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Technical Operation of Industrial Buildings on Risk Assessment

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Abstract. The object of the given research is the method to control technical operation of industrial buildings. The method is based on examining the technical state of structures and determining the damage from various scenarios of their damages. The survey results are presented as zoning maps of technical state of structures. Further, a damage map is drawn taking into account material and social losses from possible accidents. The damage areas are found for each accident scenario. These maps are applied to the building plan to get zoning according to the priority for repairing. An example of drawing these maps to control the technical operation of an industrial building is given. It is shown that survey errors can be of two types. Errors that consist in the wrong category definition of the technical structural state result in accidents or unnecessary costs for reinforcing structures. To take into ac-count possible survey errors, indicators to be used in specialized organization or maintenance service evaluations are proposed. An example of a quantitative assessment of accident risks is given taking into account inspection and technical operation errors. The technical result is to increase the operational reliability of buildings and reduce the risk of damage in case of possible construction accidents.

INTRODUCTION

A well-known method for assessing the technical state of buildings and structures according to current standards [1-6] includes (i) visual and instrumental examination of structures, (ii) field examination of environment operating parameters, (iii) testing material characteristics, (iv) specification of loads and impacts on structural elements, (v) verification calculations and development of measures to restore structural operating state. As a result of the survey, structural defects and damages are established, the degree of their bearing capacity loss is determined as a percentage to the initial standard state, and, on the basis of this, the category of the technical structural state is established (standard, operating, limited operating and accidental) Then, the sequence of measures for structure restoration is developed and the technical structural operation is controlled according to the priority of the degree of bearing capacity loss of structures, i.e. depending on the category of their technical state.

The disadvantages of this method are as follows:

1. The lack of standards to classify various structures as the established categories of the technical state; the list of values defining the decrease in the bearing capacity, in percentage, and corresponding to the categories of the technical state: standard, operating, limited operating and accidental. Generally, the resolution of this issue is the competence of an expert, i.e. the dependence on his knowledge and experience. The lack of experience can lead to errors both in assessing the technical state and in the content, cost and sequence of restoration measures (repairs and reinforcements).

For example, actual categorization of structures in accordance with their technical state shows 60 % of buildings in operating state; 35 % in limited operating state and 5 % in accidental state. Based on the survey, 60 % of

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structures were found to be in operating state; 40 % were in limited operating state and there were 0% of structures in accidental state, respectively. Because of such a survey error, a facility owner is threatened with accidents and an expert is subject to criminal sanctions. Such an error in statistical acceptance control is referred to as fictitious acceptance of batch or consumer risk [7]. To assess the risk of survey errors, the level of expert organization is proposed to be evaluated according to the indicators given below.

In other cases, actual categorization of structures in accordance with their technical state shows 60 % of structures in operating state; 40 % in limited operating state and 0% in accidental state, respectively. The results of the survey revealed that 60% of structures are in operating state; 35 % are in limited operating state and 5 % are in accidental state. This error results in unnecessary expenses for strengthening (replacement) of structures, or in the interruption in the operation of a facility and financial losses of an owner. In the procedure of statistical acceptance control, such an error is referred as to fictitious rejection of batch or manufacturer risk [7]. Since a qualified maintenance service can detect this error, to assess the risk of repair errors requires assessing both the risk of a survey error and the level of the facility maintenance service according to the indicators given below.

Thus, the risks of errors made in survey data cause significant economic and social (in the event of death or injury to people) losses and should be taken into account when operating buildings and structures.

2. When scheduling phases for maintenance work by technical state categories, risks and damages of structural failures for various scenarios of their development are not taken into account. In addition, the customer of the survey is often limited in financial resources (especially during local and global economic crises), and is forced to carry out the survey and maintenance in phases, without considering the actual state of a building as a whole and potential risks of construction accidents.

Roof repairing, for instance, reduces the risk of roof element collapse, usually within the area of a roof element or 1–2 column spaces in one span. At the same time, the delay in strengthening of such critical structures as columns increases the risk of larger accidents in the cargo area of all structures resting on this column (two column spaces in two adjacent spans). Nevertheless, possible damages from loss of equipment, injury and/or death of people in the area of the collapse should also be taken into account. A larger (in terms of the collapse area) accident at the storage area in terms of damage is likely to be insignificant in comparison with a local collapse in the area of industrial concentration of people and expensive technological equipment.

