Improving the Operational Reliability of Reinforced Concrete Culverts on Highways

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Abstract: The article considers the issues of assessing and improving the quality and reliability of culverts and the road drainage system on unpaved roads and roads with transition pavement. The reliability of culverts and pavement above the culverts was evaluated taking into account the thickness of the embankment above the road structure. The issues of the influence of the quality of culverts on the condition of the pavement are examined in detail. The relationship between the defects in culverts and the quality of the pavement is established.

1. Introduction

Improving the reliability of the road drainage system is one of the most important problems of road construction and is especially relevant for agricultural and industrial roads with unpaved surfaces [12]. Unpaved roads are subjected to water and wind erosion because of the lack of strong relationships between particles in dispersive soils. The development of water erosion processes on unpaved roads is primarily due to the unstable operation of the road drainage system [5, 10, 11].

To increase the reliability of the road drainage, it is necessary to ensure the stable operation of all its components, i.e. culverts, ditches, pavement (ensuring water removing from the roadway due to the longitudinal and transverse slope).

Improving the reliability of the road drainage system will ensure high-quality and safe traffic on the roads, as well as reduce the environmental impact of the road and prevent the occurrence of "ponds" at the culverts inlets and outlets.

As the culverts are the most important element of the road drainage system on which increased operational requirements are imposed, the quality and reliability of the culverts ultimately determine the operability of the entire road drainage system.

2. Research and analysis of the operational condition of reinforced concrete culverts on the roads

The diagnostic testing of roads was performed to analyze and systematize data on the operation of culverts, to identify the relationships between the operational condition of culverts and the road pavement (transport and operational quality and road safety). The work on the classification and systematization of defects in culverts and subgrade near the structure (25 m section on each side of the culvert axis) was carried out during the tests of culverts, [2, 3].

A study of the relationship between the operational condition of culverts and the quality and safety of traffic was also conducted for roads with improved asphalt concrete pavement [5].
For a probabilistic assessment and analysis of the dependence of the transport and operational condition of the pavement on the operational condition of culverts, it is necessary to rank data on the types of defects depending on the factor that best describes this relationship, namely the amount of embankment above the culvert (protective layer of the embankment). Establishing the relationship between the condition of the culvert and the quality of the pavement through the amount of the embankment above the culvert will allow determining the sensitivity thresholds of the system “culvert – embankment” to the impact of the traffic load and to develop a set of measures to increase the reliability of the structure in conditions close to the maximum permissible.

On the operated roads, the thickness of the embankment above the culvert consists of a combination of two elements: the thickness of the protective layer (embankment) above the culvert and the thickness of the layers of the pavement structure. It should be noted that in most standard design solutions for reinforced concrete culverts [4, 9], a protective layer above the culvert can be combined with a bedding (additional) course made of medium-sized sand or sand-gravel mix to ensure uniformity of the layer and increase its resistance to the traffic load, however, on unpaved roads and roads with transition pavement such a layer is absent and the road is designed with a minimum elevation of the embankment above the culverts.

As the thickness of the embankment above the culvert is not allowed to be established directly on the operated road (by well-boring) because of the possibility of damage to and destruction of the body of the culvert, the average thickness of the embankment above the culvert was determined geometrically, according to the results of leveling or tacheometric survey.

The systematization of culvert defects was carried out in two categories: culvert defects and pavement defects caused by the condition of culverts [2, 8].

Culvert defects: 1 - stagnation of water at the culvert heads; 2 - local destruction of reinforcements of ramps; 3 - siltation of the culvert; 4 - violation of the tightness of the joints; 5 – separation of culvert rings; 6 - partial damage of culvert heads.

Pavement defects caused by the condition of the culverts: 7 - rutting; 8 - potholes; 9 - waves; 10 - subsidence; 11 - blow-up failures; 12 - opening of the culvert body.

The results of the systematization are shown in table 1.

**Table 1. The distribution of culvert defects on unpaved roads and roads with transition pavement.**

| Culvert diameter | Number of observations | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|------------------|------------------------|---|---|---|---|---|---|---|---|---|----|----|----|
| 0,75             | 9                      | 4 | 0 | 9 | 9  | 6 | 2 | 9 | 0 | 0  | 7  | 1  | 0  |
| 1,00             | 39                     | 10| 20| 17| 21 | 18| 22| 36| 0 | 9  | 19 | 6  | 1  |
| 1,25             | 6                      | 0 | 3 | 1 | 3  | 4 | 3 | 6 | 0 | 0  | 3  | 2  | 0  |
| 1,50             | 30                     | 15| 14| 11| 14 | 4 | 6 | 23| 0 | 4  | 8  | 9  | 0  |
| 2,00             | 15                     | 9 | 6 | 3 | 9  | 2 | 12| 12| 1 | 5  | 0  | 1  | 0  |
| TOTAL            | 99                     | 38| 43| 41| 56 | 34| 43| 86| 1 | 18 | 37 | 19 | 1  |

In addition, it is necessary to systematize data on the levels of the operational condition of the road pavement [6] to establish the probability of occurrence of the pavement defects from the culvert defects. The results of the systematization are shown in table 2.

