Geophysical prospecting and well reliability indicators

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Abstract. The paper considers the issues of well reliability indicators (strength, durability, safety) determined using the results of geophysical prospecting of the technical condition of the support as initial data. It is shown that it is possible to establish (recognize) the technical condition of bearing elements of well support, if according to the results of instrument studies, the types of damages are identified, their dimensions are established and actual strength parameters are calculated. Forecasting of service life is connected with the identification of a support element limiting service life of wells and determination of dominant mechanism of its damage for predicted operation period. The definition of well safe operation life is connected with the development of well reliability system. An example of elements included in the well reliability system is given, each of which is assigned a corresponding significance factor. The evaluation algorithm of the impact of properties of reliability system elements on its safe operation life is shown.

1. Introduction
The strength, durability and tightness of a well as a capital construction object are determined by the corresponding properties of the support.

Therefore, it is difficult to overestimate the importance of geophysical prospecting in order to determine the technical condition of support elements, in particular, well bearing structures – casing strings.

It is possible to determine (recognize) the technical condition of the casing if:

• as a result of instrument studies the types of damages are identified and their characteristic dimensions are determined;
• according to the obtained data, the actual strength parameters of the studied casing strings are calculated (values of excessive internal and external pressures, at which maximum stresses arising in the areas of damage are equal to the yield point of the material).

The solution of diagnostic problems is always connected with reliability forecasting for the nearest period of operation [1].

It is possible to predict the service life of wells if there is statistics related to the technical condition of the main bearing element of the support – production casing and the dominant mechanism of its damage for the predicted period of operation is established.

Gamma-percentile (or standard) service life is established when data on actual well service life are accumulated [2].

Leakage of the support (casing strings and cement sheath) affects the safety of well operation, can provoke fluid migration and lead to well liquidation [3].
2. Definition of actual strength indices of load-bearing elements

The load-bearing elements of the support, which receive the working loads during construction and operation of wells, include casing strings (intermediate and operational, respectively).

It should be noted that as the object of calculation the casing strings (except for very thick-walled ones) meet the engineering criterion of fineness [4] and belong to the class of thin-walled roller shells.

The analytical calculation of cylindrical roller shells having an arbitrary cross-sectional configuration is extremely complex [5] and is generally related to the division of the cross-sectional contour into regions having a constant radius of curvature. By way of example Figure 1 shows the cross section of a string with deformed cross section.

![Figure 1. Oval cross-section in the form of joint of cylindrical plates of different radii.](image)

As can be seen, the casing is presented in the form of articulated cylindrical plates I and II (Figure 1) having radii \( r_1 \) and \( r_2 \) respectively. The solutions for plates are built together with boundary conditions of deformation continuity in places of their connection.

As can be seen, the analytical calculation of casings with cross-section of an arbitrary configuration is extremely difficult.

Therefore, prior to the development of software based, in particular, on the finite element method, there were no methods to calculate the strength of damaged strings. The exception is temporary guidelines for calculation of casing strings worn out by tool joints of a drill string [6].

However, in the calculation formula, the trough-like working lost clear lines and a string with increased values of ovality and wall variation (relative to their normalized value) became the calculation scheme of the damaged string.

The development and implementation of strength calculations of software based, in particular, on the finite-element method eliminated all difficulties related to modeling of the actual configuration of damaged casing strings.

At the moment there is a set of methods for strength calculation of damaged casing strings by data of geophysical study (GIS) of technical condition [7]. At the same time, each particular damage required the individual procedure for calculating casing strings.

Typical types of damages were determined as a result of the GIS analysis of the technical condition of casing [8].

The calculations of actual strength parameters of casing strings according to GIS data “crossed the T’s” in the issue of recognizing the technical condition of bearing elements of the support. In practice, this made it possible to focus on the selection of safe loads for casing strings both during construction and operation of wells.

The design support allowed the engineering staff to be oriented in determining safe loads for casing strings.

