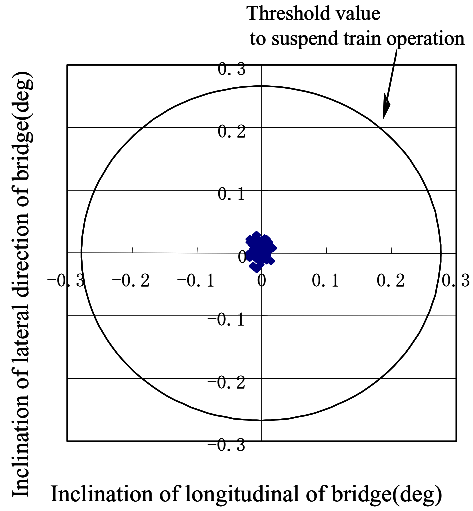

Fig.5 Scattered diagram of the inclinations of a certain bridge pier

THE THRESHOLD VALUE OF THE CLINOMETERIC TYPE SCOUR MONITORING DEVICE

The clinometric type scour monitoring device gives alarms when inclination of the bridge pier exceeds certain threshold values. There threshold values are based on the existent maintenance limits of track irregularity(Table 1).

The relationships between the inclination of a bridge pier and the vertical and horizontal transition is follows(Fig.6):

Vertical gap $\theta_1=4\cdot 10^{-4}(La\cdot Lb/(La+Lb))B_1/D$

Horizontal gap $\theta_2=4\cdot 10^{-4}(La\cdot Lb/(La+Lb))B_2/H$

where

θ_1 : Inclination angle of the bridge pier for vertical gap(radian)

θ_2 : Inclination angle of the bridge pier for horizontal gap(radian)

Table 1 Maintenance limits of track irregularity(mm)

	Line over 120km/h	Line over 95km/h	Line over 85km/h	Line over 45km/h	Line below 45km/h
Longitudinal level(B_1)	15	17	19	22	24
Line(B_2)	15	17	19	22	24

La : Span of bridge girder of one side(m)

Lb : Span of bridge girder of another side (m)

B_1 : Instruction value for track irregularity of longitudinal level (mm)

B_2 : Instruction value for track irregularity of line (mm)

D : Horizontal distance between the edge of foundation and the rail(m)

H : Vertical distance between the edge of foundation and the rail(m)

The smaller of θ_1 and θ_2 is chosen to be the threshold value of train suspension. The maintenance limits of track irregularity are constant anywhere but the threshold value of the device changes by each bridge due to be the threshold variance of bridge heights. Generally the threshold values are set between 0.2° and 0.5° in this rule. The inclination that is observed at all the bridges is much smaller than threshold values(Fig.4 and 5).

When the inclination of the bridge pier exceeds the threshold value, the device gives the alarm to the train operation room through the wired network along the track for transmitting the data of the various sensors; such as rain gauges, seismometers, anemometers, and so on, and train operation is suspended. However in order to get rid of the influence of the passing train(Fig.4), the clinometric type scour monitoring device does not issue an alarm without 2 minutes excess of inclination over the threshold value.

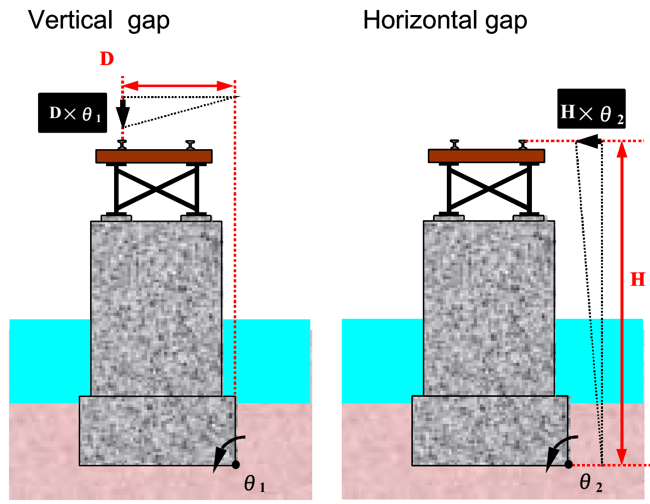

Fig.6 Relationship between the inclination of bridge pier and the gap of it

The cost of the clinometric type scour monitoring device is about ¥300,000 per device. The initial cost per bridge is approximately ¥4,000,000 including three monitoring devices and establishment of devices, power supply and wired network. This device have installed since 2000 in East Japan Railway Company area. It installed 6 bridges in 2000, 70 bridges in 2001, and will install 69 bridges in 2002.