**Table 2. The distribution of culvert defects on unpaved roads and roads with transition pavement.**

| Culvert condition | Number of observations | Number of defects | Condition of the road pavement |
|-------------------|------------------------|------------------|-------------------------------|
|                   |                        | 1 | 2 | 3 | 4 | 5 | 6 |    |    |    |    |    |    |    |
| Excellent         | -                      | - | - | - | - | - | - | -  |    |    |    |    |    |    |
| Good              | 15                     | 9 | 4 | 2 | 0 | 0 | 4 | 4  | 8  | 2  | 1  |    |    |    |
| Satisfactory      | 46                     | 19| 23| 19| 29| 0 | 21| 3  | 12 | 24 | 7  |    |    |    |
| Unsatisfactory    | 38                     | 10| 16| 20| 27| 34| 10| 3  | 1  | 7  | 27 |    |    |    |
| TOTAL             | 99                     | 38| 43| 41| 56| 34| 43| 10 | 21 | 33 | 35 |    |    |    |
It is clear from the analysis of the data presented in tables 1 and 2 that such defects as siltation of the culvert, violation of the tightness of the joints between the culvert rings and the separation of the culvert rings are the most critical by assessing the performance of a culvert. Therefore, it is necessary to assess the likelihood of a particular culvert defect taking into account the pavement defects.

The main hypothesis in determining the relationship between the operational condition of the road structures and the quality of the pavement is that the quality of the pavement depends on the operational condition of the road structure and the thickness of the protective layer of the embankment above the culvert, while the size and shape of the hole are not taken into account [1, 9].

For a probabilistic assessment and establishing a relationship between the quality of the road pavement and the operational condition of the road structure, it is necessary to rank data on the thickness of the protective layer of the embankment above the culvert. The protective layer is determined taking into account the thickness of the pavement, because in the field it is impossible to unambiguously determine the thickness of each layer of pavement and find the boundary between the pavement and the embankment above the culvert.

The test data of road structures on unpaved roads and roads with transition pavement located in the Khabarovsk Krai are presented in the study [5]. The statistical values were processed in the STATISTICA 10 program. The results of statistical data processing (the thickness of the embankment above the culvert and the condition of the pavement) are shown in Figures 1-3.

![Scatter chart for Condition of pavement, point and Thickness of the embankment above the culvert, m](image)

**Figure 1.** Scatter chart.
Figure 2. Statistical evaluation of the thickness of the embankment above the culvert.

Figure 3. Statistical evaluation of the condition of the pavement.
The distribution of the statistical value was checked against the criteria of normal, logistic and lognormal distribution in the STATISTICA 10 program and an empirical formula was selected to establish the dependence of the level of operational condition of the pavement on the thickness of the embankment above the culvert. The selection of formulas was done on the basis of the least squares method and was guided by the main provisions of the methods of linearization of closed nonlinear systems. The resulting dependencies are presented in Figure 4.

**Figure 4.** Nomogram of the condition of pavement over the culvert from the thickness of the embankment over the culvert and the condition of the culvert.

Based on the graph (Figure 4) it can be seen that the thickness of the embankment above the culvert plays an important role in assessing the operational condition of roads with transitional and lower types of pavement, agricultural and industrial roads, namely:

- with an increase of the embankment above the culvert to 1.20 m or more, the influence of the operational condition of the culverts practically disappears when assessing the quality and safety of the traffic on the road;

- when the thickness of the embankment above the culvert is less than 0.40 m (excluding the thickness of the pavement, which is most often represented by a layer of crushed stone mixture C1 with a thickness of 20 cm on agricultural roads), it is impossible to ensure a good condition of pavement because of the increased impact of the traffic load on the structure and the embankment.

Such culvert defects as a violation of the tightness of the joints and the separation of culvert rings (culvert condition up to 3 points) exert the greatest influence on the quality of the pavement over the culverts. The presence of these defects sharply worsens the quality of the pavement above the culvert if the embankment above the culvert does not exceed 1.00 m.

3. **Improving the reliability of reinforced concrete culverts**
   It is necessary to reduce the degree of influence of the condition of the culvert on the road pavement and timely perform works on repair and maintenance of road structures to improve the quality, durability and reliability of the road drainage system.
At present, two methods of culverts backfilling are widespread: in the pit and in the embankment (Figure 5).

