Inspection and assessment of concrete pipe culverts under highways in Tatarstan

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Abstract. The experience of examining small culverts of artificial structures, carried out by a number of specialized organizations, shows that on some highways of the country up to 80% of pipes have some degree of damage. This article provides data from field surveys of pipes located on the main highways of Tatarstan. Survey data is needed to identify common problems at concrete culverts in Tatarstan. Field data were also analyzed using statistical software to identify factors contributing to the degradation of concrete culverts. The article presents a method for assessing the risk of developing negative phenomena when maintaining concrete pipes. The proposed risk assessment method allows predicting and preventing the occurrence of such phenomena.

Keywords. Highways, culvert, concrete, pipes, inspections, statistics, durability.

1 Introduction

The construction and operation of highways can cause a number of negative changes in the environmental situation in the adjacent territory [1-3]. This is especially true for artificial structures, of which small culverts account for 85-90%. During the construction of the roadbed, the natural terrain on the right-of-way is disturbed, and the vegetation layer is removed. All this leads to changes in the surface runoff and water regime of the territory [4-6]. Erosion of the soil and underlying soils leads to both the formation of ravines, and to the violation of the stability of artificial road structures and the roadbed.

The experience of the survey of small culverts of artificial structures conducted by a number of authors and specialized organizations [7-9] shows that up to 80% of the listed structures have some degree of damage on individual highways [10-12]. Statistics show that the most widespread damage is at the exit section. These include the erosion of the exit heads, their deformation and destruction, the collapse of part of the embankment, the erosion and destruction of the fortification behind the exit heads, the formation of local erosion and gully formation [13-15]. On some sections of roads, especially in rough terrain, this type of destruction reaches 100%. The second most widespread is the silting of pipes and small bridges [2, 16, 17]. One of the factors that cause damage to the culvert, its heads and fortifications, is the silting of the pipe.

Siltation of culverts occurs quite often and is found in various regions, especially in conditions of increased soil erosion. In the Moscow Region, siltation ranges from 9% when

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the entire pipe is silted up to 58% when half of the pipe body is silted up [13, 18, 19]. Siltation of pipes on the Pridnестровская Railway is 36 % [16]. On the roads of the south of the Far East, 6% of the surveyed pipes are silted up [20, 21].

More than 7 thousand culverts are located on the roads of Tatarstan. The efficiency of small culverts is one of the components of the successful operation of the highway [22, 23]. The lack of data on the condition of culverts on the roads of Tatarstan determined the need for this study.

The purpose of the study is to analyze the technical condition of artificial structures on the roads of Tatarstan and identify the factors contributing to the degradation of concrete culverts.

2 Materials and methods

2.1 Field surveys

Field surveys include inspection and visual assessment of individual elements of roads and road structures, as well as instrumental measurements of parameters and transport and operational characteristics [24].

Culverts were examined in the summer. The survey was preceded by the collection of materials in design and operational organizations.

On each of the structures:
- the main parameters of the roadbed were measured (the width of the embankment below and above, the thickness of the embankment layer above the pipe), the deformations of the roadbed and the roadway were described;
- the main parameters of the pipe were determined (the size of the hole, the length of the links, the total length, the state of the joints, the type and size of the input and output heads, the deformation of the heads, the destruction of fortifications);
- the condition of the inlet and outlet channels was described.

It is not possible to determine the amount and degree of damage to the pipes during the pre-repair period, there is no data on the dynamics of damage, water levels and other hydraulic characteristics.

2.2 Processing the results

The results were processed in the STATISTIKA program. Principal component analysis, cluster analysis, discriminant analysis, correlation analysis, and descriptive statistics were used.

The general purpose of multiple regression is to analyze the relationship between several independent variables (also called regressors or predictors) and a dependent variable (response). The multiple correlation coefficient $R$ is the positive square root of the R-square (multiple coefficient of determination). This statistic is useful when performing multivariate regression (i.e., using multiple independent variables), when it is necessary to describe the relationship between one and several variables.

The linear multiple regression model is the simplest to understand from a mathematical point of view and, from a practical point of view, the easiest to interpret. The linear multiple regression equation is:

$$ Y = a + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n, $$

(1)

where $Y$ is the calculated value of the effective feature (response function); $X_i$ arguments or factors (code values); $b_i$ – partial regression coefficients showing the degree of influence of each of the factors on the response function; $a$ – free member.