DESCRIPTION OF THE PROPOSED METHOD

Technical operation of a building is usually performed in compliance with the actual technical state which is shown to be determined with errors during a periodical survey. On the other hand, the violation of operational regulations may result from a facility owner's ignoring the survey results, the timetable and the required scope of the survey. Poor-quality repair or reinforcement performed because of the deficiencies in the maintenance service may also increase the risk of an accident.

The proposed method to control technical operation of buildings and structures is to perform a standard survey of the technical state of a building or structure resulting in the risk calculations for each local scenario of structural collapse and to build various types of risk maps for risk-oriented management of the technical state of buildings and structures. Moreover, the risks of accidents are determined taking into account the risks of errors in investigation and technical operation that can be assigned according to formalized rules.

To assess the risk of survey errors, the following indicators of the level of expert organization are estimated: 1) engineering and technical personnel (group E1) – compliance of personnel qualification; periodic improvement of employees' qualifications; 2) material and technical base (group E2) – availability of premises and office equipment; availability of verified measuring instruments, the level of metrological support; availability of certified laboratories for control and testing; level of information support; 3) reliability and reputation (group E3) – compliance of the work performed, conclusions and reports with regulation requirements; availability of a certified quality management system; work experience, geography of the work performed; customer satisfaction (by the number of lawsuits). The assessment is carried out with expert-based method providing a generalized indicator of an expert organization activity ranging from 0 to 1. The final assessment is proposed to be determined with respect to the weight coefficients:

$$E = 0.4\times E_1 + 0.3\times E_2 + 0.3\times E_3 \tag{1}$$

To assess the risk of technical operation errors, the following performance efficiency indicators of the operation service are estimated: compliance with the personnel qualifications; advanced professional training of employees; metrological support of maintenance procedures; compliance of the equipment with the operation quality requirements; availability of a maintenance program with an indication of the frequency and volume; availability of programs, techniques and regulations for work performance; completeness of documentation of procedures; availability of quality policy and good quality motivation system; the number of production stops due to the fault of the shop operation service; conducting internal audits of the service efficiency. Operation service evaluation is carried out with expert-based method to find a generalized indicator as an arithmetic average ac-cording to estimated variables ranging from 0 to 1.

To formalize an expert's view and increase the consistency of expert assessments rounded to five-hundredths, decision rules have been proposed [8] (Table). Applying standard judgments on one of three criteria depends on the type of indicator being assessed. For example, the personnel qualification correspondence may amount to 3/4 of the potential (three out of four employees correspond) – the estimate of 0.75. Internal audits may be irregular given the periodicity is regulated in the operational documentation by the judgment "documented and partially implemented" and the estimate of 0.70.

TABLE 1. Decision rules of expert judgement.

Expert judgement	Standard judgments on criteria correspondence between		
0.90 ... 1.00	Established requirements	Scale of application	Documentation and implementation
0.65 ... 0.85	Apparent correspondence (excellent)	Full potential (results)	Documented and being implemented
0.40 ... 0.60	High correspondence (good)	Nearly 3/4 of the potential (results)	Documented and partially being implemented
0.15 ... 0.35	Average correspondence (satisfactory)	Nearly 1/2 of the potential (results)	Not documented and partially being implemented
0.00 ... 0.10	Low correspondence (unsatisfactory)	Nearly 1/4 of the potential (results)	Not documented and not being almost implemented

In view of the above, the proposed method for controlling technical operation of a building or structure is reduced to the sequential implementation of the following stages.

1. Building survey in accordance with current regulations (GOST 31937-2011, SP 13-102-2003 etc.).
2. Identification of the error risk in a facility through expert evaluation.
3. Identification of the error risk during technical operation through facility operation service evaluation.
4. Financial risk mapping (damage map) specifying material and moral dam-age on the building plan based on production documentation, location of equipment and workplaces.
5. Spatial risk mapping on the building plan indicating the damage areas during the failure of load-bearing structures (columns, walls, beams, trusses, slabs) according to various scenarios of the accident development.
6. Zoning of load-bearing structures on the building plan by categories of the technical state based on survey results.
7. Zoning the sequence of repair and/or reinforcement of structures by over-laying damage, accident risk and technical state maps in the building plan for various types of load-bearing structures.
8. Calculations of the structural collapse probability according to various scenarios determined by well-known methods. Clarification of the sequence of repair/strengthening of structures of various types depending on the results of calculation.

The damage map is based on the production documentation depending on the cost of damaged technological equipment, unreleased products and the number of personnel in the collapsed area. The spatial risk map is drawn on the building plan to show areas with different values of risks in case of structural collapse according to different scenarios. Time sequence and technical content of the operational control of a building are linked to the risk maps mentioned.