At the same time, naturally, there was a question about the value of error of calculations (for strength of damaged pipes) and its connection with instrumental errors at GIS of casing strings. The value of relative error of calculations is determined based on the following [9].

The results of calculations in accordance with procedures [7] are excessive external \( P'_{kr} \) and internal \( P'_{tr} \) pressure (MPa), at which maximum stresses in damaged strings are equal to the yield point of the material. The limit pressure values are calculated according to the following formulas:
where $P'_{kp}$ and $P'_{r}$ – nominal values of limit overpressures for pipes of the type size under consideration (MPa); $K_1$ and $K_2$ – dimensionless factors of reduction of load capacity of damaged pipes to excessive external and internal pressures, respectively.

It shall be noted that:
- obtaining expressions for calculating $K_1$ and $K_2$ as a function of nominal wall thickness $\delta$ (mm) and characteristic damage size $u$ (mm) made the basis of methods for calculating the strength of damaged casing strings;
- expressions for calculation of $K_1$ and $K_2$ are individual for each diameter $D$ of casing pipes and their type of damage.

It is understood that in such a case, the relative error in calculating $P'_{kp}$ and $P'_{r}$ arises precisely from the error in determining $K_1, 2$.

Let us consider the algorithm for calculating the relative error.

The expressions for calculating the coefficients $K_1, 2$ were derived from the statistical processing of arrays of their discrete values calculated on finite-element models of damaged pipes.

The basic provisions for obtaining discrete coefficient values were as follows:
- load reduction factors were taken to be equivalent to the effective stress concentration factors (which, under loads constant over time, show how many times the presence of a defect reduces the load capacity of the structure);
- effective stress concentration coefficients were taken equal to inverse values of theoretical stress concentration coefficients.
- theoretical coefficients of stress concentration were calculated observing the geometric similarity of finite-element models and damaged casing strings.

Thus, with regard to the theory, the expressions for calculations of load capacity reduction factors met the requirements for strength calculations of damaged structures. The theoretical aspect did not introduce errors in determining coefficients $K_1, 2$.

Let us look at functional dependencies for calculating the coefficients $K_1, 2$.

The general view of expressions is as follows:

$$K_{1,2} = C_1 \cdot \exp(C_2 \cdot u)$$

where $C_1$ and $C_2$ – coefficients defined by expressions:

$$C_1 = c \cdot \delta + d$$

$$C_2 = a \cdot \delta - b$$

where $u$ (mm) – characteristic damage size; $a, b, c, d$ – numerical coefficients ($d$ – dimensionless, $a, b, c$ – dimensional); $\delta$ (mm) – thickness of the pipe wall.

From formula (2), it can be seen that the parameter specifying the magnitude of the error in determining the coefficients $K_1, 2$ is the extent of damage “$u$”.

It shall be noted that “$u$” is:
- established according to the data of geophysical surveys of the technical condition of casing strings;
- related to the actual (minimum) thickness of pipe walls in the area of damage, except for dimensions of pipe cross-section deformation (radial deflection).

The instruments, according to which “$u$” is determined, have different values of absolute error, in particular 0.5 mm or 1.5 mm. It is understood that “$u$” will have the same absolute error $\Delta u$.

The relative error $\varepsilon_1(K1,2)$ in calculating the $K1$ and $K2$ coefficients caused by the error in determining “$u$” was calculated using the first differential technique.

At the same time, it was found that at $\Delta u = 0.5$ mm the relative error of calculation of residual strength parameters is as follows:
• for pipes with ratio \( \frac{\delta}{D} \geq 0.06, \varepsilon_1(K1, 2) = 5–10\%; \)

• for pipes with ratio \( 0.02 < \frac{\delta}{D} < 0.06, \varepsilon_1(K1, 2) = 11–14\% \).

For engineering calculations, the permissible error value makes 15\% [5].

