We are IntechOpen, the world's leading publisher of Open Access books
Built by scientists, for scientists

4,800
Open access books available

122,000
International authors and editors

135M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Chapter

Hybrid Modeling of Offshore Platforms' Stress-Deformed and Limit States Taking into Account Probabilistic Parameters

Gennady Yu. Shmal, Vladimir A. Nadein,

Nikolay A. Makhutov, Pavel A. Truskov and Viktor I. Osipov

Abstract

Offshore platforms should be referred to critically and strategically important objects of a technosphere due to technological and operational challenges, on the one hand, and the danger potential level, on the other hand. Environmental, social and economic losses occurred over several decades of accidents and disasters in unique Great Britain, Norwegian. The Russian and the USA platforms were evaluated in death of dozens of operators, destruction of platforms, environment contamination and hence in multi-bullion losses. All of these indicate insufficiency of currently taken engineering solutions, providing structure strength, operational life and safety. The scientific, design, expert and supervising organizations in Russia and in the world are developing and improving mathematical and physical methods, implementing the probabilistic formulations for accidents and disasters, risk assessment and risks reduction on offshore platforms. The solutions of the following problems are included: extension of the comprehensive computational and experimental strength, operational life and survivability analysis to the cases of nonroutine events, accidental and catastrophic conditions; numerical justification of modelling of critical elements, zones and points with the maximum tension, deformations and damages occurring under impacts of external extreme seismic, ice, wind, low temperature; implementation of comprehensive diagnostic methods for damage states evaluation within nonlinear and probabilistic fracture mechanics; and use of new structural design and technological systems for reduction of negative extreme impacts as well as emergency protection systems. The solution of the specified problems is illustrated by case studies of the Russian specialists for each life cycle stage of the platforms offshore Caspian and Kara Seas and Sea of Okhotsk.

Keywords: offshore platform, offshore technologies, safety of engineering systems, design solutions, analysis of the emergency situations, limit states, crash protection, seismic loads, technical diagnostics

1. Articulation of issue

Further development of the modern international community is going hand in hand with the intensive growth of fuel and energy raw materials consumption in all spheres of activity. Meanwhile, in the majority of on-land oil-and-gas regions, resources of oil and gas are exhausted and the possibilities of further increase of the discovered and usable economically recoverable reserves are complicated.

With this knowledge in mind, lately we can see special, increasing interest in a problem of the seas and oceans' oil and gas resources development [1, 2].

The gas and oil fields are discovered in 108 countries of the world. Ultimate reserves of gas reached 172 trillion cubic meters, of oil—172 billion tons; at the beginning of the twenty-first century, the world gas production was equal t0 2.6 trillion cubic meters, while oil production was 3.3 billion tons.

Initial recoverable hydrocarbon resources of the World Ocean continental shelf (up to 500 m isobathic line) and the inner continental shelf are estimated equal approx. to 370 billion tons of fuel oil equivalent (TFOE), including more than 200 trillion cubic meters of free gas and about 155 billion tons of oil and condensate.

The primal gas resources in water areas are concentrated within the shelf of the Northern Asia—44.5 trillion cubic meters. Its bigger part is located offshore in the Kara Sea. Offshore gas resources of Eastern Europe, North and South America and the Middle East are also comparable and considerable relative to ones in Northern Asia (21–24 trillion cubic meters).

In the world, since the 1940s, the multiple sea platforms (SP) are engineered and operated with a wide range of parameters and are used for offshore petroleum and gas production. The largest of them are five platforms of the USA, Norway and Russia. They provide production at sea depths up to 2.5 km and well-drilling up to 10–13 km. About 10 platforms are in operation in Russia: on Caspian, Okhotsk seas and on the seas of the Arctic Ocean. The most significant of them are the platforms "Piltun-Astokhskaya-A (former Molikpak)," "Piltun-Astokhskaya-B," "Lunskaya-A," "Orlan," "Berkut" and "Prirazlomnaya" (**Figure 1**). Length of already constructed offshore pipelines is about 300 km. In long term, the need of Russia in offshore projects includes the necessity to provide functioning of about 50 SPs.