IMPROVEMENT OF THE CLINOMETRIC TYPE OF SCOUR MONITORING DEVICE

The clinometric type scour monitoring device issues an alarm when the inclination of bridge pier exceeds the preset threshold value. There is room for improvement in this device as follow:

(1) Though a bridge pier is scoured and begin to incline, train operation cannot be suspended until an inclination exceeds the threshold value.

(2) The risk of scour depend on whether a pier inclines quickly or slowly, but the device cannot measure a speed of inclination.

In order to improve these points, it could be considered a way to forecast a future inclination and apply it to the rule.

We examined some methods to forecast a future inclination statistically by using time series of the inclination of the bridge pier. In this examination we have tried to find a suitable model to represent a time series of inclination and to forecast a future inclination by using this model. For this purpose, we carried out experiments first using a reduced scale pier to take data of time series of inclination.

A process of the examination are shown below:

(1) An experiment is carried out with a reduced scale pier as an actual bridge pier inclines by scouring the foundation. This experiment takes data of time series of inclination.

(2) We examine how to forecast a future inclination with the past time series by using the data above.

THE EXPERIMENTS IN INCLINATION WITH REDUCED SCALE PIER

The experiment was carried out with approximately 1/20-scaled stone rectangular solid imitated bridge pier. In the experiment, a reduced scale model standing on the ground was made to incline, and the progress of the inclination of the model was measured every second with the clinometric type scour monitoring device on the top of the model. In order to make the model pier incline without a thrust by outer force, columns of frozen sand were set under the model by digging the ground and supported a half of the weight of the model shown in Fig.7. These columns of frozen sand melted gradually with the heat of the natural environment, and then the model pier lost support and began to incline slowly. The experiment was repeated by changing the length of overhang and the height of earth burying the model. An example of the time series of the inclination data taken by the experiment is shown in Fig.8. It shows that the time series has long-term patterns of growth of the inclination (a sign denotes the direction of inclination) and the other series also have a same trend.

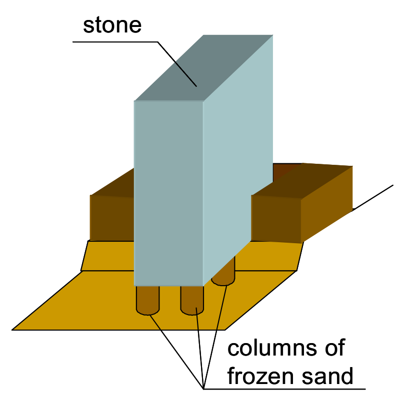

Fig. 7 Experiment in inclination

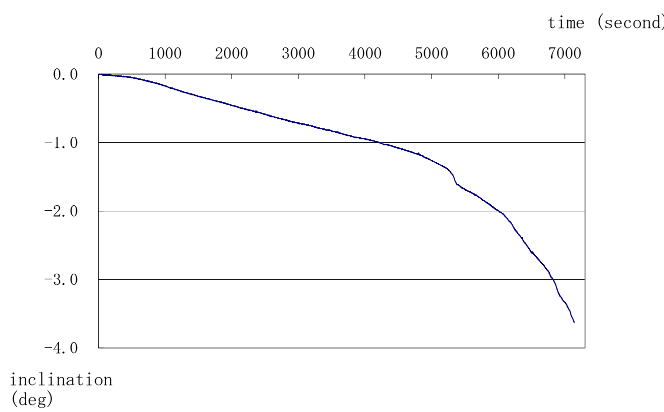

Fig8 Time series of inclination

METHOD OF FORECASTING THE INCLINATION

A method of forecasting the inclination was examined by using the data explained in the preceding chapter. In order to put this method to practical use, the ability of the scour-monitoring device already set at bridge must be considered for the examination of the method. In short, a suitable model for representing the time series of the inclination must be as simple as possible to be computed by the device.

As already mentioned in the preceding chapter, the time series of the inclination obviously has the movement called trend, which is long term and only in one direction. This trend is not linear but curvilinear, and there are several mathematical models to represent curvilinear trend. Since the time series seemed to grow at a constant percentage, two models with this characteristic are useful for the forecast. They are expressed as follows.

