SPECIFIC FEATURES OF STANDARD INSPECTION OF ENGINEERING STRUCTURES IN MAJOR CITIES

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Abstract

Despite similarities in structural forms, design development, and construction methods, urban bridges differ substantially from highway bridges. Despite these differences, a uniform technical surveillance system is in use for both urban and highway bridges. Therefore significant modernization of the technical surveillance system is required, as well as application of advanced management methods for bridge maintenance using state-of-the-art information technologies.

In course of the implementation of the BMS “MOST” for the City of Moscow new inspection methodology aimed at recording the actual status of urban bridges, as well as assignment of necessary repairs for their elements had been developed. Specific features of the methodology include, first of all, an expandable catalog of standard elements enabling their differentiated description and the use of a special inspection scheme, which allows locating the standard element within a bridge.

Keywords: Urban bridges, Bridge management system, Standard inspection, Standard elements.

Despite similarities in structural forms, design development and construction methods urban bridges differ substantially from those for highway bridges. This is due to the integration of urban bridges into the city landscapes and the particularities of their operating conditions, as well as different kind of traffic, utility networks, decorative architectural details, and sanitary and environmental protection elements.

Despite these differences, a uniform technical surveillance system is in use for both urban and highway bridges. It consists of permanent, current and periodic inspections carried out on a regular basis. The main purpose of inspections is to ensure prompt identification of damages and to access of the scope of required repairs and seasonal maintenance. The objectives of bridge investigations include assessment of their condition state, load bearing capacity and durability, identification of causes of damages, assignments for further use and repair. According to the existing surveillance system the intervals of inspections are once every 5 to 10 years, regardless of the actual condition of a bridge.

Said system, implemented in the 1950-60s, is aimed at recording the real status of the structure and supporting current and seasonal repairs. All records are paper-based. This precludes the use of recent methods of data storage and processing, as well as efficient planning and optimization of the required resources for bridge operation and maintenance. Furthermore, the quality of inspections and the objectivity of conclusions and recommendations are entirely dependent on the qualifications and partiality of an inspector. The Customer is not in a position to control this system. Under the conditions of permanent shortage of funds, modernization of the existing surveillance system and the bridge management methods through the implementation of recent information technologies is required.

The example of such implementation is the use of a novel type of inspection called “diagnostics”, which was introduced in 1996 for federal highways in Russia. The procedure of diagnostics is similar to a standard inspection. When carrying out the diagnostics, the inventory data of a facility and the condition of its elements are assessed and recorded, and the results are entered into an electronic database "MONSTR".

The need for modernization of the technical surveillance system is especially evident when one considers that bridge inspections had virtually not been carried out in the past 15 years. The main reason for that is modification of the objectives and tasks of investigations (special inspection). Instead, a so-called “pre-design investigation” is performed as an integral part of surveys and studies for the development of bridge's repair design. These are financed with funds allocated for major bridge repairs. Pre-design investigation is aimed specifically for the purpose of developing recommendations relating to design and technological solutions for major repairs. The conventional inspections had been given up due to the vague character of their objectives against the background of immense expenses on the scale of an entire bridge network, and also due to the fact that no detailed investigation is needed in order to include a bridge in a repair plan (a periodic inspection by a qualified inspector is sufficient).

In 2001-2002, the Bridge Management System (BMS) for the city of Moscow (Kuznetsov et al., 2003) had been implemented. Originally, it was planned to use FHWA package “Points” (Robert et al, 2003) as a basic software product for the BMS development. However, the limited range of standard elements (CoRe Elements) and the fact that the Points software and its’ analogues focus primarily on highway bridges, does not permit the consideration of the specific structural and operational features of urban bridges and similar facilities, as mentioned above. Therefore, the developers had to expand and modify some of the methods used for bridge structure analyses, standard inspection, cost prediction and optimization.

The methodology proposed by the authors refers primarily to expansion and customization of the nomenclature of standard elements (SE) by means of introduction of new types of the elements determining the main characteristics of structures (load bearing capacity, durability, safety, architectural features, etc. – see Table 1). Other important aspects of the suggested methodology, essential for describing a bridge and using inspection results, are the applicability of a SE catalogue and SE location identification by prior development of an inspection scheme (Yekimov et al., 2003).

This new methodological approach accounts for specific structural properties of a bridge and prescribes appropriate technologies and types of repair (strengthening, sanitation, restoration of lost volumes, secondary protection and preventive measures, etc.), thereby controlling the main characteristics of bridge structures (functionality, durability, including secondary protection, architectural features) in the process of bridge operation.