In the world history of development of the continental shelf, a number of disasters and serious accidents with catastrophic consequences occurred due to lack of attention to measures for identification and mitigation of threats for safe operation is wrote. The 15 most dramatic accidents on drilling vessels and platforms of various types (semisubmersible, submersible, mobile, stationary) happened during the last 40 years were followed by:

- great loss of lives (up to 164 people) occurred due to limited space on the platform, evacuation difficulties and vulnerability of personnel to thermal fire impact and toxic effects caused by combustion products;

- infilling and destruction of platforms infrastructure;

- offshore areas and airspace pollution; and

- vegetal and animal life demise.

Most economic direct loss suffered after the disaster on the platform in the Gulf of Mexico (USA) and was more than 20 billion dollars, while indirect losses reached

Figure 1.
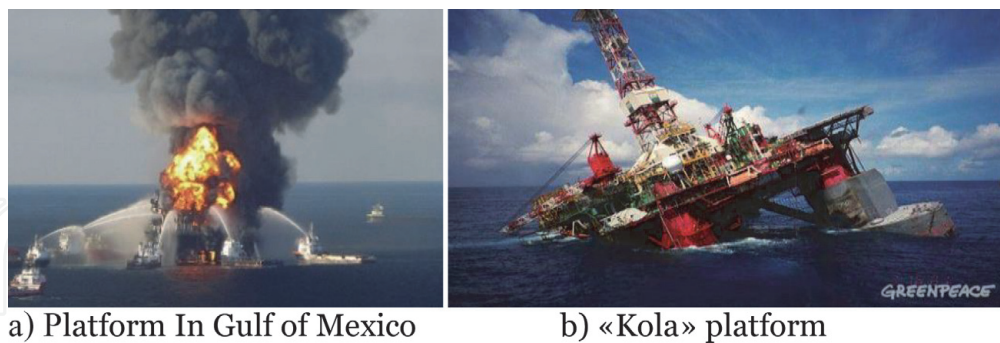*Large offshore platforms in Russia.*

Figure 2.
Disasters of large scale platforms in USA (a) and Russia (b).

60 billion dollars; the direct economic loss suffered from flooding of the "Kol'skaya (Kola)" platform (Russia) is about 200 million dollars.

Review of accidents with catastrophic consequences (death of great number of people, large-scale ecological contamination or material losses) occurred on oil and gas production platforms demonstrate reduction in number during recent years. This can be explained by the platforms' technological and design performance improvements and application of modern safety systems (**Figure 2**).

Evaluation of information about accidents and disasters occurred on offshore drilling rigs of various types makes it possible to combine and classify all accidents in accordance with major, internally connected accidents sources (**Figure 3**):
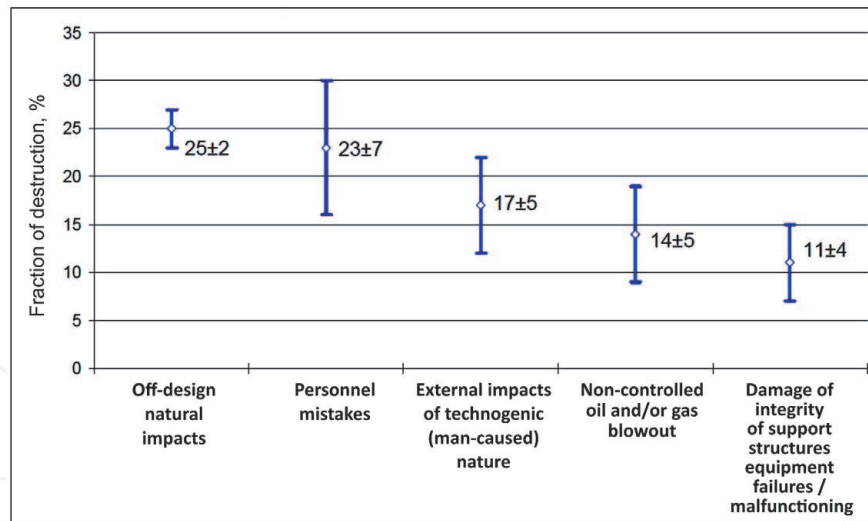
Figure 3.
Characteristic of accidents on oil and gas production platforms.

uncontrolled release of oil and/or gas from the well; damage of integrity of load bearing (or supporting) structures, as well as equipment failing (or malfunctioning); personnel mistakes; external impacts of technogenic (man-induced) nature (allisions with seagoing vessels, helicopters fall, subversive actions); and off-design impacts of the natural environment.