In equations, the values of variables are mostly discrete, that is, they are codes, not real physical quantities.
3 Results

3.1 Condition of culverts

The inspection of pipes in Tatarstan was carried out on four roads with sections of different technical categories: Kazan – Ufa (to Menzelinsk), Kazan – Orenburg (to Bugulma), Kazan – Perm (to Baltasi), Kazan – Ulyanovsk (to Buinsk). The listed roads are located in various orographic zones. The Kazan – Ufa highway crosses the Western, Eastern Predkamye and Eastern Zakamye, the Kazan – Orenburg highway passes through the Western Predkamye, Western and Eastern Zakamye. The Kazan-Perm highway is located in the Western Kama region, and the Kazan – Ulyanovsk road crosses the Volga region.

427 culverts were examined on these roads. The bulk of the pipes are made of concrete (Table 1). Despite the lack of technical standards and standard projects, 22 technically smooth metal pipes – 5.15% of pipes-are installed on the roads of Tatarstan. Technically smooth pipes can cause large flow rates to flow out of the pipes. As a result, there is a destruction of fortifications at the exit and the formation of washouts behind it, which also does not improve the environmental situation.

Table 1. Pipe material.

| Material | Quantity | Percentage |
|----------|----------|------------|
| Concrete | 400      | 93.68      |
| Metal    | 22       | 5.15       |
| Stone    | 4        | 0.94       |
| Small bridge | 1 | 0.23        |

On the roads, concrete pipes with a single hole predominate: round pipes with a diameter of 1.5 and 1.0 m and rectangular pipes with a cross section of 3.0×2.5 m and 4.0×2.5 m (Table 2).

Table 2. Distribution of pipes by diameter and cross-section.

| Pipe diameter, m | Quantity | Percentage | Pipe cross section, m | Quantity | Percentage |
|------------------|----------|------------|-----------------------|----------|------------|
| 0.3              | 1        | 0.27       | 0.8×0.67              | 1        | 2.32       |
| 0.4              | 3        | 0.8        | 2.5×1.5               | 2        | 4.65       |
| 0.5              | 3        | 0.8        | 2.4×2.0               | 1        | 2.32       |
| 0.6              | 1        | 0.27       | 3.0×2.0               | 1        | 2.32       |
| 0.65             | 1        | 0.27       | 2.5×2.5               | 3        | 6.97       |
| 0.75             | 31       | 8.27       | 3.5×2.0               | 1        | 2.32       |
| 0.8              | 4        | 1.07       | 3.0×2.35              | 1        | 2.32       |
| 1.0              | 179      | 47.73      | 3.0×2.5               | 12       | 27.91      |
| 1.1              | 2        | 0.53       | 3.5×2.5               | 2        | 4.65       |
| 1.2              | 2        | 0.53       | 3.0×3.0               | 2        | 4.65       |
| 1.25             | 7        | 1.87       | 4.0×2.5               | 13       | 30.23      |
| 1.4              | 1        | 0.27       | 3.4×3.0               | 3        | 6.97       |
| 1.5              | 135      | 36.0       | 4.5×2.5               | 1        | 2.32       |
| 1.7              | 1        | 0.27       |                       |          |            |
| 1.75             | 1        | 0.27       |                       |          |            |
| 2.0              | 1        | 0.27       |                       |          |            |
| 2.5              | 1        | 0.27       |                       |          |            |
| 3.5              | 1        | 0.27       |                       |          |            |

On the surveyed roads, siltation of the pipe body and heads, erosion of the embankment slopes at the heads, destruction of the fortification, erosion of the channel behind the
fortification, gully formation, debris clogging of the inlet and outlet channels, deformations of the heads, metal technically smooth pipes and the location of pipelines in the culvert were found (Table 3).

**Table 3.** Results of the survey of culverts.

| Highway            | Quantity, pcs. | Siltation of the pipe body, % | Siltation of the head, % | Erosion of the embankment slopes at the heads, % | Destruction of the reinforcement, % | Pipelines in the pipe, % |
|--------------------|----------------|-------------------------------|--------------------------|-----------------------------------------------|-----------------------------------|--------------------------|
| Kazan – Ufa        | 190            | 22.34                         | 18.09                    | 7.45                                          | 9.58                              | 0.53                     |
| Kazan – Orenburg   | 164            | 18.29                         | 51.67                    | 2.44                                          | 32.15                             | 6.1                      |
| Kazan – Ulyanovsk  | 26             | -                             | 34.0                     | 11.0                                          | 7.0                               | -                        |
| Kazan – Perm       | 47             | 20.24                         | 10.6                     | 8.5                                           | -                                 | 4.26                     |