In order to implement the given concept, four main types of SE have been incorporated in the BMS General Catalogue:

- Functional standard element describing a part of a bridge or a structure from the viewpoint of its functional purpose and specific structural form (beam, slab, column, parapet, etc.);
- Standard material describing the material of which a functional SE is made (reinforced concrete, steel, cast iron, wood, plastic, etc.);
- Standard connection, describing joints, attachments, structural linkage and connections of a functional SE (riveted, bolted and pin joints, concrete joints and monolithic concrete structures, etc.).
- Standard protective and decorative coating applied over a functional SE or material for the purpose of secondary protection against corrosion or for improving the architectural appearance (waterproofing insulation, painting, coating with tiles, etc.).

In any case, only a structure or part of a structure may be designated as a SE, which:

- can be an object for repair of rehabilitative or preventive character, i.e., a standard element is normally a prefabricated or an erection element of a structure;
- is accessible for external examination and whose location can be identified on a facility and shown in an unambiguous manner on an inspection scheme. An exception would be an entire structure inaccessible for maintenance or parts of a structure, the wear of which can adversely affect the characteristics of a bridge (i.e., safety of operation, load bearing capacity, durability and external appearance). Their condition can be assessed on a basis of indirect indicators.

Only one category of condition can be assigned to a standard element. If any local damage is present it is permissible to add other standard elements with dimensions corresponding to the scope of local repair work.

Furthermore, the catalogue allows for the associated SE ("T" track elements, cables, manifolds, etc.), which are used to calculate additional work associated with bridge repair, such as relocation of utility lines and traffic control, and its' cost. Since maintenance of such elements is carried out by independent agencies, no assessment of their condition is made in the course of standard inspections.

Due to the use of the abovementioned SE, there is a possibility for comprehensive description of a bridge, by representing it in the form of multi-level tree-like structure of standard elements. This allows the consideration, for the purpose of forecasting and planning, the structural environment and quality of SE, as well as specific technological features and nomenclature of repair work.

Table 1: Relations between the types of standard elements with types of work and assessment of their condition

Type of standard element	Assessment of condition state	Type of repair work
Standard element	By functional properties, including load bearing capacity, stability and safety	Strengthening (reinforcement), straightening, and regulation of forces
Standard joint		Strengthening (reinforcement) or replacement of joints, provision of safety reserve
Standard material	By durability, architectural value	Restoration of damaged surfaces and lost volumes (e.g., replacement of protective coating on concrete, repair of reinforced concrete, local asphalt-concrete repairs etc.), restoration or improvement of the quality of primary corrosion protection materials (penetration, impregnation, hydrophobization, deposition, etc.), repair and maintenance measures of preventive character
Standard protective/ decorative coating		Provision or restoration of secondary corrosion protection, painting, restoration or replacement of tiling, seasonal maintenance work

Standard materials, joints and protective / decorative coatings are closely interrelated with the "parent" (functional) SE by the software, but they can be considered, and are actually considered in a number of cases, as separate and independent elements.

Since a SE is an object for certain repair or maintenance work, its description has, first of all, a technological meaning. This allows the usage of a limited set of SE for the description of /for the structuring of not only bridges, but also other facilities of transport infrastructure of the City of Moscow (pedestrian underpasses tunnels, parking lots, embankments, etc.), i.e., to expand substantially the range of application of the management system (from 390 up to 1100 facilities). For example, the SE "Reinforced Slab" is used for description of slabs for bridge spans, bridge decks, tunnel roofs, pedestrian passages etc.

The general catalogue of Moscow BMS now describes 220 SE. For comparison, in analogous systems, the number of SE does not exceed 70 to 100 types. This had led to justified concerns about the excessive increase in labor intensity of inspections and decrease in calculation speed in course of use of Moscow BMS. The developers of the system have paid special attention to this problem and made efforts to ensure that an inspection of an average bridge could be carried out within 2 to 3 hours. This objective has been accomplished by application of the following principles:

- ✓ Division of a bridge into elements (structuring) should be simple and comprehensible; SE should be reasonably located within a given area (structure);
- ✓ The methodology of inspection should be based on conventional and comprehensible investigations and condition assessments, monitoring (observations over extended periods of time), rapid analyses and simple field testing methods;

- ✓ The methodology should not require from the inspector the solution of complex quantitative problems of mutual effects of the structural environment, spatial work, assessment of load bearing capacity, etc.