The probability of accident that may occur during a year on the Unit is in the range from 8×10^{-5} up to 1.6×10^{-3} per year, and this conclusion is based on the data in the Declaration of Industrial Safety for four Russian production platforms and nine floating drilling rigs.

2. Comprehensive issues of industrial safety in the process of the continental shelf development

2.1 Risks analysis

One of the first places in the field of strategic planning takes the problem of scientific and methodological frameworks building, while in the field of safe shelf development takes scientifically grounded criterion base. At the same time, it is considered that strategic risks of the Russian continental shelf development can be an essential part of strategic risks of national security.

In view of the foregoing, the main objectives of the Institutes of the Russian Academy of Science (RAS) and the leading security matters sectoral scientific research institutes are as follows [1–3]:

- risks' theorization based on fundamental risk analysis database collected and studied in the process of research works in social, natural and technical science of fundamental base. Risks function R(t) is analyzed in three main spheres of activity—social (N), natural (S) and technogenic (T), forming the uniform complex social-and-natural-and-technogenic system functioning in time t

$$R(t) = F_R\{R_N(t), R_S(t), R_T(t)\}; \tag{1}$$

- formulation of the generalized model of the specified complex system with definition of its main components N, S, T role in terms of values of basic risks

parameters R(t)—probabilities of occurrence of P(t) negative processes and events (dangers, challenges, threats, crises, disasters and accidents) and consequential losses U(t)

$$R(t) = F_R\{P(t), U(t)\} \tag{2}$$

$$P(t) = F_P\{R_N(t), R_S(t), R_T(t)\} \tag{3}$$

$$U(t) = F_U\{U_N(t), U_S(t), U_T(t)\} \tag{4}$$

- identification of negative events scenarios with regard to a complex system and quantitative risk assessment R(t) through parameters of main triggering and affecting factors—dangerous energies E(t), substances W(t) and information flows I (t)

$$R(t) = F_R\{E(t), W(t), I(t)\}. \tag{5}$$

On the basis of Eqs. (1)–(5), categorization of emergency situations, high-risk objects and dangerous processes in terms of risks R(t) is developed. Objectively, the norm settings, regulation and control in the area of safety provision as per safety and security major components (i.e., social and economic, military, scientific and technical, industrial, environmental and demographic) when using risks nominally comes down to ratio

$$R(t) \leq [R(t)], \tag{6}$$

where $[R(t)]$ is acceptable risks level.

The $[R(t)]$ value is set and defined by bodies of the highest public administration with consideration of abilities and the capacity of the country, level of scientific justifications and domestic and international experience. The realization of the requirement (6) [1–3] will be provided proceeding from the position that the defining risks of R(t) are two groups of risks:

- individual risks (1 per year) of life and health loss caused by abovementioned negative processes and events; and

- economical risks (rubles per year, dollars per year) caused by negative processes and events that are taking into account vulnerability of social *(N)*, natural *(S)* and technogenic *(T)* areas according to Eqs. (1)–(4).

The economic damages due to loss of lives and human health and environmental and technical infrastructure damages are included in the economic risks R(t). Scientific justification of acceptable risks [R(t)] includes development of methodology of definition of critical (limiting, inadmissible) risks Rc (t) and fixing of risks margin n_R in the form of

$$[R_c(t)] = \frac{R_c(t)}{n_R} \tag{7}$$

For quantitative assessment of value of risks Rc (t) relevant to accidents and disasters on SP all basic, Eqs. (1)–(7) can be used while the value of risks margin n_R shall be greater than unity ($n_R \geq 1$). Considering the best domestic and foreign practices, the variation for risks margin can be rather wide ($2 \leq n_R \leq 10$) at the beginning.

Based on (1)–(7), actions to provide enhancement of safety and security with the corresponding economic expenses Z(t) shall be developed. The actions directed to reduction of risks R(t) value to the level [R(t)] have to be effective and correlate with the levels of estimated risks R(t)

$$Z(t) = \frac{R(t)}{m_z},$$
(8)

where m_z is the performance factor of economic costs for reduction of economic risks ($m_z \geq 1$).

