Application of the reliability assessment results for pumping stations's modernization

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Abstract. Work on the modernization of irrigation pumping stations in our Republic has a great relevance. Technical modernization and reconstruction of pumping stations require a reliable scientifically based methodological approach. Each pumping station regularly keeps records and controls the operation of equipment and facilities. These data in processed form can be applied in the modernization of irrigation pumping stations. On the example of the analysis of the reliability characteristics of the Kiziltepa 2 pumping station (Uzbekistan), a methodology has been developed to justify the modernization and the order of replacement of the main equipment. Comparison of the results of calculation of quantitative parameters (criteria) of reliability of pumping station equipment with the data of field tests of aggregates showed that they can diverge. Therefore, the operational reliability assessment should be carried out comprehensively, and not only the results of a full-scale survey should be taken into account, but also the quantitative parameters of the reliability of the pumping station calculated according to previous years of operation. The use of this technique will make it possible to dispense with complex tests to assess the residual life of equipment parts by destructive testing methods.
Keywords: pump, operation, repair, reliability theory, pumping unit, failure, modernization

1 Introduction

Irrigation pumping stations make up the base of the machine water lifting of the Republic of Uzbekistan, with the help of which more than 50% of the land is irrigated [1,2]. Their operation takes place in very difficult conditions [3,4]. Therefore, the issues of their energy-efficient use are of great practical importance [3,4,5]. Different types of measures are used to improve the efficiency of irrigation pumping stations operation [6,7]: rational use of hydraulic structures included in the pumping station [8,9], improvement of water intake conditions of pumping stations and regulation of supply and discharge channels [10,11,12],

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increasing the efficiency of pumping units [13,14,15], optimization of operating modes of pumping units [16,17,18]. But the most cardinal and fundamental way is considered to be modernization and reconstruction of pumping stations [19,20,21,22]. For example, in [19] it is shown that the effectiveness of such measures can increase by 14-15%. The article [21] discusses the need for reconstruction and modernization of pumping stations in case of emergencies. In the works [13,15,18,19], the possibility of increasing efficiency while reducing the cost of reconstruction is evaluated. [22] describes the case of choosing axial pumps when updating and upgrading pumping station equipment.

The absolute majority of pumping stations in the Republic of Uzbekistan have long since exhausted their technical resources, are physically and morally obsolete, and operate in notoriously non-energy efficient modes [1,2,5]. One of the priority directions for improving the efficiency of machine water supply is the reconstruction of irrigation pumping stations and large-scale reconstruction (rehabilitation) and modernization of irrigation pumping stations are currently underway in the Republic [1,2,3].

Usually, the conclusion about the need for reconstruction of a pumping station is made based on the results of a survey of the pumping station (i.e. technical condition), data on reliability indicators for past periods, etc. At the same time, the results of field surveys of the object are more often used [2,5,26], quantitative characteristics (criteria) of reliability calculated by the methods of reliability theory are used less often [23,24,25]. The practical application of reliability theory also consists in the development of test methods and evaluation of their results [5,27,28] reliability control methods, methods for determining the optimal level of quality of the designed equipment [29], determining the expected real efficiency of functioning, assessing the risk of failure [28,29,30]. The practical application of reliability theory also consists in the development of test methods and evaluation of their results [5,27,28] reliability control methods, methods for determining the optimal level of quality of the designed equipment [29], determining the expected real efficiency of functioning, assessing the risk of failure [28,29,30]. All this allows you to organize optimal maintenance and reduce operating costs [31,32].

The purpose of the research is to evaluate and analyze the operational reliability of the Kizil–tepa-2 pumping station and develop methods based on them to justify the need for modernization. The object of the study is the Kizil–tepa-2 pumping station.

Research objectives are evaluation of operational reliability parameters based on data from the Kizil-tepa-2 operation services and development of a methodology to justify the need to modernize pumping station equipment based on the analysis of operational reliability characteristics.

The scientific novelty lies in the fact that, for the first time, based on the assessment of the technical condition of the main resource-determining units of the Kizil-tepa-2 pumping equipment, using the methods of reliability theory, a methodology has been developed to justify the need for modernization and determine the order of replacement of pumping units at irrigation pumping stations with a large number of similar units.