A five-point system has been adopted for assessment of the condition of a SE, with basic categories corresponding to major types of repair work (preventive, current and major repairs). This approach permits an inspector to assess the condition based on the questionnaire like: “Yes, No, May be”, which eliminates to some extent the subjectivity of assessments, because most disputable judgments refer to intermediate conditions of structural elements between definitely good and definitely poor. In his case, a doubtful or uncertain condition may be rated as Category 2. At the same time, from the viewpoint of further data processing and prediction on the basis of a BMS, three categories are not sufficient. For this purpose, two intermediate categories have been added: 1.5 and 2.5, corresponding to situations when existing damages of structures have not reached the level of basic categories 2 and 3. From the viewpoint of automated management procedures, Category 1.5 implies the need for planning of preventive repair work, and Category 2.5 is the lower limit for permissible wear and a signal for including a given structure in the list of most urgent remedial actions (Table 3). It should be pointed out that the term “permissible” refers to such a degree of wear, which allows the use of a given element with the required degree of safety during the period until the commencement of repair work. Depending on the type of SE, this period varies from 2 to 14 years.

The criteria for assessment of the degree of functional defects are different for each element. For example, for bearing elements – bridge span beams and support elements – the condition is assessed on the basis of any hazardous damages affecting their strength (cracks, deflections) and deformation, which indicate a decrease in or insufficiency of the load bearing capacity. For reinforced concrete elements, the degree and intensity of structural abnormalities and reinforcement steel corrosion are assessed. If the destruction of concrete (e.g., within a compression zone) or corrosion of reinforcement steel under tension result in functional disturbance of a bearing structure (for example, in a decrease in the bearing capacity), then this fact should be taken into account when assessing a bearing element. One of the criteria for evaluating a disturbance of a function of the bridge deck coating or pedestrian walkways is reduced speed of traffic caused by the inadequate coating. For waterproofing insulation, a 100% wear corresponds to a condition, in which it has exhausted all its functional properties, and an inspector observes leakage of water through cracks and joins in slabs.

An important aspect of the methodology of standard inspection is the fact that despite its stringent formalization and the need for assessment from the viewpoint of functional suitability of an element, an inspector is free to use different assessment criteria, reflecting thereby various aspects used for decision making with respect to repair of a bridge. Depending on particular circumstances, an inspector may assess the condition of elements from the following viewpoints:

- External appearance of an element;
- Degree of wear permissibility;
- Need for certain types of repair work;
- Presence of certain damage.

A corresponding description and standards are contained in the classifiers of the General Catalogue.

Table 3 provides an example of classification of different conditions of a standard element – Reinforced Concrete – based on different criteria.

In case of inaccessibility of an element in the course of standard inspection, for example, a bridge deck slab covered from the bottom by a suspended ceiling, an assessment is made by BMS software on the basis of the rated service life and a deterioration model of a standard element adjusted to take into consideration specific features of a given bridge (Eynutin et al., 2004).

As has been noted earlier, the methodology of standard inspection does not include conventional assessment of the condition of elements with respect to the effect of the identified faults on the load bearing capacity and durability of a bridge (*VSN 4-81*, 1981, *Instruction on diagnostic of highway bridge structure*, 1999). This is the purpose of a special inspection or pre-design investigation, which are carried out in conformity with the applicable standards and using special means for diagnostics, testing methods and computations (*Methodological recommendations for maintenance of highway bridges*, 1999, *SNiP Norm 3.06.07-86*, 1988)