Based on the drawn risk maps, possible accidental damages due to structural collapse are predicted, a sequence of measures to restore their operating state by the type of structures and sections of a building is designed. The latter can be as-signed taking into account the structural zoning (temperature, sedimentary, anti-seismic blocks) or technological features (production areas). Owing to scheduled operational inspections, examinations and expertise, defect and damage diagrams are drawn by a facility area and are applied to the maps of their zoning for possible risks of failure of certain structures. Once these maps are matched, a spatial state-based maintenance model is developed taking into account the “damage/accident damage” ratio at each local section of the facility’s structural system.

Damage maps are drawn separately for each type of a structure: columns, trusses (beams), floor slabs and wall panels. Type of construction depends on the type of the building’s structural system: frame, wall, mixed, etc. Risk maps are also made “layered” for each type of a structure. When analysed, the column damage map is applied to the column accident risk map. The maps of damage and accident risks for other types of structures are considered separately.

Resulting from the analysis of the overlaid maps, we obtain a strategy for maintenance and repair. The greater the damage and the higher the damage from an accident, the more intensive the maintenance activities are (in terms of content and time). Graduation in maintenance operation term and repair is visually marked with different colours (possibly in automatic mode). Thus, risk-oriented management of the technical state of buildings and structures is performed to provide minimum values of potential damage in case of possible structural failures.

APPLICATION OF THE METHOD PROPOSED

A production shop being a two-span one-storey building of a frame structural system with dimensions of 24×42 m in the axes is being examined. Reinforced concrete frame consists of columns, rafter beams and roof slabs with dimensions of 3×6 m. The arrangement of equipment with cost zoning as well as the localiza-tion of workshop personnel are shown in Figure 1.

Fig. 1 shows that the main equipment valued at 100 million rubles and operated by 10 employees is located in the А–Б span. Auxiliary equipment worth 18 million rubles and operated by 4 employees is located in the А–Б span. Permanent Accommodation Office (PAO) located in the workshop in the axes А–Б/1–2 is operated by 4 engineers. Since the staff work in 3 shifts, workers stay in the ad-ministrative building for 2 hours because of changing rooms, showers, a toilet, a canteen, rooms for engineers and meetings available there. Thus, the probability of their being in the workshop equals 22/24 and 2/24 in PAO, respectively.

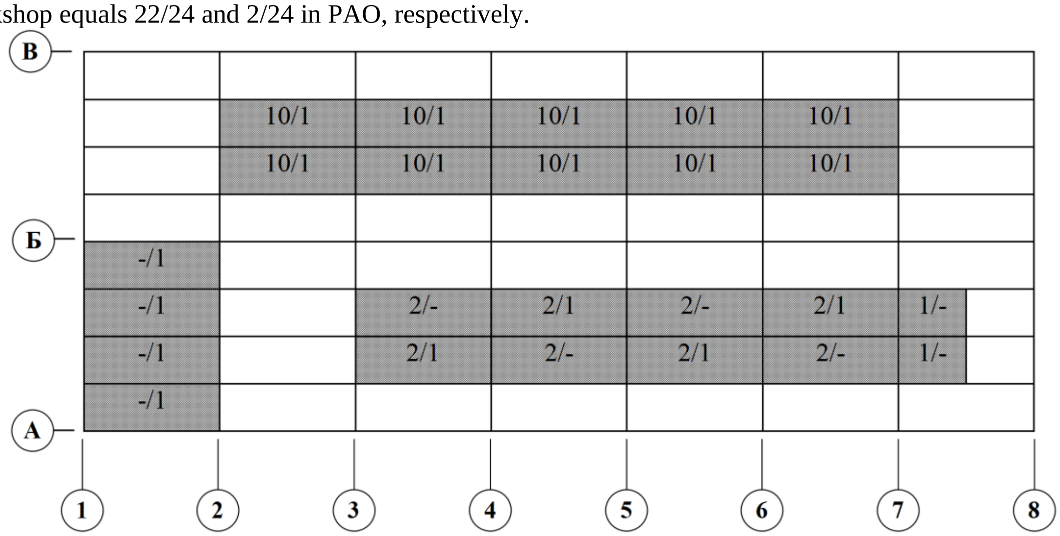

FIGURE 1. Equipment zoning and shop worker localization: in the numerator – equipment cost, million rubles, in the denominator – number of jobs.