2 Methods

The research methodology consists in collecting, processing and analyzing data from field surveys and the pumping station operation service, assessing operational reliability based on probabilistic and statistical methods of reliability theory [23,24,25].

The Kizil – Tepa 2 pumping station is located in Navoi region, in the central part of the Republic of Uzbekistan and has been in operation since 1985. The pumping station operates from April to October with a maximum load (up to 23 units) in July-August. The station is equipped with 26 horizontal pumps of type D 6300 - 80 (24 NDS) driven by synchronous electric motors with a capacity of 2000 kW (Fig.1).

Fig. 1. Engine room of the Kiziltepa 2 pumping station.

The characteristic features of the pumping station are the same type of horizontal centrifugal pumps distributed over two machine halls and the uneven loading of pumping equipment during the year. Table 1 shows the processed data for the Kiziltepa -2 pumping station for 2009-2019.

Table 1. Performance indicators of Kiziltepa -2 for the period under review

Pump Unit (PU) number	Number of repairs for the entire period of operation			
	Capital repairs	Current repairs	Number of failures	Number of repair hours
PU 1	10	8	9	4012
PU 2	10	6	7	4200
PU 3	10	-	1	5010
PU 4	10	-	3	5700
PU 5	7	-	5	4270
PU 6	10	-	3	3400
PU 7	8	2	6	4000
PU 8	10	9	10	4300
PU 9	8	-	10	4200
PU 10	10	-	7	3141
PU 11	10	3	4	5000
PU 12	10	-	8	4500
PU 13	9	2	6	2900
PU 14	10	-	6	2880
PU 15	10	-	4	3025
PU 16	8	-	7	3730
PU 17	10	9	10	5100
PU 18	10	3	10	5910
PU 19	9	8	10	2858
PU 20	8	7	8	3100
PU 21	10	5	8	2410
PU 22	9	6	10	3200
PU 23	8	7	10	3210
PU 24	9	4	5	4156
PU 25	10	-	3	3150
PU 26	9	4	8	3720
Total	242	83	178	

In total, 242 capital and 83 routine repairs were carried out during the period under review, 178 failures and accidents were recorded.

The main indicators of reliability include: probability of no-failure operation P(t), probability of failure Q(t), frequency and intensity of failures, the availability coefficient, the coefficient of technical use, etc. [23,24].

Failure is an event (damage, accident) consisting in a malfunction of the pumping station [23,24,25]. Failures that cause a malfunction of the pumping station can be observed not only as a result of various damages and accidents of individual elements of the station itself (internal failures), but also as a result of external causes (external failures), such as a power outage as a result of accidents in the power system, an unexpected increase or decrease in water levels, etc. In order to assess the operational reliability of the pumping station for the modernization of equipment, we considered only internal failures.

Various distribution laws are used to mathematically describe experimental random variables. In the theory of reliability of mechanical systems, the following three distribution laws are most often applied:

1. Normal (Gaussian).
2. Exponential.
3. Weibull.

These three laws are in good agreement with various types of behavior of random variables that characterize machine failures, sudden failures and wear (aging of components, parts).

In [30], based on the analysis of pumping stations in Azerbaijan (where there are more than 1,000 pumping stations for various purposes), it was determined that the operating time of pumping units to failure corresponds to the Weibull distribution. The periods between failures were conditionally considered as non-recoverable.

To estimate the probability of trouble-free operation of P, either Weibull's law or a normal distribution is taken. The Weibull distribution law determines the time of failure occurrence during the period of running-in of parts (assemblies, aggregates). During normal operation, the uptime is in good agreement with the exponential law. When wear of parts prevails, the normal distribution law is well suited.

The exact formulas for the probability of failure-free operation (for a normal distribution) have the following form [23,24,25]:

$$P(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^\infty e^{\frac{-(t-T_{aver})^2}{2\sigma^2}} dt \qquad (1)$$

Where σ is the mean square deviation; T_{aver} is the average time (mathematical expectation) of operating time for failure;

To assess operational reliability based on internal failures, we will use the formula to determine the probability of failure-free operation [24,25]:

$$P(t) \approx \frac{N_0 - \sum_{i=1}^{t/\Delta t} n_i}{N_0} \qquad (2)$$

Where N_0- the initial number of units in operation, *n*- the number of units.