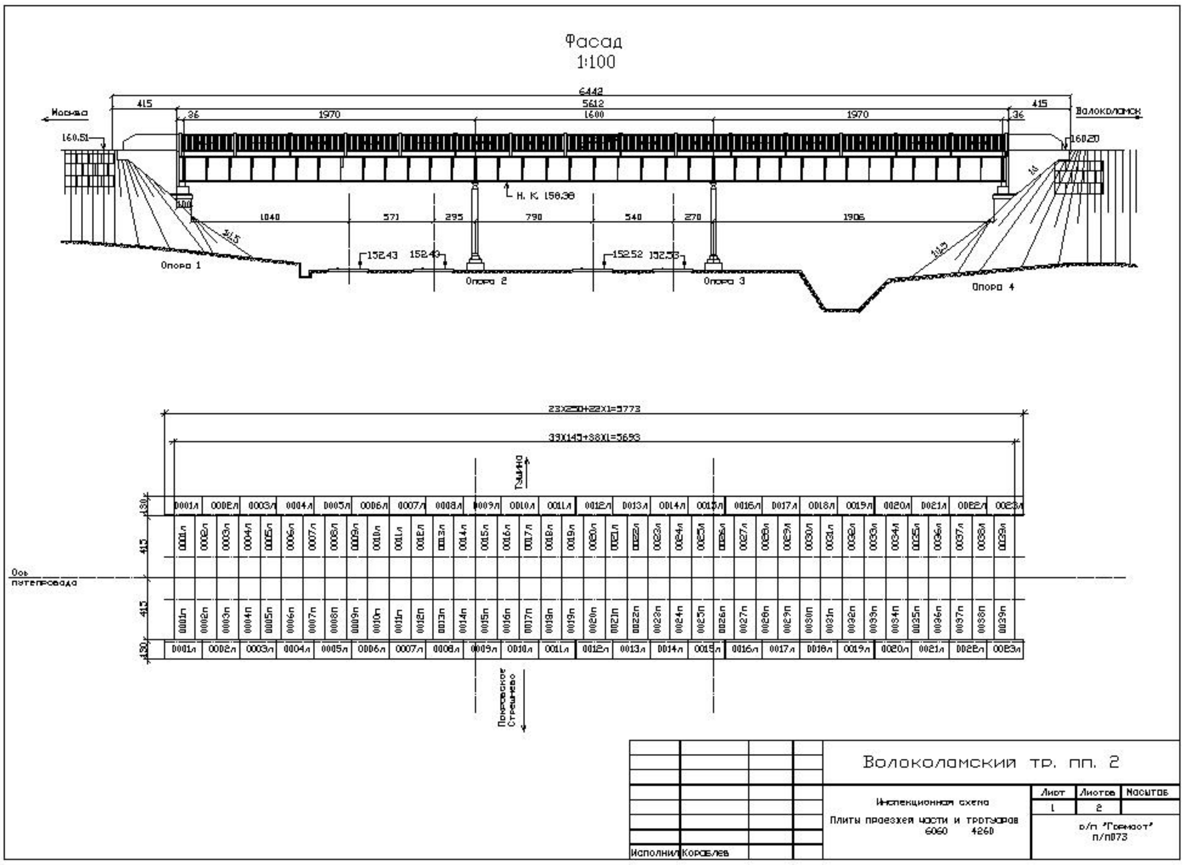

Figure1. The example of inspection scheme of the bridge

In the process of preparations for a standard inspection, the bridge is divided (structured) into standard elements, structural groups and major components. An inspector is guided by his knowledge of the bridge design, internal interrelations and technology of repair work, as well as, by the standard elements catalogue. This four-tier structuring permits an inspector to simplify the use of the “repair rules” and automate the cost estimation of restoration of parts and components taking into account the structural and associated environment. The results of such structuring are reflected in the inspection scheme, which becomes a “map” of elements’ conditions (see Figure1). This presentation can be used in the future for visualization of the bridge condition.

Table 3: Signs of different condition categories of a SE – Reinforced Concrete

Condition state	Assessment of external appearance	Degree of wear	External signs	Type of required repair
1	Good	Less than 10%	Satisfactory appearance, virtually no damage and defects (permissible are whitish film on the surface, minor construction faults up to 5mm deep, technological cracks without signs of corrosion in concrete).	Scheduled maintenance work
1.5	Not very good	10-20%		Preventive maintenance
2	Poor	20-40%	Unsatisfactory appearance, 1. insufficient thickness of protective layer in concrete (reinforcement is visible through concrete layer), 2. surface destruction (network of surface cracks), 3. cracks with signs of reinforcement damage, 4. deposition of concrete leaching products on the surface, stalactites and stalagmites, 5. surface frost destruction of concrete protective layer,	Current (local) repairs

			weathering of coarse aggregate down to a depth of 1cm in thin-wall elements (up to 12cm thick), 6. individual corrosion cracks up to 0.5mm, 7. reduced bearing capacity of individual reinforcement bars by up to 25%, 8. lamination and chipping of concrete protective layer along individual corroded reinforcement bars; lamination and separation of "patches", etc., 9. frost destruction and corrosive separation of concrete protective layer with exposure of reinforcement net in elements more than 12cm thick.	
2,5	Very poor	40-60%		Major repair
3	Unaccept-able	60-80%	Objectionable appearance, 1. reduction in the bearing capacity of reinforcement by over 25%, 2. reduced strength of concrete (loosening) and frost	Replacement or repair

			destruction of concrete behind reinforcement (r-bars are exposed) in massive elements, 3. concrete destruction accompanied by seepage of water through concrete, 4. exposure of reinforcement net in thin-wall elements (12cm thick and less), 5. deep destruction, moistening and swelling of destruction products, chipping of concrete and repair layers, 6. complete destruction of concrete walls and partitions with exposure of internal cavities in hollow elements, 7. crushing and chipping of concrete from reinforcement framework and grid, 8. concrete destruction (loosening) by frost and corrosion in compressed areas and at pre-stressed bars.	

Note: The wear is indicated in the Table as percentage of the maximum permissible wear degree for a given element

When developing an inspection scheme, complex (integrated) facilities and multi-level overpasses are considered as a set of individual facilities (transit viaducts, garage viaducts, up and down ramp viaducts, etc.).

There are two types of standard inspection: primary and regular. In the course of a primary inspection, a passport of a bridge is drawn up, an inspection scheme developed and the inspection itself carried out (examination of a structure and filling-in of relevant forms). In the course of a regular inspection, only examination and filling-in of forms are performed. Inspection schemes and forms are stored in the database and retrieved by an inspector prior to the inspection.

