Experience in application of acoustic emission method for estimation of building construction condition

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Abstract
In this paper the experience in practical application of the acoustic emission (AE) method for estimation of the crane trestle condition at the Sayano-Shushenskaya Hydroelectric Plant after an accident, and the perspectives of the AE method for estimation of the building construction condition have been considered. To estimate the crane trestle condition at the Sayano-Shushenskaya Hydro, cyclic loadings of massive reinforced concrete constructions of the crane trestle were used. The Kaiser effect was applied for estimating stresses operating in the construction. The technique for estimation of the building construction condition has been developed and approved, which allows for defining the occurrence of structural damage beforehand. Results of the studies conducted is useful in monitoring of the critical structures.

Keywords: Acoustic Emission (AE), reinforced concrete, Structural integrity

1. Introduction

The method of acoustic emission (AE) is a rather effective testing method, which is widely used in mechanical engineering, atomic power engineering, oil and gas industries, as well as for integrity testing of pipelines, inspection of processing equipment in chemical industry, aircraft, and astronautics. Year after year the field of AE method application extends. The AE method has been widely enough regulated. In the civil engineering the AE method finds expanding applications, both in nondestructive inspection, and for estimation of the building structures condition, as well as in monitoring. In contrast to traditional nondestructive methods for construction testing, the AE method allows for estimating processes occurring in the construction structure, for locating a progressive defect and defining the defect influence on the load-carrying capacity of the construction.

The Scientific Research Engineering and Technological Institute for Concrete and Reinforced Concrete (NIIZHB) named after A.A. Gvozdev (Moscow) is engaged in study of the practical use of the AE method in civil engineering [1, 2, 3]. Results of such study are used in applied problems solving. Experts from NIIZHB took part in rectification of consequences of an accident at the Sayano-Shushenskaya Hydro. The constructions of the machine room and crane trestle of the hydro power station were inspected. As a result of the accident the crane trestle column located near the hydroturbine unit No. 2 (the column along the axis G/B2) sustained great damage. The column top part was completely destroyed. The column bottom part had cracks in the width of 10-55 mm opening. By the time of in-situ testing the column top part was embedded in a concrete anew. Into the cracks in the column bottom part the epoxy repair compositions were injected. The column bottom part was additionally strengthened with a concrete collar. A number of minor damages were found in beams and columns located at other places of the crane trestle.

2. Information on the crane trestle at the Sayano-Shushenskaya Hydro

The crane trestle arranged in the turbine room of the Sayano-Shushenskaya Hydro is a multi-span reinforced-concrete frame, and bears two one-legged gantry cranes. The load-carrying
capacity of each crane is 500/100/10 ton/thrust. The crane full weight is 467,815 kg; the bridge weight is 133,150 kg; and the weight of hand carts with gears is 166,970 kg. The crane wheel load on a rail is max 100,000 kg. The crane rests against 8 wheels on each side. The crane trestle is arranged in an arch with a radius of 462.8 m. The crane trestle frame rigidity is assured by overall sizes of the crane trestle columns (column cross-section is 1.2 x 3.4 m) and a crane girder (the size of crane girder cross-section is 3.4 x 2.3 m). The contraction joints break down divide the crane trestle into six parts. The crane girders are made of a cast in-situ reinforced concrete. The span of crane girders is 12 m. The crane girder section is of intricate shape. The crane girder is monolithically connected with a gantry girder. Further, the support of turbine room wall is adjacent to the gantry girder. The crane girders are reinforced with stiff reinforcement in the form of two trusses made of standard sections, with two rolled I beams and Class AIII reinforcement bars of different diameters.

3. In-situ experiment technique

The in-situ tests of the crane trestle were carried out at the time of disassembly of hydro-turbine unit No. 4. The total weight of the rotor lifted and the metal cross tile the rotor was fastened to was 750 ton. Two cranes were used for rotor lift and displacement to the erection site (Fig. 1). During the rotor lift and displacement, deflectometers with 0.001-mm resolution were used for measuring displacements of the crane girders of the crane trestle. The AE signals were also recorded.

![Fig.1. Rotor displacement](image_url)

The AE measurements were performed by an 8-channel AE system A-Line 32d. This device allowed for registering low-frequency signals from 5 kHz. Two types of piezoelectric transducers with a working band of 30 to 300 kHz and AE transducers with a working band of 10 to 60 kHz were used as sensors.

The crane trestle constructions were tested for the following load schedule:

- Loads due to one crane without cargo (vertical load of 767 ton);
- Loads due to two adjacent cranes without a cargo (vertical load of 1535 ton);
- Load from crane carriage braking (horizontal load of 65 ton);
- Loads due to two adjacent cranes with a cargo of 759 ton (vertical load of 2285 ton);
- Repetitive loading of constructions by one/two cranes without a cargo.