![Figure 5. Schemes of reinforced concrete culverts backfilling.](image)

The stress-strain state was evaluated in the GenIDE32 software package to establish the reasons of the formation of deformations of the pavement, body of the embankment and the destruction of the joints of the culvert rings.

The axisymmetric structure of the embankment with a thickness of the embankment above the culvert of 0.50 m was adopted as the design scheme. The problem was solved as a ground-geological environment for the plane deformation state of the structure, without the possibility of lateral expansion at the boundaries of the system.

The following parameters were taken as design characteristics:
1. The design load NK-14
2. The loading configuration according to the clause 4.4.5 of Russian National Standard (GOST) 32960-2014.
3. Type of action - static load.
4. The characteristics of soils and materials are shown in table 3.

**Table 3.** List and characteristics of layers.

| Name                        | Modulus of deformation (elasticity), MPa | Angle of internal friction, ° | Adhesion coefficient, kN | Poisson’s ratio |
|-----------------------------|------------------------------------------|-------------------------------|--------------------------|-----------------|
| 1. Reinforced concrete of the culvert | 36.5 103                                 |                                | 850                      | 0.35            |
| 2. Crushed stone mix        | 55                                       | 33                            | 25.4                     | 0.24            |
| 3. Stiff loam               | 26                                       | 22                            | 20                       | 0.35            |
| 4. Soft sandy loam          | 18                                       | 16                            | 17                       | 0.35            |
| 5. Sand gravel mix          | 45                                       | 36                            | 7                        | 0.30            |

The safety factor of the system “culvert – embankment” was calculated for each loading scheme (Figure 6 and Figure 7).
As can be seen from Figure 6 and Figure 7, under the influence of the design load NK14, the stability of the system “culvert – embankment” is lost (tends to zero) over a significant area. This means that regardless of the method of culverts backfilling, the thickness of the protective layer above the culvert equal to 50 cm (30 cm sand-gravel mix, 20 cm crushed stone mix) is insufficient to ensure reliable operation of the system “culvert – embankment” during the entire service life.

To increase the stability of the system, it is recommended to reinforce the soil around the culvert by creating a spatial frame structure due to the layering of a geocell system filled with stone-sand and/or gravel-sand mixture with continuous grain sizing (not more than 80 mm) to form a protective prism around the culvert (Figure 8) [7].

Figure 6. The safety factor of the embankment on the culverts (backfill in the embankment).

Figure 7. The safety factor of the embankment on the culverts (backfill in the pit).
1 – pavement; 2 – embankment; 3 – culvert; 4 – bed of stone-sand and/or gravel-sand mixture; 5 – geocell system; 6 – protective layer of stone-sand and/or gravel-sand mixture; 7 – protective layer covering the culvert body.

Figure 8. Scheme of the system “culvert – embankment” reinforcement.

The recommended scheme is also calculated in the GenIDE32 program for loading NK14 and the method of culvert backfilling in the embankment (Figure 9).

Figure 9. The safety factor of the embankment on the culverts reinforced with geocell structures (backfill in the embankment).

4. Conclusions
Based on the analysis of practical measurements and theoretical studies, we can clearly say that there is a non-linear relationship between the operational condition of the culvert and the quality of the pavement above the culvert. It should be noted that the greater the thickness of the protective layer over the road structure is, the less its operational condition affects the quality of the pavement.

As a result of the studies, it was found that with an increase in the embankment above the culvert to 1.20 m or more, the influence of the operational condition of the culvert practically disappears when assessing the quality and safety of traffic on the road. Also, according to the results of mathematical
modeling, it was found that when the thickness of the embankment above the culvert is less than 0.40 m (excluding the thickness of the pavement, which is most often represented by a layer of crushed stone mixture C1 with a thickness of 20 cm on agricultural roads), it is impossible to ensure a good condition of pavement because of the increased impact of the traffic load on the structure and the embankment.

It is proposed to use the patented method of reinforcing the system with geosynthetic materials (geocell) to increase the reliability and stability of the system “culvert – embankment.”

The calculations of the system “culvert – embankment” reinforced by geocell structures according to the recommended method showed that the safety factor of the embankment around the culvert increased by 7–10 times. In addition, the load on the culvert was significantly reduced (2–3 times), because it is redistributed to the protective layer and the embankment around the culvert due to the reinforcing and wireframe properties of the geocells.

Reducing the impact of the traffic load on the walls and joints of the culverts will prevent and slow down the development of premature deformations and increase the reliability of the system “culvert – embankment”.

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