The failure rate *f(t)* is the ratio of the number of failed units per unit of time to the initial number of units operated. It is determined by the approximate formula [24,25]:

$$f(t) \approx \frac{\Delta n(t)}{N_0 \Delta t} \qquad (3)$$

Where *Δn(t)* is the number of units that failed in the interval from *(t-Δt/2)* to *(t+ Δt/2)*; *Δt* is the time interval.

The failure rate *λ(t)* is the ratio of the number of failed products (aggregates) per unit of time to the average number of products (aggregates) that continue to work properly.

An approximate formula for determining the failure rate is as follows [24,25]:

$$\lambda(t) \approx \frac{\Delta n(t)}{N(t)\Delta t} \tag{4}$$

Where $\Delta n(t)$ is the number of products (aggregates, assemblies) that failed in the interval from $(t-\Delta t/2)$ to $(t+\Delta t/2)$; Δt is the time interval; $N(t) =(N_{i-1}+N_i)/2$, where N_{i-1} is the number properly working products (aggregates) at the beginning of the time interval Δt_i; Ni- the number of properly working products (aggregates) at the end of the time interval Δt_i;

The availability coefficient is the ratio of the total uptime of T_{uptime} to the sum of the total uptime and total repair time T_{repair}.

$$K_a = \frac{T_{uptime}}{T_{uptime} + T_{repair}} \tag{5}$$

3 Results and discussions

Table 2 and Figures 2-3 present the results of the calculation of operational reliability parameters calculated by formulas (1)-(5). According to the operation service, a total of 242 capital and 83 routine repairs were carried out during the period under review, 67 failures and accidents were recorded. The average number of units was 8,159 hours, the total number of hours in repair and downtime was 1,082 hours, with an average of 3,888 hours.

Table 2. The results of calculating the parameters of operational reliability of the Kizil-tepa-2 pumping station for the period under review, taking into account internal failures.

Unit number	Reliability probability	Failure frequency	Failure rate	Availability ratio
PU 1	0.1	0.9	1.8	0.61
PU 2	0.3	0.7	1.4	0.74
PU 3	0.9	0.1	0.2	0.67
PU 4	0.7	0.3	0.6	0.68
PU 5	0.5	0.5	1.0	0.71
PU 6	0.7	0.7	1.4	0.74
PU 7	0.4	0.4	0.8	0.68
PU 8	0	1	2	0.69
PU 9	0	1	2	0.63
PU 10	0.3	0.7	1.4	0.73
PU 11	0.6	0.4	0.8	0.67
PU 12	0.2	0.8	1.6	0.72
PU 13	0.4	0.6	1.2	0.69
PU 14	0.4	0.6	1.2	0.68
PU 15	0.6	0.4	0.8	0.65
PU 16	0.3	0.7	1.4	0.68
PU 17	0	1	2	0.70
PU 18	0	1	2	0.62
PU 19	0	1	2	0.52
PU 20	0.2	0.8	1.6	0.70
PU 21	0.2	0.8	1.6	0.67
PU 22	0	1	2	0.65
PU 23	0	1	2	0.57
PU 24	0.5	0.5	1	0.64
PU 25	0.7	0.3	0.6	0.65
PU 26	0.2	0.8	1.6	0.67

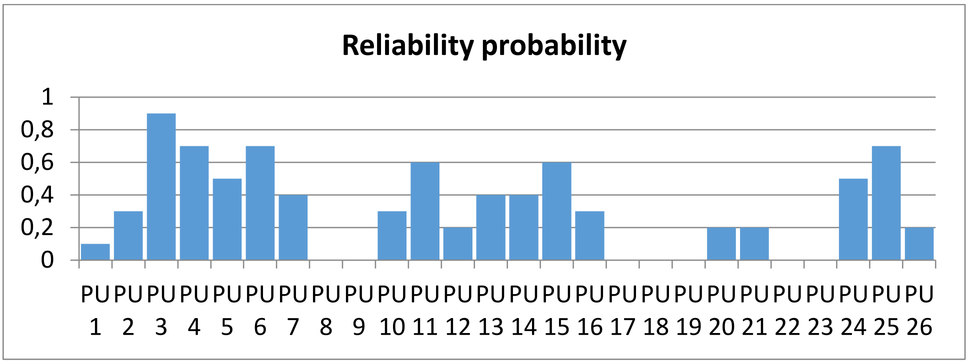

Fig. 2. The probability of trouble-free operation (Reliability probability) of pumping units, taking into account internal failures