4. Technique of acoustic-emission measurements
In preparation of AE equipment for measurement, it was necessary to solve a problem of acoustic noise and vibration effect in the turbine room of the Sayano-Shushenskaya Hydroelectric Plant. The analysis showed that the low-frequency sensor having the working frequency of 10 to 60 kHz appeared ineffective. It was impossible to eliminate noise even if the threshold and the frequency filtering were selected. The problem of noise and vibration effect on measurement of AE signal parameters was solved by using the sensor having working frequency of 30 to 300 kHz in combination with the frequency filtering, and also using a plasticine as a contact surface between the AE sensors and the construction concrete. The sensors were fastened to the structure by magnetic clips.

The AE sensors were fixed on the columns and the crane girder opposite to the hydroturbine unit No. 2 (column B2 and SH/2-3, the crane girder B2-SH/2-3) and opposite to the hydroturbine unit No. 8 (columns B8 and SH/8-9, crane girder B8-SH/8-9). On the column B2 the sensors were fixed at two levels – at a height of one meter from the level of the turbine room platform and at a height of two meters from the level of the hydroturbine unit floor. Before making measurements, the standard procedures of AE device preparation were carried out. All repair works were stopped for the time of in-situ testing. This reduced the sound level in the turbine room. Measurement of AE signals was made continuously during the whole period of testing both at the static position of the cranes and cargo, and also during their movement. When recording the AE data, additionally, the crane and cargo positions were fixed. The AE equipment used allowed to record in real time the AE signals parameters for each channel: amplitude, energy, duration, activity, and frequency of AE signals, etc. The crane trestle testing by the AE method aimed to estimate an actual operation of the crane trestle, as well as to detect defects in the damaged and/or reinforced constructions, and to determine a danger level of such defects. As scientific hypotheses the following were accepted:

- Use of cyclic loadings of reinforced concrete constructions of the crane trestle and the Kaiser effect allow to detect data on a stress level and damages. The scientific hypothesis is based on the known positions of the Kaiser effect discovered for metals, brick and concrete, of which essence lies in the fact that at repeated loading of the construction the acoustic emission will not occur until the level of previous loading, is exceeded. The Kaiser effect can be disturbed at loads exceeding 0.7 – 0.8 R, when the internal damages exist in the construction.

- Change of the flow of AE events allows to define an elastic or inelastic stage of concrete work. The statistical processing of measurement results characterizes the level of danger of growing defects in the structure of concrete construction. The hypothesis is based on the fact that the flow of AE events is tightly bound to the construction condition, that is, inelastic deformations of concrete and growth and integration of cracks; destruction of the concrete compressive zone is characterized by a long duration of the AE signals and considerable growth of the AE events flow.

5. Results of AE measurements

The cyclic loading of the crane trestle constructions were carried out by two adjacent cranes without a cargo. The number of construction loading cycles was two. The cranes in an adjacent mode moved twice over 20 minutes from the erection site to hydro turbine unit No. 4, and return. During the first cycle of loading 23 AE signals were recorded in column B2. During the second cycle of loading no AE signals were recorded. Thus, the Kaiser effect is fulfilled at repetitive loadings.
Fig. 2 Results of AE activity measurement in column B2 when applying the load of two adjacent cranes carrying 750 ton cargo and the load due to own weight of two adjacent cranes.

As an example, Fig. 2 shows the AE activity-time diagram. The diagram is constructed by results of the AE measurements, when the crane loads are applied to column B2. In the first case the load due to two cranes with a cargo was applied. In the second case the column was acted on by the load due to two adjacent cranes. In the first and second cases the cranes were arranged opposite to the column B2. From the diagram (Fig. 2) follows that the activity of AE signals depends on the applied load level. The load of 750 ton due to two cranes with a cargo caused the AE activity with an average rate of 47.2 /sec. During the first loading the flow of AE events has an evidently decaying nature, and when holding under constant load, the AE signals do not appear. After a two-hour interval, tests were repeated, and the column B2 was loaded with a one crane load. Five AE signals were recorded. The recorded flow of AE events has a decaying nature. This allows for making a conclusion that the column B/2 has no defects.

Results of crane girders testing in two spans for action of load from the crane carriage braking showed that the AE activity was insignificant (one and three AE signals were recorded, respectively).

The AE measurements allowed for making a conclusion that the crane trestle constructions had no defects, and the crane trestle was in good operating condition. As an advanced technology for using the AE method for monitoring of the building or facility condition, we consider the algorithm for computing statistical criterion in the AE system A-Line 32D developed by “Interunis” Ltd. together with the MSTU n.a. N.E. Bauman (Moscow) [4].