The general expression for the analysis and the sea platforms safety provision as per risks criteria based on Eqs. (1)–(8) is the following:

$$R(t) = F_R\{P(t), U(t)\} \leq [R(t)] = \frac{R_c(t)}{n_R} = m_z \cdot Z(t).$$
(9)

In the Eq. (9), practically are represented all set above main:

- scientific risks $R(t)$ analysis via its basic components $P(t)$, $U(t)$;

- justification of acceptable risks $[R(t)]$;

- scientific-methodological justification of risks' tolerance $R_c(t)$ and risks' margins n_R; and

- development of methodological recommendations on formation and implementation of the actions directed to risks R(t) reduction to the acceptable level [R(t)] providing optimal expenses Z(t) with the set efficiency factor m_Z.

2.2 Potential hazards characterization in the technical area when developing the sea shelf

With the progress and complication of engineering of technogenic aspects in the field of sea shelf development the analysis of man-caused (technogenic) offshore accidents and disasters becomes one of the most vital tasks of fundamental, inter-disciplinary research; applied scientific and technical developments; development of diagnostic and monitoring systems; and designing of barriers and protection means. The ultimate purpose of such research works and development becomes the problem of evidence-based assessment of comprehensive risks and adjusting these risks to acceptable levels by use of expressions (1)–(9).

The analysis and generalization of the numerous data (in the most developed countries, such data bases amount thousands and tens of thousands facts) make it possible to carry out certain classification of technogenic and natural and man-made accidents and disasters [3]. Classification of accidents can be performed on scales of the countries and territories affected by them, on number of the victims and injured persons and on economic and ecological damage; in such classification, seven general groups can be identified: planetary, global, national, regional, local, object-based and local emergency and catastrophic situations (**Figure 4**).

The events resulting in similar serious accidents within technogenic field can also be classified by potential hazard and in this line can be named objects of the nuclear, chemical, metallurgical and mining industry, unique engineer
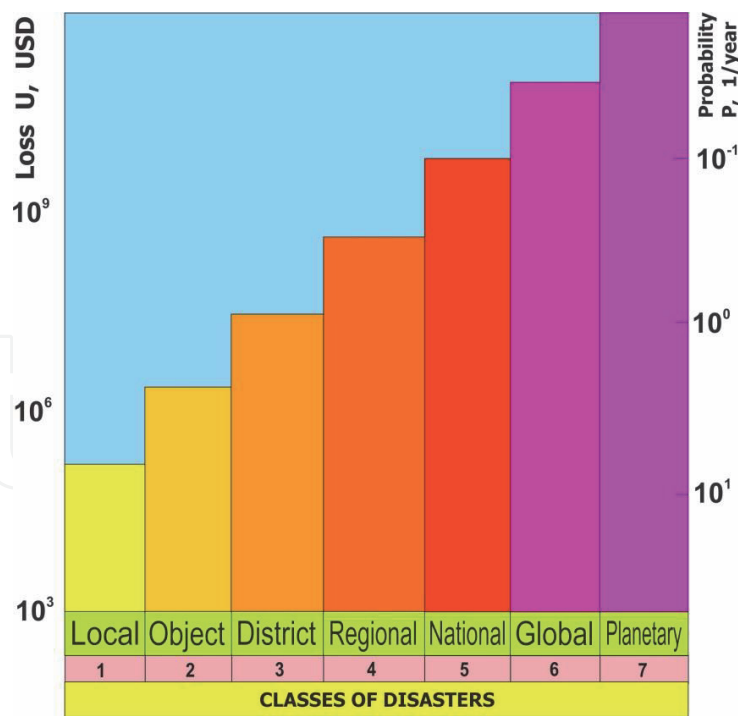
Figure 4.
Losses (damages) and frequency of natural and man-made accidents and disasters.

constructions (dams, platforms), offshore development objects (sea platforms, hydrocarbons storage tanks, LNG plants), the transport systems (airspace, surface and underwater, on-land) that provide transportation of dangerous cargos, large number of people, main gas-, oil pipelines and product lines. In this line, the hazardous objects of defense industry also shall be mentioned.