3. Conclusions
1. Calculations of residual strength help to prevent emergency situations related to non-conformity of operating loads of actual strength of casing strings, which improves safety of well construction and operation.
2. The calculation error of residual strength of damaged pipes will be within the range of permissible values, if the absolute error of pipe wall thickness (or radial deviation of cross section) during geophysical studies of technical condition does not exceed 0.5 mm.
3. The calculations according to GIS data (technical condition of casing strings) place increased requirements for their accuracy and reliability.

4. Determination of well life indicators
4.1. Forecast of residual well life
Forecasting of residual well life is performed based on the following:
• residual well life is determined by the residual life of production string [10];
• the dominant type of damage to production casing strings for the predicted period of operation is the total corrosion wear of the internal surface. This type of damage is identified on the basis of GIS analysis through the study of production well strings with different service life;
• residual life is forecast on the basis of characteristic reflecting the reduction of carrying capacity of string pipes at the increase of corrosion damage depth.

Such characteristic is represented by expressions for calculation of load capacity reduction factors of pipes (to excessive external and internal pressures) at general corrosion damage of internal surface [11].

Let us illustrate the above by the calculation of residual life of pipes with the diameter of 168.3 mm. Let us accept that the operational load of the forecast period of operation is excessive internal pressure \( P_{\text{in.ex.}} \).

The characteristic of reducing the carrying capacity of pipes with the diameter of 168.3 mm at the total corrosion of internal surface is as follows:

\[
K_2 = (0.0235 \cdot \delta_f + 0.8038) \cdot \exp((0.0304 \cdot \delta_f - 0.5455)u)
\]

where \( K_2 \) – coefficient of reduction of load capacity of damaged pipes to excessive internal pressure; \( \delta_f \) – actual thickness of pipe wall, mm; \( u \) – depth of corrosion damage, mm. \( \delta_f \) and \( u \) are set at casing non-destructive testing at the moment of calculation.

The criterion of the maximum condition of the pipes is the reduction of the wall thickness to the maximum permissible value \([u]\). \([u]\) is calculated from the expression converted with respect to it:

\[
[u] = \frac{\ln\{[K_2]/(0.0235 \cdot \delta_f + 0.8038)]\}}{0.0304 \cdot \delta_f - 0.5455}
\]

\([K_2]\) – permissible value of the load reduction factor:

\[
[K_2] = n_2 \cdot P_{\text{in.ex.}} / P_{\text{r}}
\]

where \( P_{\text{r}} \) – excess internal pressure at which maximum stresses in the damaged pipe walls are equal to material yield point, MPa. The value \( P_{\text{r}} \) is calculated, for example, according to [7]; \( P_{\text{in.ex.}} \) – operating load for the forecast operation period, MPa. Pressure character – static (re-static); \( n_2 \) – factor of safety to internal pressure.

Residual life \( T \) (years) of casing strings is calculated by formula
where $V = \frac{\Delta \delta}{\Delta t}$ (8)

where $\Delta \delta$ – changes of thickness of a wall by $\Delta t$ time period (year) for which it occurred (mm).

5. Conclusions

1. The residual service life of operational casing is forecast taking into account its technical condition and individual reserve of load capacity to operational load.

2. This is rational since individual forecasting of operational life of objects usually leads to the increase of their average life, as well as to inter-repair periods of operation [12].

3. However, if another dominant mechanism for damage to production strings is installed according to GIS data, for example, a combination of total corrosion damage to the inner and outer surfaces of the string pipes, this will require the development of an appropriate methodology for calculating their residual life.

5.1. Determination of gamma-percentile life

The gamma-percentile life is determined according to the statistics on their actual service life. Such data, in particular, can be the results of Safety Expert Review (SER) of wells.

Table 1. Distribution of the number of wells by extended service life

| Extended operation life | Number of wells, % |
|-------------------------|-------------------|
|                         | 2007 | 2008 | 2009 | 2010 | 2011 |
| full                    | 57.8 | 55.2 | 90.3 | 81.1 | 91.1 |
| reduced                 | 38.4 | 41.0 | 5.1  | 16.2 | 5.5  |
| not extended            | 3.8  | 3.8  | 4.6  | 2.7  | 3.4  |

Let us consider one example. Table 1 shows the SER results related to the extension of safe operation life of wells at underground gas storage facility from 2007 to 2011 [13].