The algorithm for computing statistical criterion provides for formation of a sample of the AE signal parameter flow. In an online mode an informational parameter of the AE signal is sampled, as well as the condition according to which samples are formed. Samples are formed either according to the quantity of recorded AE signals, or according to the set time interval $\Delta t$. On the basis of the sample of AE signal parameters, distribution bar charts are built, from which statistical characteristics of distribution are computed, such as an average value, a mode, a dispersion, etc. The next stage of computations is normalizing of sample values and computation of normalized entropy. As an example, let us consider the performance of entropy of amplitude distribution $N(A)$. Normalizing of values of the AE signal amplitude in the sample allows for obtaining an amplitude probability density in the sample, expression (1).
Here, $N_{A_i}$ numerical value of the amplitude of the sample; $\sum_{i=1}^{N_i} N_{A_i}$ - the total value of the amplitude in the sample.

$$\gamma_i = \frac{N_{A_i}}{\sum_{i=1}^{N_i} N_{A_i}} \quad (1)$$

Using expression (2), we obtain the normalized entropy, $S^H$

$$S^H = \frac{\sum_{i=1}^{N_i} (\gamma_i \cdot \ln(\gamma_i))}{\ln N_h} \quad (2)$$

Normalizing of the amplitude distribution entropy results in that with a density being $\gamma_i = \frac{1}{N_h}$, $i = 1 \ldots N_h$ with the maximum value of entropy of 1 (chaos maximum). For distribution with a single value (chaos minimum) we will obtain zero value of entropy. The conducted investigations of reinforced concrete constructions have shown that the following relationship (3) can be selected as an identification parameter,

$$F = A_{mod}(S^H_{A}) \quad (3)$$

Function (3) is dependence of the mode of AE signal amplitudes on the relative entropy of this distribution. The mode is the most frequent values of amplitudes in the sample. The relative entropy of distribution is limited within $0 \ldots 1$ and characterizes a chaotic character of the process taking place in the construction material.

Let us consider an example of the algorithm for computing statistical criterion for estimating condition of a reinforced concrete beam. The beam was tested in NIIZHB. The beam was made of self-stressing concrete, compression strength class B45. To prepare a concrete mixture, Portland cement (PC) was used as a cementing component, grade M500-DO, manufactured by the Starooskolsky works. The self-stressing concrete was produced by mixing Portland cement M500-DO and an expansion agent (EA) manufactured according to OTY 5743-023-46854090-98. Granite gravels of 5-20 mm fraction and sand of fineness modulus $M_k=2.2$
mm were used as aggregates. Reinforcing bars were arranged in the beam lower part. Prestressed reinforcement of A-V Class, diameter 16 mm, was used as the main reinforcement. The reinforcement was pretensioned by means of hydraulic jacks using a pump station. The value of reinforcement prestress with regard to all losses was 100 MPa. AE sensors were fastened on the beam side surface by means of a waxy-resin compound. Acoustic contact between the AE sensor and concrete was provided with a contact grease. Load to beams was applied by the hydraulic jack and the manual pumping station. Focused concentrated application of the jack load was carried out through a stiffening distribution cross tie to the beam at two points located at distance of 520 mm from ends. The beams pivotally rested on two supports. The distance from the beam ends to the supports was 150 mm. The step mode was accepted as the load application mode. A loading step was 10 to 15% of a breaking load. The test was carried out to failure of the sample. Fig. 3 shows the prototype sample design and its test pattern. The diagram (Fig. 4) shows the F-function value of diagnostic diagram according to expression (3). This function is two-parameter dependence of the mode of distribution amplitude \(A_{\text{mod}}\) on the relative entropy \(S^H_A\).

![Diagnostic diagram of sample condition](image)

**Fig. 4** Diagnostic diagram of sample condition (a); Data approximation by a linear trend (b, c)
The diagrams in Fig. 4 were constructed according to the beam testing data and show the numerical values of F-function arranged in zone I, in zone II, and in zone III. Zone I is typical for the most stages of beam loading. Formation of normal or diagonal force cracks with an opening width up to 0.3-0.5 mm, and increase in beam deflection will not substantially change the manner of arrangement of F-function numerical values. Prior to destruction (stress level in beam $\sigma/R = 0.95$), zone II appears. At this stage cracks penetrate in the construction, their opening width increases, and the beam deflection rises. Additional loading of the sample results in occurrence of zone III. Occurrence of main cracks is characteristic of zone III, beam deformations grow nonlinearly, and compression area concrete starts to deteriorate. The successive transition from zone I to zone II and then to zone III is characterized by change in a slope angle of linear relationship (4) whereby the approximation of numerical values of F-function takes place.

$$y = A + Bx$$

The slope coefficient of straight line “B” of the linear dependence (4) changes its numerical values from positive values (zone I) to negative ones (zone II and zone III); in this case the slope angle of linear dependence can vary by 90° and more. Further construction operation at the given level of loading will result in its destruction. Thus, use of the informational statistical criterion obtained through application of the AE method allows for estimating the accumulation of damages in the course of construction service, and for defining occurrence of the limit state beforehand.

6. Main conclusions

- The performed in-situ tests of the crane trestle of the Sayano-Shushenskaya Hydro using the AE method have allowed for making a conclusion that the crane trestle structures have no defects and the crane trestle is in operating condition. To estimate the crane trestle constructions condition, scientific hypotheses based on the Kaiser effect and on estimation of the AE events flow have been accepted.
- The technique for estimation of accumulation of damages in building constructions during their operation has been developed that allows for defining occurrence of structural damage beforehand. Results of the studies conducted are useful in monitoring of the critical constructions.

References