At the same time, a majority of accidents and disasters are followed by infringement of stress conditions and depletion of lifetime of the most loaded components in routine situations or in emergencies. The probabilities P(t) characterizing frequency of disaster accidents occurrence in peace time ranges from $(2–3)\cdot10^{-2}$ up to $(0.5–1)\cdot 10^{-1}$ per year, while damages (losses) U(t) ranges from 10^{11} to 10^{9} dollars per accident. At the same time, their risks R(t) vary in the limits from 10^{4} dollars per year to 10^{10} dollars per year ranging from 104 dollars/year up to 1010 dollars/year.

In view of said above, the new fundamental and applied scientific tasks needed to be set at national and international levels, for instance:

- mathematical theory of disasters and probabilistic theory of risks;

- physics, chemistry and mechanics of emergencies and disasters;

- limit states, strength and lifetime theories taking into account accidental and emergency situations;

- theory of hardware, functional and integral protection in case of emergency of objects, operators and personnel;

- theories of monitoring and forecast of scenarios and technogenic (man-made) disasters consequences (using airspace, airborne and ground-based systems); and

- scientific methods, technologies and hardware for mitigation of consequences of emergency situations of technogenic nature.

7

Based on the level of potential hazard, according to the legislation requirements and taking into account accidents occurrence risks, the abovementioned objects of a technosphere can be split in four (4) main groups (**Figure 5**) for each of which corresponding safety requirements are provided:

- the objects subject to technical regulation (STR) with the main damages to objects themselves;

- the hazardous production facilities (HPF) with the main damages to production sites and objects which safe operation is provided under the law on industrial safety—there are hundreds of thousands of such facilities;

- the critically important objects (CIO) which damages affect members of the Russian Federation; and

- the strategically important objects (SIO) which damages are followed by losses to the country and the bordering states.

For the continental shelf infrastructures, the number of the objects to be analyzed is reduced by one or two orders.

In the system of initial standards, specifications and guidelines used for design and calculations of SPs were included the following documents:

- Russian regulations database:

GOST 27751-88 "Reliability of structural units and foundations. Basic calculations methodology.", 1988;
SNiP 2.01.07-85 "Loads and impacts", 1996;
SNiP 2.06.04-82*, "Loads and impacts on hydrotechnical structures (waves, ice and sea vessels)", 1995 & 1983;
Marine Registry. FDR/OFR Guidelines, 2001;
VSN 41-88, "Industry Specific Code of Practice for design of offshore ice-resistant fixed platform (OIRFP)", M., 1988;

- Foreign regulations database:

Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design, API Recommended Practice 2A-LRFD, 1993, Washigton;
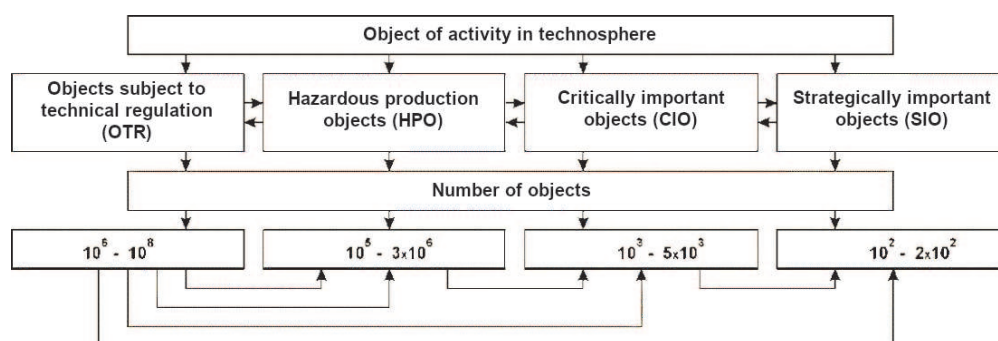

Figure 5.
Diagram of analysis of potentially hazardous objects of the technosphere.

Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Structures in Ice Environments, API Recommended Practice 2N (RP 2N), 1995, Washington;
CAN/CSA-S471-92, "General Requirements, Design Criteria, the Environment, and Loads", A National Standard of Canada, 1992; Toronto; Commentary to CSA Standard CAN/CSA-S471-92, "General Requirements, Design Criteria, the Environment, and Loads", 1992, Toronto;
CAN CAN/CSA-S473-92, "Offshore Structures", A National Standard of Canada, 1992 CAN CAN/CSA-S16.1-94, "Limit States Design of Steel Structures", A National Standard of Canada, 1992, Toronto;
DnV, "Structural Design, General", Rules for classification of Fixed Offshore Installations, 1993;
DnV, "Structural Reliability Analysis of Marine Structures", 1992. DnV, Offshore Standard OS-C101, Design of Offshore Steel Structures, General, 2001; ISO 19906, 2010 (ISO/DIS 19906 "Petroleum and natural gas industries - Arctic offshore structures", 2010).
Above documentation was used for definition of the main basic specified characteristic load during design of the sea platforms intended for use at a sea depth from 20 to 70 m to 200–250 m.

2.3 Types, design diagrams and cases

Implementation of the proposed recommendations and norms covers the structures with vertical and inclined sides, monopods and multicolumn constructions. In the documents, the rules of definition of the main loads conditioned by action of all potentially dangerous ice features subject to consideration are given. In **Figure 6**, the various structures design versions are presented.

The following loads are subject to analysis:

Global conventional and extreme loads on conical and vertical constructions: sheet and rafted ice; ice ridge compression; ultimate moving force (ice field crowding force); global (abnormal loads); ice islands (stopped by a construction).
Local ice pressure (for vertical and inclined surfaces): solid ice area; and ice fragments area.
Ice loads dynamics: shock actions and interaction "ice—construction" (self-excited); ice load change in time; fatigue ice impact; ice grinding impact; and regelation.
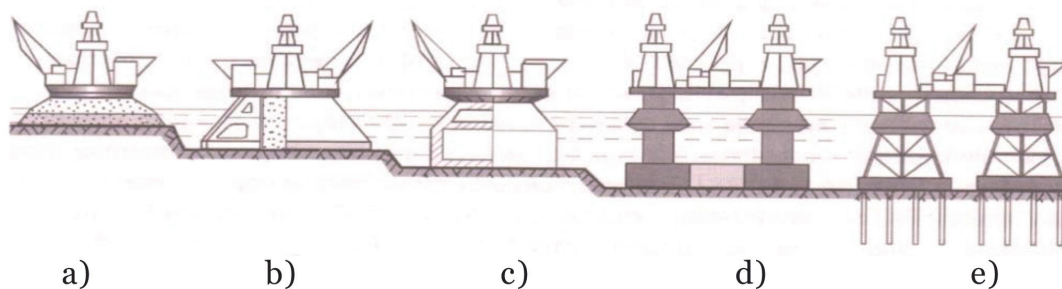

a)   b)   c)   d)   e)

Figure 6.
Types of sea platforms dependent on the sea depth (for standard soil conditions): (a) the artificial pad, depth is up to 5 m; (b) the caisson-island fixed along contour, depth up to 15–20 m; (c) the monopod or monokone, depth is up to 25–30 m; (d) shell support; and (e) the truss-shell type supports, depth 25–30 m and more.

Utility	Fixed to the bottom			Floating		Islands	
Design	Gravity based	Pile supported	Integrated	With anchor mooring	Dynamic positionable	Outlined	Non-outlined

Table 1.
Ice resistant oil and gas utilities.

Broadly speaking, the offshore oil and gas facilities can be classified by the following signs: structural materials; design features; methods of fixing to a bottom; ice resistance indications; and functional features. The design features of offshore oil and gas facilities incorporate the following types: stationary platforms; submersible and semi-submersible platforms; pendulum constructions; tension structures; platforms of SPAR type (with the underwater cylindrical foundation); access bridges and pier sites; and dams and unpaved sites.

Ice-resistant constructions can be grouped as follows (**Table 1**).

2.4 Russian shelf specific conditions

The Russian continental shelf area exceeds 6 million sq. km that takes about 25% of a shelf zone of all the World Ocean. The Arctic and Far East shelf areas are the areas of the greatest interest.

With respect to environmental, bathymetric, engineering-geological, seismic and other conditions, the shelf of Russia is different from others due to a number of features:

- severe ice conditions (large drifting ice fields, ice ridges, floating ice hummocks, etc.);

- shallow waters (depths less than 100 m) leading to significant increase in wave loadings;

- high level of seismicity (on the Far East shelf); and

- difficult engineering and geological conditions.