Non-extension of service life is considered as a failure (event when operational condition of an object is violated [4].

Comment to Table 1:

• starting from 2009, the number of wells with the maximum service life is dramatically increasing. Explanation – in 2007–2008, a significant number of SERs was carried out for wells with service life of more than 30 years (40, 50 and more). Such wells extended their service life at the second SER of wells;

• the number of wells, the service life of which is not extended, is almost stable.

From the latter it is concluded that the probability of failure-free operation of wells $\gamma$ at service life from 30 to 50 years is on average 96 %.

It shall be noted that the method of statistical data processing is the simplest, while the conclusions are essential. In accordance with the obtained value of gamma-percentile life, the service life of underground gas storage facility was adjusted. In this case, the gamma-percentile life is an operational indicator of well reliability.

Note – Operational reliability index – reliability indicator, point or interval estimation of which is determined by operation data.

Let us note the representativeness of sampling comprising eight hundred (800) wells, as well as different reasons of well failures, namely:

• leakage of production string;
• intercasing pressure;
• fluid migration, etc.
Despite various reasons, the wells were classified as one group – failed. In the practice of engineering reliability analysis this is possible on the basis of the principle of the same consequences, when random events (failures, damages, etc.) can be included in the common classification group leading to the same consequences [14].

6. Conclusions
1. The determination of actual gamma-percentile life requires the accumulation of statistics on actual well life.
2. It appears that such data should be generated for wells of each field separately.

7. Well reliability
From the classical perspectives of the reliability theory, an object (technical system) is divided into elements interacting with each other according to some logical schemes – a reliability structure diagram is designed. The reliability of the system is dependent on the probability of failure-free operation of all components.

It is essential that the elements of technical systems are mass-produced products for which reliable statistical estimates of reliability indicators are possible [13].

Since wells are not objects of mass production, it is understood that the system theory is not suitable for studying their reliability.

In practice, the applied methods are used to study and forecast well reliability [15], the main components of which are as follows:
1. strength and durability calculations of well bearing structures;
2. determination of safe operation life.

When solving the issue of extension of the safe operation life of wells, the following measures are taken:
1. residual well life is calculated;
2. well reliability system is created, consisting of i elements (for example, production string, annular space, wellhead area). Each element is assigned a significance factor \( \delta_i \);
3. impact of reliability system components properties on safe operation life is assessed.

Quantitative estimates of the state of the above objects are obtained using the methodology proposed in [15].

It is essential that the reliability of elements is evaluated by the characteristics of their state, for example, as shown in Table 2, where the code \( a_i \) – numerical value of the characteristic.

| State characteristic | Degree of reliability | Code, \( a_i \) |
|----------------------|-----------------------|---------------|
| During operation, the casing leakage along the threaded joints was noted. Repair works to eliminate leakage of threaded joints of the casing were performed two or more times. Triangular threaded pipe joints | Low | 1 |
| During operation, the casing leakage along the threaded joints was noted. Repair works to eliminate leakage of threaded joints of the casing were performed once. String OTTG, OTTM joints | Average | 2 |
| During operation, the casing maintained its tightness. String joints include metal-metal hermetic seal | High | 3 |

The integral characteristic of objects within the well reliability system is the \( K_0 \) coefficient, which is calculated using the following formula:

\[
K_0 = \sum_{i=1}^{5} \left( a_i \cdot \delta_i \right)
\] (9)

The value of \( K_0 \) coefficient determines not only the degree of reliability of a well, but also the reduction of its residual life, as shown in Table 3.
The extended safe operation life \( T_{oct}^B \) of a well is defined as the product of its residual life and coefficient \( C \):

\[
T_{oct}^B = T_{oct} \cdot C \tag{10}
\]

As can be seen, the extension of safe operation of wells is caused by the use of qualimetry methods.