On the Kazan – Ufa highway, 190 pipes were examined, of which 42 pipes have siltation, a pipeline is located in 1 pipe, the silting of the head has 79 pipes, 16 structures are littered. On the Kazan – Orenburg highway, 164 pipes were examined, of which 31 pipes are silted, 10 pipes are located in pipelines, the silting of the head has 96 pipes, 18 pipes are littered. On the Kazan – Perm highway, 47 pipes were examined, of which 10 pipes have siltation, 2 pipes have pipelines, the silting of the head has 26 pipes, 4 pipes are littered. On the Kazan – Ulyanovsk highway, 26 pipes were examined, of which the silting of the head has 13 pipes, 2 pipes are littered.

Siltation of various degrees was detected in 83 pipes, which is 19 % of the examined pipes (Table 4, Fig. 1).

**Table 4.** Silting of the pipe body.

| Percentage of silting of the pipe body from its height | Quantity | Percentage |
|-------------------------------------------------------|----------|------------|
| no silting up                                         | 344      | 80.56      |
| 10 %                                                  | 48       | 11.24      |
| 20 %                                                  | 11       | 2.58       |
| 30 %                                                  | 4        | 0.94       |
| 40 %                                                  | 3        | 0.7        |
| 50 %                                                  | 13       | 3.04       |
| 60 %                                                  | 3        | 0.7        |
| 70 %                                                  | 1        | 0.24       |

**Fig. 1.** Silting of the pipe.
On the surveyed roads, in addition to the Kazan – Ufa road, pipelines were located in a number of culverts, which is a gross violation of the norms. The number of such violations on various roads ranges from 0.53 % to 6.1 %. Table 4 shows the total number of pipes examined (Table 5).

Table 5. The presence of pipelines in the pipe body.

| Percentage of the area Occupied by the pipeline | Quantity | Percentage |
|------------------------------------------------|----------|------------|
| No piping                                      | 414      | 96.98      |
| 10 %                                           | 1        | 0.23       |
| 20 %                                           | 3        | 0.70       |
| 30 %                                           | 5        | 1.17       |
| 60 %                                           | 1        | 0.23       |
| 70 %                                           | 1        | 0.23       |
| 90 %                                           | 2        | 0.46       |

The overflow of water over the embankment or the break, with the rapid release of the opening of the structure, can cause the erosion of the channel in the lower stream. This process can be accompanied by the formation of ravines and the destruction of the exit fortifications. In accordance with [24], the erosion of watercourses at the heads of culverts is not allowed on roads of all categories.

The greatest number of destructions, 32.15 %, is found on the Kazan-Orenburg road. Table 6 shows data on the destruction of pipe fortifications on the roads of Tatarstan.

Table 6. Destruction of fortifications.

| Type of destruction                                      | Quantity | Percentage |
|----------------------------------------------------------|----------|------------|
| No destruction                                           | 356      | 83.37      |
| The entrance fortification was destroyed                 | 15       | 3.51       |
| The exit fortification                                    | 22       | 5.16       |
| Was destroyed both                                        | 21       | 4.92       |
| Fortifications were destroyed/there were no fortifications| 13       | 3.04       |

Concentrated water runoff at the exit from the structure leads to maximum damage and gully formation in the downstream of road culverts, which is confirmed statistically (Table 7).

Table 7. Distribution of ravines.

| The presence of a ravine                           | Quantity | Percentage |
|--------------------------------------------------|----------|------------|
| No ravines                                       | 392      | 91.8       |
| Ravines in front of the pipe                     | 1        | 0.24       |
| Behind the pipe                                  | 20       | 4.68       |
| Ravines in front and behind the pipe             | 14       | 3.28       |

Washouts of the embankment at the heads occur in 19.4 % of the examined pipes, of which washouts at the entrance heads have 4.68 %, at the exit heads – 11.24 %, at the entrance and exit pipes – 3.52 % (Table 8).
The correlation analysis of the studied parameters (variables) revealed the dependencies and correlation coefficients. As a result, the following multiple regression equations are obtained.