The methodology of standard inspection has been tested in 2002-2004 at the most of structures in Moscow (about 1200 bridges, pedestrian underpasses, embankments, etc.) Based on the inspection results, repair plans were developed for the period of 2005-2006 and, which is especially important, diagnostics plans and measures aimed at preventing emergency situations. It should be also pointed out that during the previous years less than 30 special bridge inspections and about 130 regular inspections (i.e., about 30% of all bridges) were carried out annually. In general, a standard inspection turned out to be significantly more productive as compared with examinations carried out within the framework of conventional technical surveillance. Within two years, the use of standard inspections allowed to make up for the long-time lag in the assessment and control of condition state of infrastructure in Moscow city. In addition, the introduction of the standard inspection procedures eliminates the need for periodic examinations and investigations not related to accidents and emergencies, and allows to carry out special inspections only on the basis of the BMS prescriptions, as well as in conformity with the adopted repair plans (pre-design investigations). This will result in the following:

- It will ensure regular and systematic character of technical surveillance;
- It will make assessments of bridge conditions more informative and objective;
- It will ensure in a timely and reliable monitoring of 100% of supervised facilities.

According to quantitative indicators, most of the bridge facilities in Moscow are of minor and medium size. Large bridges account for about 25% of all bridge facilities (see Figure 2).

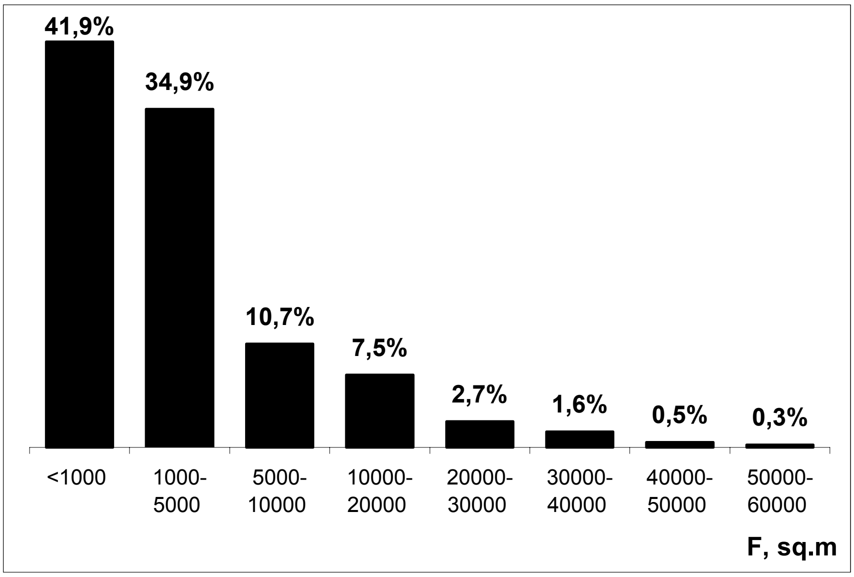

Figure 2. “By size” distribution of bridge facilities in Moscow

Based on the results of an inspection, the number of standard elements in different bridges is from 5 to 13,000 (see Figure 3). A statistical analysis has indicated that the number of standard elements is more dependent on structural features of a bridge than on its surface area. The relationship between the bridge area and the number of standard elements varies within a wide range and has a low correlation factor. At the same time, for an approximate assessment we may assume that the number of standard elements is on average 0.9±0.2 SE/m^2 for assembled steel and reinforced concrete bridges and 0.13±0.02 SE/m^2 for monolithic concrete bridges and tunnels. Minor bridges with a total area of up to 200 m^2, and especially pedestrian bridges with a large number of “non-bridge” elements (such as glazing, towers with staircases, ramps for wheelchairs and baby carriages), have a very large number of standard elements: it might reach 7.5±1.0 SE/m^2.