Quadratic Trend Model

$$y_t = \beta_0 + \beta_1 t + \beta_2 t^2 + \varepsilon_t$$

Simple Exponential Growth Model

$$y_t = \beta_0 \cdot \beta_1^{\,t} \cdot \varepsilon_t$$

The coefficients are updated to fit the time series by using most recent data. For example, at time *t* the coefficients are calculated by using the most recent k-steps-data, and then 3k-steps-ahead inclination is calculated by using the model with this coefficients.

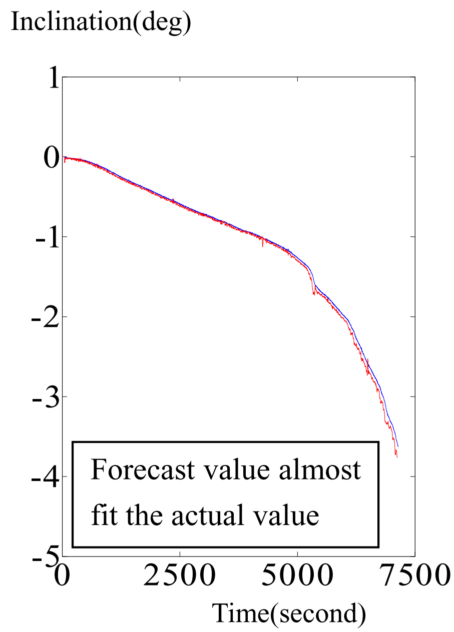

Fig.9 Result of forecast with *simple exponential growth model*

As a result of the examination by stepwise forecast error evaluation, *simple exponential growth model* probed to fit the time series better than *quadratic trend model*. A future inclination forecasted by *quadratic trend model* is sometimes unstable under the influence of data noise.

In order to examine the influence of noise realistically, noise that moves within the same range as measured at the actual bridge was added to the data obtained from the model pier experiment. As a result of forecast model fitting, the forecast by *simple exponential growth model* proved to fit well irrespectively whether the data contain noise or not. On the other hand, the forecast by *quadratic trend model* is often much more seriously discrepant with the sample time series than the case without noise.

These results show that the time series of the inclination can be fitted and extrapolated by *simple exponential growth model* better than by *quadratic trend model.* The former model is robust against the influence of noise and there is less possibility of giving false alarms.

REGULATION RULES BASED ON INCLINATION FORECAST

As already mentioned in preceding section, the result of the examination shows that there is a possibility that the progress of inclination of bridge pier is forecasted with a simple numerical model. The threshold value of inclination does not change by using method of forecast, but this method brings the advantage as follows:

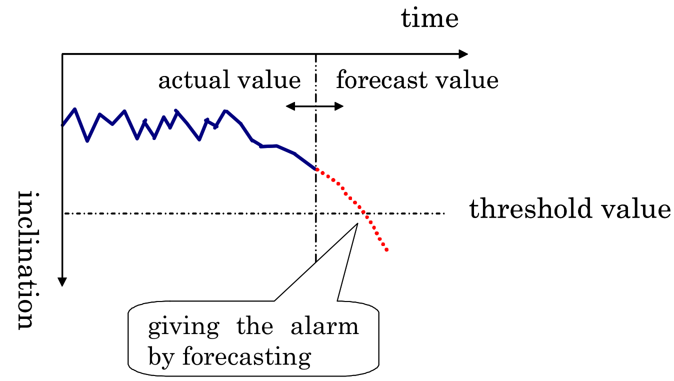

Fig.11 The basic idea of regulation rules based on forecast method

(1) An alarm can be issued before a bridge pier is in a dangerous condition, and foundation of the pier can be inspected and identified.

(2) The time when the inclination of the bridge exceeds the threshold value can be forecasted. As a result, it is clear how fast foundation of bridge pier is scoured and the danger of train passing over the bridge can be judged.

From the practical point of view, the forecast may not be necessarily very accurate, but it is necessary that the accuracy of the forecast is quantitatively evaluated prior to the application of the forecast.

CONCLUSIONS

The development of the clinometric type scour monitoring device was described in this article. JR East is currently monitoring the inclination of the piers of its 76 scour prone bridges with the device and planning to install the device on additional 71 bridges by the end of 2002. It is expected that sufficient amount of statistical data which is necessary to establish an accurate and reliable method to detect bridge pier scouring via inclination data can be obtained from daily measurement records by these operating devices.

REFFERENCE

1) O. Suzuki, M. Shimamura: Development of New Scour Monitoring Devices for Railway Bridges, Scour and Foundation, pp.331~336, Melbourne, 2000.6