Regression model of pipe siltation dependence ($Y_1$):

$$Y_1 = 0.28X_1 + 0.36X_2 + 0.27X_3 + 0.85X_4 - 0.023X_5 + 0.134X_6 + 0.031X_7 - 1.22,$$

where $X_1$ is the orographic zone; $X_2$ is the type of obstacle; $X_3$ is the number of holes in the pipe; $X_4$ is the diameter of the pipe; $X_5$ is the length of the pipe; $X_6$ is the type of head; $X_7$ is the height of the embankment above the pipe.

If we leave only the most significant variables for this model, it looks like this:

$$Y_1 = 0.31 + 0.36X_2 + 0.88X_4 - 0.02X_5 - 1.087,$$

where $X_1$ is the orographic zone; $X_2$ is the type of obstacle; $X_4$ is the diameter of the pipe; $X_5$ is the length of the pipe.

Regression model of the dependence of the siltation of the head ($Y_2$):

$$Y_2 = 1.58 + 0.21X_1 + 0.103X_2 + 0.19X_3 + 0.24X_4 - 0.24X_5 + 0.073X_6 + 0.025X_7,$$

where $X_1$ is the orographic zone; $X_2$ is the type of obstacle; $X_3$ is the diameter of the pipe; $X_4$ is the length of the pipe; $X_5$ is the length of the pipe; $X_6$ is the type of head; $X_7$ is the height of the embankment above the pipe.

Regression model of the dependence of the destruction of the strengthening ($Y_3$):

$$Y_3 = 1.76 - 0.095X_1 + 0.17X_2 + 0.058X_3 - 0.60X_4 - 0.0023X_5 - 0.27X_6 - 0.014X_7,$$

where $X_1$ is the orographic zone; $X_2$ is the type of obstacle; $X_3$ is the number of holes in the pipe; $X_4$ is the diameter of the pipe; $X_5$ is the length of the pipe; $X_6$ is the type of head; $X_7$ is the height of the embankment above the pipe.

Regression model of the dependence of the destruction of the strengthening ($Y_3$):

$$Y_3 = 1.76 - 0.095X_1 + 0.17X_2 + 0.058X_3 - 0.60X_4 - 0.0023X_5 - 0.27X_6 - 0.014X_7,$$

where $X_1$ is the orographic zone; $X_2$ is the type of obstacle; $X_3$ is the number of holes in the pipe; $X_4$ is the diameter of the pipe; $X_5$ is the length of the pipe; $X_6$ is the type of head; $X_7$ is the height of the embankment above the pipe.

Regression model of the dependence of the tortuosity of the riverbed ($Y_4$):

$$Y_4 = -0.20 + 0.031X_1 + 0.067X_2 + 0.14X_3 + 0.18X_5 + 0.034X_6 - 0.094X_7 + 0.054X_8,$$

where $X_1$ is the orographic zone; $X_2$ is the type of obstacle; $X_3$ is the number of holes in the pipe; $X_4$ is the diameter of the pipe; $X_5$ is the length of the pipe; $X_6$ is the type of head; $X_7$ is the height of the embankment above the pipe.

Table 8. Erosion of embankment slopes near pipes.

| Blur type                             | Quantity | Percentage |
|---------------------------------------|----------|------------|
| No blur                               | 344      | 80.56      |
| Erosion from the top side of the embankment | 20       | 4.68       |
| Erosion from the lower side of the embankment | 48       | 11.24      |
| Washouts on both sides of the embankment   | 15       | 3.52       |

The deformation of the pipe heads can be attributed to the structural failure of culverts. On the surveyed roads, 20.61% of the pipes have various destruction of the heads. Table 7 shows the data on the destruction of heads on the roads of Tatarstan. Only on the Kazan – Perm highway there are destructions either on the entrance or exit heads. On all other roads, there are pipes that have deformations of both heads at the same time.

Table 9. Destruction of the heads.

| Destruction type            | Quantity | Percentage |
|----------------------------|----------|------------|
| No destruction             | 339      | 79.39      |
| Destroyed input head       | 32       | 7.49       |
| Destroyed output head      | 19       | 4.45       |
| Destroyed both heads destroyed | 37      | 8.67       |
Regression model of the dependence of the destruction of the head \(Y_7\):
\[
Y_7 = -0.14 + 0.11X_1 - 0.16X_2 + 0.21X_6,
\]
where \(X_1\) is the orographic zone; \(X_2\) is the number of holes in the pipe; \(X_6\) is the type of head.