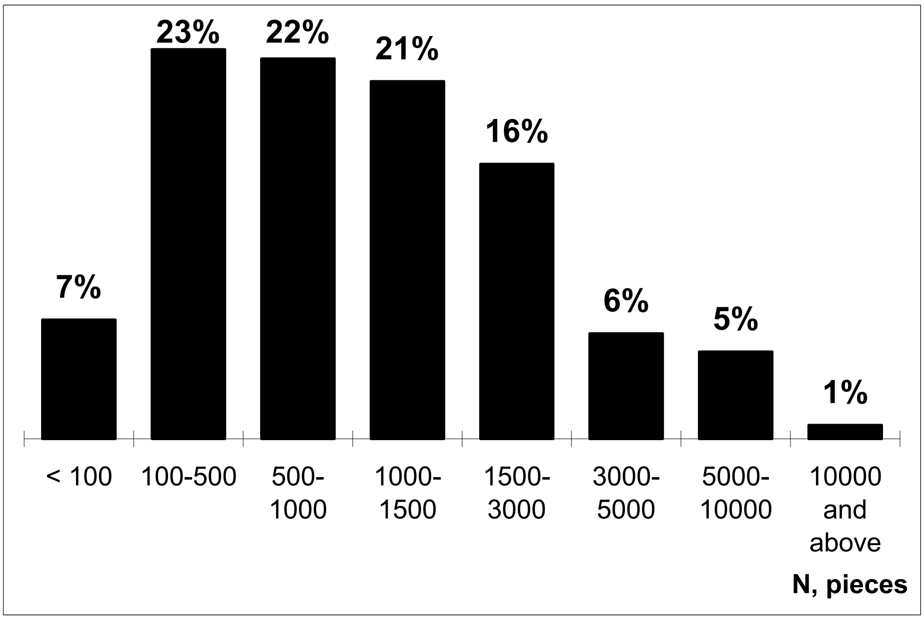

Figure 3. “By # of SE” distribution of bridge facilities in Moscow

Standard inspections were carried out by special trained engineers with previous experience in bridge investigations. In the process of first standard inspections, training was repeatable and special attention was paid to analysis of most common mistakes.

Preparation of inspection schemes included archive studies, reconnaissance of facilities, drafting with subsequent clarification of drawings and approval of the prepared schemes. This last phase of work was most time-consuming out of all types of work relating to primary inspections. On average, 32 man-hours per inspection scheme were required, equivalent to 0.0071 man-hour/m^2 of a bridge. This exceeded multifold the time required for fieldwork. However, since inspection schemes are prepared only once, i.e. during primary inspection, and are stored in the database for subsequent use during many years, the abovementioned time requirement has no substantial effect on the overall number of working hours.

In the field, an inspector carried out visual examination of a structure according to the relevant inspection scheme and filled out universal form (see Table 4). If required, measurements were made to specify geometrical parameters of standard elements. During an initial period, inspectors used classifiers of condition from the BMS General Catalogue when visiting the bridges, but as the skills were gained the use of reference materials became redundant.

In addition to assessment of the condition, an inspector indicated in the form the category of accessibility of an element and, if urgent repairs were required, type of repair work according to the catalogue. Indication of repair work type in the database is perceived by the BMS as an instruction for carrying out repairs and is included in the list of top-priority work. The category of accessibility is used in the cost estimates when planning additional expenses for construction of temporary structures and devices, as well as traffic control measures.

Table 4: An example of a filled-in universal form

Subject	Andreyevsky Bridge		Element		No. on diagram	Span 4 between beams 2 & 3						
Type of SE	Description	Cat. No.	Unit	Qty		Condition					Access	Repair
						1	1.5	2	2.5	3		
Element	Steel beam	6020	m	12	0005	✓					2	-
Material	Steel	1060	m^2	30	0005	✓					2	-
Joint	Bolted	2000	pcs.	60	0005		✓				2	1051
Protective / decorative coating	Paint	3010	m^2	30	0005			✓			2	1119
Communications	None											

The man-hour requirement for the field period of a standard inspection had been measured as time spent by an inspector on fieldwork. This measurement did not include the time required to reach a bridge. A set of 375 facilities with a total area of 1.64 million m^2 was studied. The total number of standard elements considered exceeded 150,000.

Based on these time measurements we may assert that the time required for an inspection is directly related/directly proportional to the number of standard elements (see Figure 5), which can be approximated by the following formula (correlation factor = 0.89):

$$\mathbf{T=6\ N*10^{-4}+A}$$

where N is the number of standard elements.

The effect of the area of a bridge on the time required for inspection (see Figure 6) can be expressed as follows (correlation factor = 0.76):

$$\mathbf{T=F*10^{-4}+A}$$

where F is the total area of a bridge in m^2.