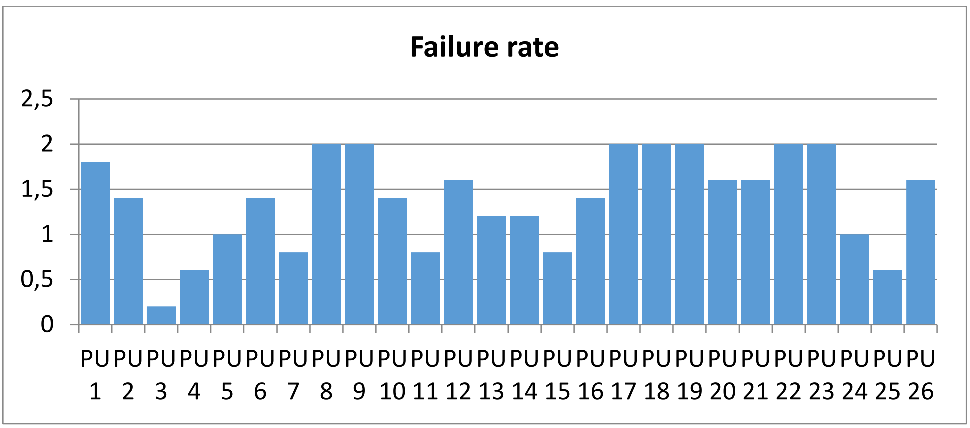

Fig. 3. Values of failure rates of pumping units for the period under review (taking into account internal failures)

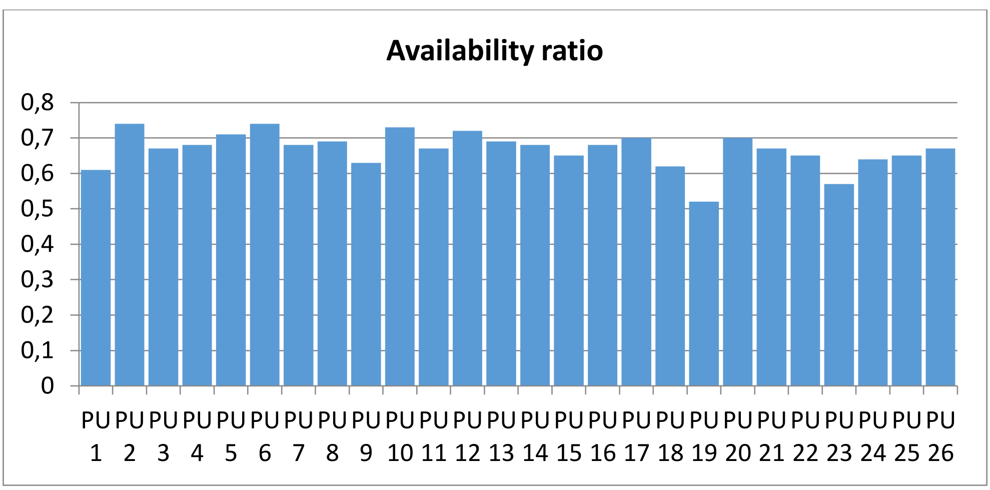

Fig. 4. The values of the availability coefficient (availability ratio) of pumping units, taking into account internal failures

Reliability parameters for external failures were evaluated for the period 2009-2019.. During this period, there were only 82 failures with a total downtime of 1,414 hours. The probability of failure-free operation of pumping station units for external failures ranges from 0.269 - 0.923. The probability of failure-free operation of units for internal failures ranges from 0.0 (PU-9,10,17,18,19,22 and 23) - 0.9 (PU-3, the number of hours in operation is 10,560, and the number of failures is 1).

The probability of failure-free operation of the pumping station (for internal failures) over the last year of the period under review was only 0.192 with a failure rate of 1.32 per year and a readiness coefficient of 0.684, which indicates extremely low operational reliability. The frequency of overhauls averaged once every 1 year with a standard overhaul period of 2-3 years.