Based on structural inspection analysis of the workshop, a map of the roof slab damage was drawn (Figure 2) depicting zones of varying technical states. The slabs were damaged only in the Б–В span because of the roof leakage. Soaked slabs are in operating state, those with slight corrosion of concrete and reinforcement are in limited operating state. Significant corrosion of concrete and working reinforcement indicates the accidental state of the slabs.

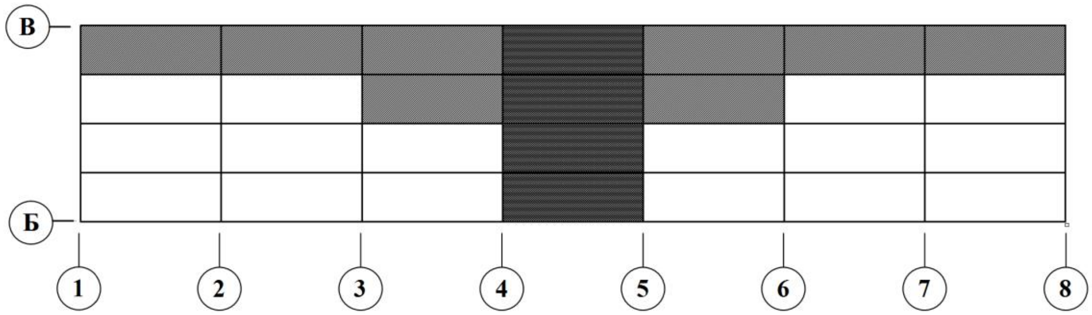

FIGURE 2. Slab zoning by technical state category: white panels – operating state; light grey panels – accidental state; dark grey panels – limited operating state.

Applying the damage map (Figure 2) to the map of possible damage during structural collapse in the Б–В span (Fig. 3), we obtain the span zoning according to the sequence of maintenance (Figure 4).

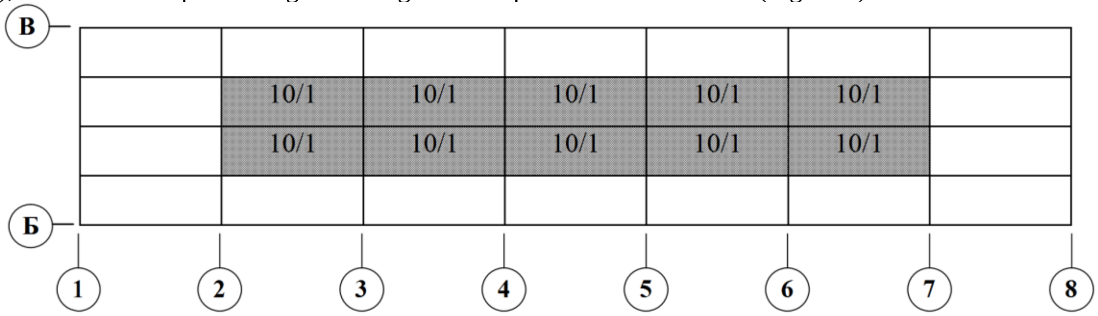

FIGURE 3. Damage map in case of span Б–В collapse.

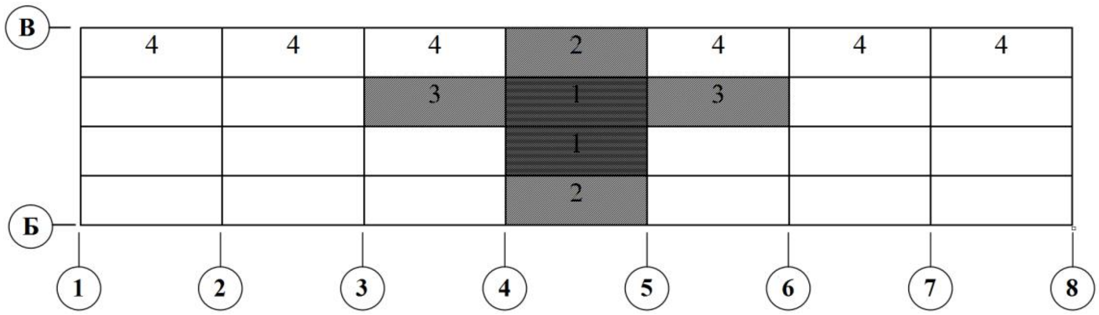

FIGURE 4. Span Б–В zoning according to the sequence of roof slab repair.