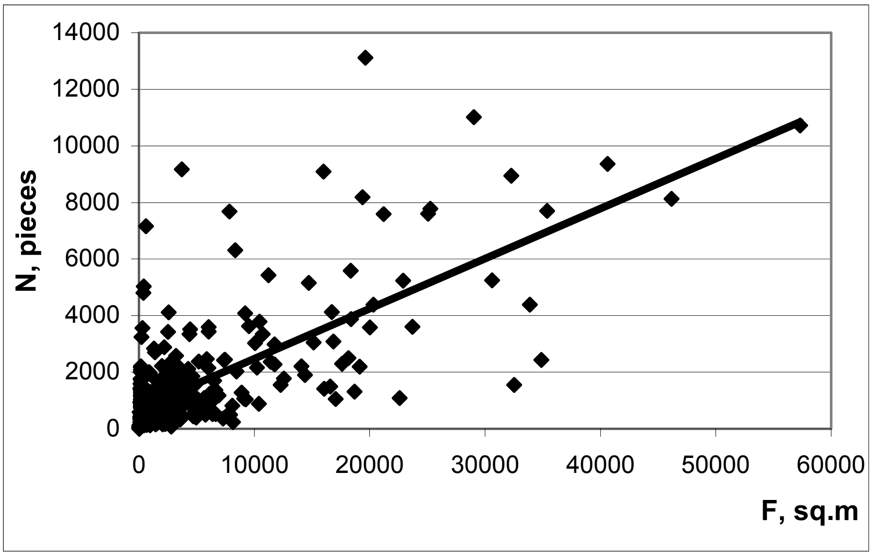

Figure 4. The relationship between the bridge area and the number of standard elements

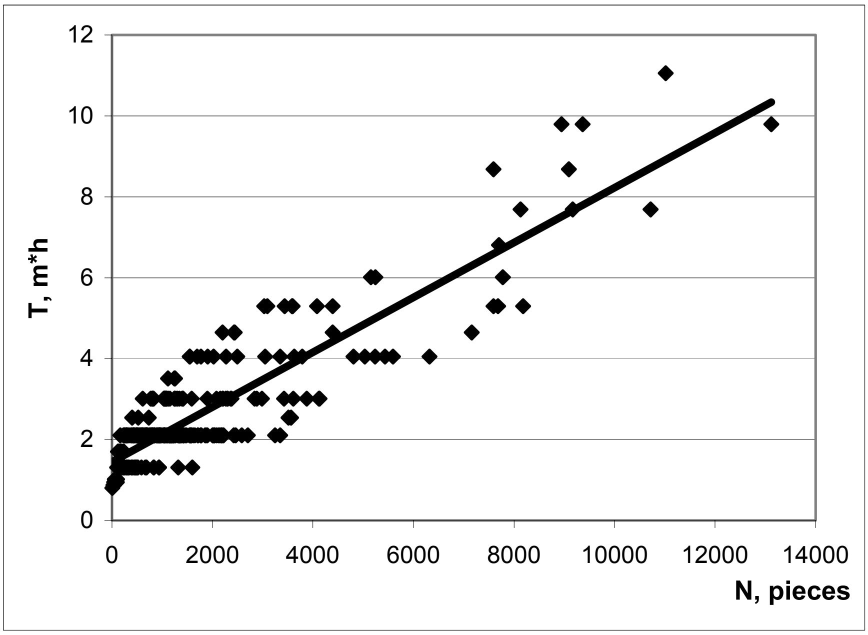

Figure 5. The relationship between the inspection time and the number of standard elements

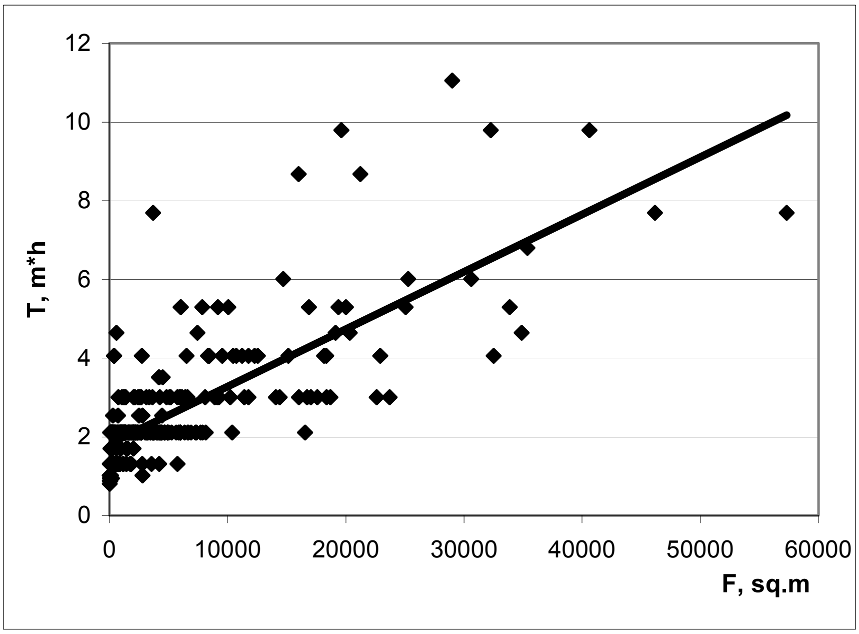

Figure 6. The relationship between the inspection time and the number of standard elements

In the above formula, A is a constant assumed to be 1.0 for minor bridges, 1.5 for medium-size bridges and 2.0 for large bridges.