Thus, the linear multiple regression equations for various defects in the maintenance of highways are obtained. The significance level of all models \(p < 0.001\) is highly significant. Substituting the corresponding codes into the equations, we can predict the development of various defects.

### 4 Discussion

According to [24], on roads of categories I-III, the deposition of silty particles in the cross section and at the heads of culverts is unacceptable, and on roads of categories IV-V, silting up to 1/10 of the pipe diameter is allowed.

The largest number of silted pipes (22.34 %) is observed on the Kazan – Ufa highway, located in the Western and Eastern Kama regions. Of these, 7.89 % of the pipes are silted up by 10 %. The anti-erosion resistance of the Pre- Kama soils ranges from 0.3 to 0.4 – the lowest in Tatarstan, which contributes to the silting of pipes. The Kazan-Orenburg highway has 18.29 % of silted pipes, 15.24 % of pipes are silted by 10 %. The Kazan – Orenburg highway crosses three orographic zones: the Western Predkamy, the Western and Eastern Zakamy. The erosion resistance in the Western and Eastern Zakamy ranges from 0.5 to 1.1 and from 0.6 to 0.9, respectively. 20.24 % of silted pipes were found on the Kazan-Perm highway, of which 17.02 % was silted up by 10 %. The Kazan-Perm highway is located in the Western Predkamy. No silted pipes were found on the Kazan – Ulyanovsk highway crossing the soils of this area are reliable against erosion. The erosion resistance of the soils of the Volga region ranges from 0.4 to 1.12.

Thus, it can be concluded that the silting of pipes occurs in orographic zones with the lowest erosion resistance. This is confirmed by the regression equation, where the orographic zone is the significant variable of equation (2).

Siltation of the structure leads to a decrease in the area of its cross-section, which in turn leads to a decrease in throughput. This can lead to a further increase in the water level before the construction, even if small water flows are passed, and during high water periods, lead to water overflowing over the road embankment or destruction. Changes in the water regime lead to waterlogging of the soil, changes in vegetation, and an increase in the groundwater level. When water is poured over the embankment or the pipe body is quickly cleared of silting, high water flow rates occur, which can lead to the destruction of embankment slopes or recedes, the formation of washouts and gullies in the lower stream. Gully formation can spread at a considerable distance from the road and reach up to several kilometers.

When a smaller diameter pipeline is located in a culvert, the live section decreases, the pipe works as silted, there is a high probability of water overflow over the road embankment and all the consequences that are observed as a result of silting of pipes.

Gully formation. As noted above, the soils of the Kama region have low erosion resistance, which is clearly illustrated by the histograms of the distribution of ravines on highways and in orographic zones. For the Western Kama Region, ravines make up 11.06%,
and for the Eastern one – 15.57 %, that is, ravines are found on the Kazan – Ufa and Kazan – Perm highways. The formation of gullies is facilitated not only by the presence of soil and soils with low erosion resistance, but also by the transition from slope runoff to river runoff.

Soil erosion at the pipe. The influence of the terrain on the processes of soil erosion is mainly determined by the slopes. On slopes with an angle of 25...30°, water erosion is aggravated by the gravitational shedding of the subsurface layer. All embankments and recesses have a slope of 1:1.5 or 1:3. The structures of the roadbed are such that they are washed away from the ground (during construction, reconstruction), and then all this enters the pipe. Consequently, the unprotected slopes of recesses and embankments when they are laid 1:1.5 are the objects of the most intense erosion.

Thus, the prevention of silting of road pipes is the fight against erosion, consisting of a number of measures, the complex application of which allows you to reduce the process of erosion, and eventually stop it.

5 Conclusions

On the roads of Tatarstan, the most dangerous for the regulatory operation of road pipes is their siltation. Up to 20% of the surveyed culverts are subject to silting, which is unacceptable for roads of technical category II and III. It is established that the silting of pipes is greatly influenced by the potential exposure of the territory to gully erosion and soil erosion.

The experimental data were processed using correlation analysis and regression equations. The analysis of the general correlations revealed a direct relationship between the silting of the pipe body and the silting of the head. This is also confirmed by partial correlations. In multiple regression equations, the following variables are significant for various road maintenance defects: orographic zone; type of obstacle being crossed; number of pipe points; diameter; pipe length; type of head; height of the embankment above the pipe.

The obtained regression equations for the occurrence of certain defects in culverts allow us to prevent the occurrence of various defects or to keep under control the condition of pipes that are subject to various failures during operation.

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