We propose as one of the measures to improve operational efficiency and reliability an option in which there will be a gradual replacement of equipment. This option is selected taking into account the operating mode of the units and the schedule of water supply of the pumping station. The sequence and order of replacement will be determined based on the analysis of operational reliability parameters (calculated above) and data from a full-scale survey of the technical condition of the units.

Table 3. The order of priority of replacement of aggregates according to the specific failure rate.

№	Pumping unit	Number of hours in operation	Failure rate per year	Specific failure rate
1	PU19	314	2	0.006369
2	PU22	342	2	0.005848
3	PU8	218	1	0.004587
4	PU25	220	1	0.004545
5	PU14	242	1	0.004132
6	PU1	266	1	0.003759
7	PU3	722	2	0.00277
8	PU16	722	2	0.00277
9	PU15	922	2	0.002169
10	PU18	962	2	0.002079
11	PU17	1370	2	0.00146
12	PU9	698	1	0.001433
13	PU12	794	1	0.001259
14	PU24	1010	1	0.00099
15	PU2	818	-	0
16	PU4	1226	-	0
17	PU5	746	-	0
18	PU6	976	-	0
19	PU7	1250	-	0
20	PU10	890	-	0
21	PU11	1394	-	0
22	PU13	530	-	0
23	PU20	986	-	0
24	PU21	674	-	0
25	PU23	410	-	0
26	PU19	365	-	0

We will determine the order of replacement of units based on the analysis of operational reliability parameters. Since all units worked for a different number of hours, we will take as a criterion the specific failure rate, i.e. the number of failures per year per 1 hour of operation of the pumping unit. To do this, we will determine the specific failure rate of each unit according to Table 1. According to the table, the first ones should be replaced by PU 19,22,8,25, etc. Aggregates PU 2,4,5,6,7,10,11,13,19,20,21 and 23 will be replaced last.

Table 4 shows the data of full-scale parametric tests of pumping units. It is considered that the pump needs major repairs if its parameters, and first of all, the efficiency decreases by more than 20% [4,5,15 и т.д.]. The nominal efficiency of 24 NDS pumps is 90%, which means that those pumps whose efficiency is less than 70% need to be repaired. But as can be seen from Table 4, the total efficiency of the pumps is 76.5%, and even those pumps that have high specific failure rates (for example, pumps PU 19 (specific failure rate 0.006369 with an efficiency of 79.1%), PU 18 (specific failure rate 0.002079 with an efficiency of 87.8%) have sufficiently high efficiency values and they do not need repair (according to the criterion of efficiency reduction).

Table 4. Efficiency values according to parametric tests of pumping units.

Pump unit number	numbers of working units	Unit efficiency	Efficiency of the electric motor	Pump efficiency
1	1,4,11,18,19	65.7	96.2	68.3
2	1,2,4,19	66.2	96.2	68.8
4	1,4,11,18,19	71.1	96.2	74.0
11	1,4,11,18	84.3	96.2	87.6
15	1,4,15	64.3	96.2	66.8
18	1,4,18,19	84.5	96.2	87.8
19	1,4,11,19	76.1	96.2	79.1
21	1,4,18,21	70.9	96.2	73.7
26	1,4,26	81.7	96.2	84.9
In average		73,6	96.2	76.5

Thus, the operational reliability assessment should be carried out comprehensively, and not only the results of the in-situ survey should be taken into account, but also the quantitative parameters of the reliability of the pumping station calculated from the data of previous years of operation. Since the energy efficiency of the pumping station is affected not only by the efficiency of pumping units, but also by the amount of operating costs (failures lead to an increase in such costs) [31,32].

4 Conclusions

1. Gradual replacement of equipment is proposed as one of the measures to improve operational efficiency and operational reliability. The sequence and order of replacement are determined based on the analysis of quantitative parameters of operational reliability.

2. Data on the technical condition of pumping units obtained from the results of field tests and surveys and the results of the evaluation of reliability parameters (criteria) obtained as a result of statistical processing of data from the operation service may differ.

3. The operational reliability assessment should be carried out comprehensively, and not only the results of the in-situ survey should be taken into account, but also the quantitative parameters of the reliability of the pumping station calculated from the data of previous years of operation.

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