The scatter of points (see Figures 4 and 5) is attributed to differences in the condition state of bridges, to accessibility to SE, as well as to individual skills of inspectors.

The effect of the condition of an element on the man-hour requirement, expressed as an index of the technical condition [1], is not of well-defined character and is expressed as an area, rather than as a curve (see Figure 7). This is probably attributable to the fact that during the first inspection forms had to be filled in for all elements, independently of their actual condition. Despite this fact, a certain tendency toward higher man-hour requirement for standard inspection is observed with deterioration of overall condition of structures. During successive inspections, when the intact elements are considered by the system by default as Category 1, this relationship can have clearer forms.

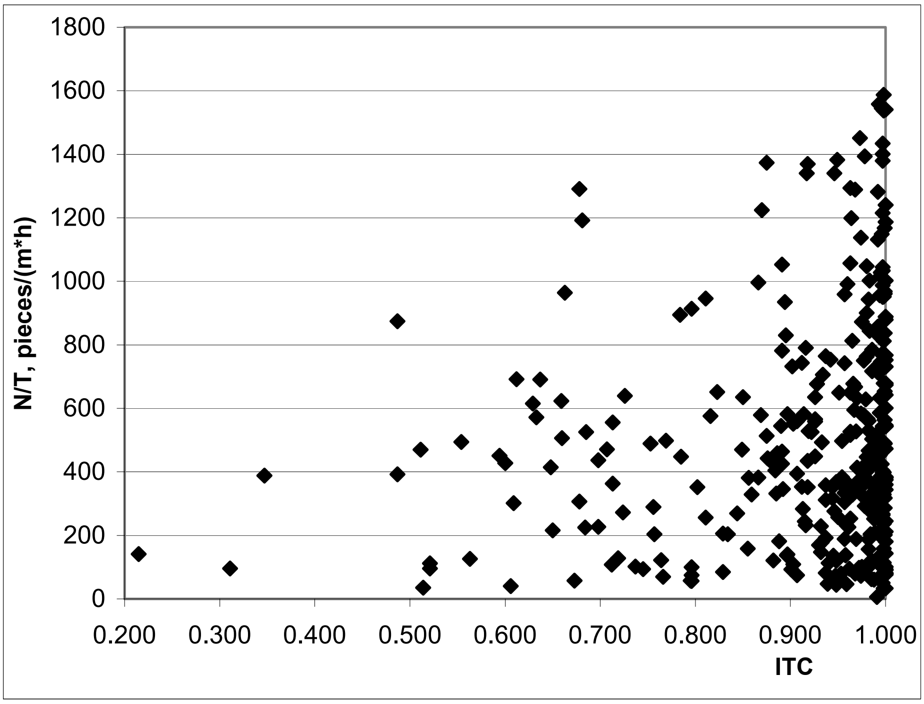

Figure 7. The relationship between the inspection time and the index of the technical condition of the bridge (ITC)

In general, based on the initial experience gained, we can make a statement that the man-hour requirement for fieldwork during standard inspections averages 0.00052 man-hour/m^2. In other words, an inspector is able to inspect 1920±80 m^2 of a bridge per one hour of work.

When assessing the total man-hour requirement for a standard inspection, provided that it is carried out once every two years, the following ratio should be used:

$$\mathbf{T=2*T_P/t+T_R}$$

where $\mathbf{T_P}$ is the man-hour requirement for a primary inspection, including preparation of an inspection scheme,

t is an estimated service life of a bridge;

$\mathbf{T_R}$ the time required for a regular inspection.

The values of $\mathbf{T_R}$ and $\mathbf{T_P}$ include a field period, the time spent by an inspector to reach a bridge and return to the office, as well as the time required for entering the inspection results into the BMS database. The average time required today for a standard inspection in Moscow is 6.63 hours with an average area of an inspected bridge of 4,486 m^2, i.e., 0.00148 man-hour/m^2.

An analysis of the time requirement has indicated that standard inspection is comparable with respect to the man-hour requirement with current and periodic examinations, and that its substitution for the examinations would not result in a significant increase in resources spent on technical surveillance.

In addition to the tabulated forms, inspection results can be presented as histograms of distribution of the number of standard elements in different conditions. Such histograms permitting a prompt assessment (visualization) of the condition of a bridge and types of repair work by the form of distribution, depending on the location and the relative value of the distribution maximum. In addition, histograms make it possible to monitor the quality of inspections, because their serrated or discrete configuration is in most cases a consequence of mistakes in the condition assessments or, less frequently, an underestimation by the inspector of the intermediate conditions of elements, i.e. "1.5" and "2.5".

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