In the given example, the damage area during the damaged slab collapse coincides with that of these slabs (dropping slab dispersion is not provisionally taken into account). Given load-bearing structures of other types (columns, beams, trusses) are considered, the damage area will depend on the structural system. In this case, zoning of specified structures by technical state categories requires drawing the damage map (Figure 2), zoning the damage area, and then proceeding with drawing a map of possible damage and zoning according to the sequence of repair/reinforcement.

It follows from Figure 3 and Figure 4 that the collapse of damaged slabs in axes 4-5 will result in the failure of main equipment worth 20 million rubles, the eventual death of two workers and losses associated with unreleased products. In addition, exterior envelop opening caused by the collapse of 4 roof slabs can lead to de-frosting of the workshop heating system in winter.

RISK ANALYSIS

General relative economic damage from the i-th accident scenario caused by the load-bearing structure collapse:

$$U_i = T_i + c_{pt,i} \times L_i. \tag{2}$$

Relative economic damage index from the breakdown in technological process:

$$T_i = T_d / T_s, \tag{3}$$

where T_d – possible damage to technological process from the collapse of the area A_d; T_s – possible damage to technological process from the collapse of the whole building area A_s.

Possible damage to the technological process from the collapse of the entire workshop building (T_s), according to Figure 1, equals 118 million rubles. Losses from unreleased products, clearing and installation costs are not considered (provisionally). Possible damage to the technological process from the collapse of the area in the axes Б–В/4–5 (T_d) equals 20 million rubles.

Relative economic damage index from the breakdown in technological process during roof slab collapse is calculated by Eq. (3):

$$T_1 = 20 / 118 = 0/169.$$

Relative social damage index:

$$L_i = L_d / L_s. \tag{4}$$

Calculation of social damage index in relation to the frequency of people presence under the collapse zone:

$$L_d = \Sigma n_i \times t_i / 24, \tag{5}$$

where n_i – the number of people under the zone of possible collapse; t_i – time spent by people under the zone of possible collapse during a day, in hours; i – the number of people presence configurations in the collapse zone.

The social damage index in the roof slab collapse with respect to the time spent by workers in the workshop is:

$$L_d = 2 \times 22 / 24 = 1.83 \text{ people.}$$

When the entire building collapses, the social damage index is calculated depending on the frequency of people presence under the collapse zone:

$$L_s = n \times t / 24, \tag{6}$$

where n – total number of people in a building; t – time spent by people in a building during a day, in hours.

The maximum value of social damage index with respect to three-shift continuous work in the shop is:

$$L_s = 18 \times 24 / 24 = 18 \text{ people.}$$

Relative social damage index during the roof slab collapse by Eq. (4) is: $L_1 = 1.83/18 = 0.102$.

Social risk coefficient expressed in the ratio of the damage from human losses to damage caused to the technological process during the collapse of the entire building is:

$$c_{pt} = L_s \times VSL / T_s, \tag{7}$$

where L_s – social damage index; VSL – average cost of living; T_s – possible damage to the technological process from the entire building collapse.

According to calculations of the average cost of living by GDP ($ 27 893) in the Russian Federation and the average life expectancy (72.7 years), *VSL* is recommended to equal 4.0 million rubles for the Russian Federation [9]. Then the social risk coefficient is $c_{pt} = 18\times4 / 118 = 0.61$.

General relative economic damage from the roof slab collapse in the axes Б–В/4–5 by Eq. (2) is:

$$U_1 = 0.169 + 0.61\times0.102 = 0.231.$$

Suppose, the probability of accidental roof slab collapse $P_1 = 2\cdot10^{-4}$ in the local area Б–В/4–5 was determined according to one of the well-known methods [10–14]. Then the risk of an accident is determined by Eq. (8):

$$R_i = P_i\times U_i / (K_{ex}\times K_e), \tag{8}$$

where P_i – accident risk from the *i*-th accident scenario; U_i – accident damage from the *i*-th accident scenario; K_{ex} – incorrect rejection risk index; K_e –maintenance and repair risk index.

Once the coefficients $K_{ex} = 0.92$ and $K_{ex} = 0.95$ are expertly determined by the above indicators, the accident risk according to the scenario under consideration by Eq. (8) is:

$$R_1 = 2\times10^{-4}\times0.131 / (0.92\times0.95) = 0.30\times10^{-4}.$$

The final version of the sequence of repair and reinforcement is determined after such calculations performed for all types of dangerous structures.

CONCLUSION

The new method of technical operation control is applied to buildings and structures mainly for industrial purposes and designed to assess the technical structural state and organize operational control of buildings and structures. The technical result consists in increasing the operational reliability of buildings and structures and reducing the damage risk in case of possible construction accidents.

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