### Table 3. Reliability levels and factors of well residual life reduction

| Well reliability factor \( K \) | Well reliability level | Well residual life reduction \( C \) |
|----------------------------------|------------------------|----------------------------------|
| 0.8–1.0                          | Very high              | 0.9                              |
| 0.64–0.8                         | High                   | 0.7                              |
| 0.37–0.64                        | Average                | 0.5                              |
| 0.2–0.37                         | Low                    | 0.3                              |
| 0.0–0.2                          | Very low               | 0                                |

It shall be noted that formally the safe operation terms are forecast taking into account the operating conditions, as well as the technical condition of both the bearing structure and the objects of the well reliability system.

### 8. Conclusion

1. Geophysical studies of technical condition are closely connected with the definition of reliability indicators (strength and durability) of wells, but without design tracking of well indicators the GIS results are not informative.

2. The use of GIS results as initial information for calculations is a powerful incentive to improve methods and means of diagnostics of the technical conditions of wells.

### References

[1] Birger I A 1978 *Technical Diagnostics* (Moscow: Mechanical Engineering) 234 p

[2] GOST 27.002-15 *Equipment reliability. Terms and definitions* 2016 (Moscow: Standartinform) 41 p

[3] *Safety rules for oil and gas industry* 2013 Federal norms and rules of industrial safety series 08 iss 19 (Moscow: ZAO “Sci. and Techn. Center for Res. on Industr. Safety Probl.”) 288 p

[4] Novozhilov V V 1951 *Thin shell theory* (Moscow: State publ. of shipbuild. Liter.) pp 344

[5] Boyarshinov S V 1973 *Basics of machine construction mechanics: “Safety rules for oil and gas industry”* Federal norms and rules of industrial safety series 08, iss 19 (Moscow: Mechan. Engineer.) 456 p

[6] Goncharenko A M 1975 *Temporary guidelines on calculation of worn-out casing strings* Approved by Deputy General Director Grozneft: Valid from 18.11.1975 (Grozny: SevKavNIPineft) 10 p

[7] *Instructions for calculation of damaged casing strings and casing strings under special operating conditions* 2007 STO Gazprom 2-2.3-117-2007 Approved by Deputy Chairman of the Board of OAO Gazprom A G Ananenkov on 22.11.2007 (Moscow: RPI Gazprom) 71 p

[8] Klimov V V 2001 Technical condition of well case in fields and underground gas storage facilities: problems and their solution, Review In *Drilling of gas and gas condensate wells* (Moscow: RPI Gazprom) p 65

[9] Tolpaev V A, Fedorov N G and Kolesnikov V V 2007 On calculation error of residual strength of casing strings according to GIS data *Onshore and offshore construction of oil and gas wells* 9 32–4 (Moscow)

[10] Fedorov N G 2017 *Cement shells and well durability* *Oil facilities* 8 86–8 (Moscow)

[11] *Instructions for calculation of well life and residual life: STO Gazprom 2-3.2-346-2009* 2009 (Moscow: Gazprom Expo LLC) 36 p

[12] Bolotin V V 1984 *Forecasting the operational life of machines and structures* (Moscow: Mechan. Engineer.) 321 p
[13] Shamshin V I, Fedorov N G and Dubenko V E 2014 On definition of terms of safe operation of oil and gas wells Onshore and offshore construct. of oil and gas wells 3 30–2
[14] Efremov L V 2008 Practice of probabilistic analysis of reliability of computer-based technologies (St. Petersburg: Nauka) 216 p
[15] Methodological recommendations for assessment of risk of accidents of hydraulic structures of reservoirs and industrial waste accumulators 2001 Approved by VODGEO Research Institute, 01.01.2001; coordinated by Emercom of Russia, order no 9-4/09-644 of 14.08.2001 (Moscow)