In designing platforms for the Russian shelf, as a rule, it is necessary to consider a combination of at least three factors from listed above. This is unlike world practice.

When selecting this or that type of platform jack design along with environmental conditions, it is necessary to take into account the impact of the field development general scheme, production method and hydrocarbons transportation technology as well as terms of platform fabrication and transportation on site.

When developing scientifically grounded methodology of design of gravitation-type platforms for use on Russia shelf, i.e., design providing the required reliability and safety level and, as much as possible, based on the lessons learned by the international and Russian specialists in design, construction and operation of platforms, it is necessary to:

- analyze the Russian and foreign regulating documents;

- set up an integral approach to platforms reliability and safety assurance at different stages of their life cycle;

- select correct existing and develop new methods of definition of environment loads;

- develop the concept of consideration of engineering-geological conditions;

- provide consideration of the level, nature and duration of dynamic impacts;

- formulate additional requirements to be imposed on sea engineering surveys; and

- justify the range of design cases for assessment of bearing capacity and stress-deformed state of the system "construction—foundation."

2.5 The analysis of external and internal factors and threats for safety of sea platforms

The analysis of threats for off-shore oil and gas production platforms is the first stage of the accidents' risks analysis for the specified objects and provides estimation of their safety level [1, 2]. The threat for SP is the probabilistic characteristic defining a possibility of the impact of affecting factors of specific type, intensity and duration in response to some dangerous (extreme) event that can take place both in the territory of the object and in the external environment. Therefore, the analysis of threats for SP has to be preceded by assessment of dangerous events which can initiate impact of the affecting factors on platforms.

The secondary dangers occur and provoke secondary affecting factors when some object's process modules – SP parts are damaged. The possibility of initiation of these secondary threats will be defined by vulnerability of an object in relation to the primary threats. Thus, the analysis of threats has to be made in an agreement with assessment of vulnerability of the SP parts in relation to the affecting factors acting on them.

The danger to SP is defined by the pattern of random events or processes (Th): extreme external natural and technogenic impact, wrong personnel actions and operating conditions of the object technical systems having the potential which can lead to accident. Examples of such events are: seismic activity, extreme wave or ice loads (external dangers), loss of the oil tank containment or of fatigue damages accumulation (internal dangers). The danger of an extreme event is a random variable which, in the simplest case, can be characterized by the probability of occurrence of an event $P(Th)$ during a certain period (1 year) or the during the platform's operational lifetime (**Figure 7**).

Threats for SP are characterized by impacts on an object of the affecting factors of dangerous events. The threat is also a random event (process) H, which
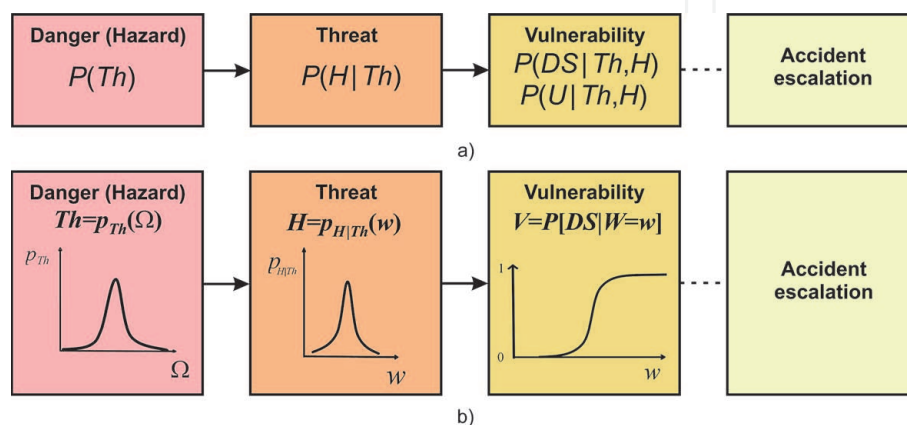

Figure 7.
Presentation of accident occurrence and development as a complex event. (a) Probabilities of the elementary events are described with the help of point estimations, and (b) probabilities of the elementary events are described with the help of probabilistic determination.

can take place in case of occurrence of a dangerous event and be characterized by conditional probability $P(H|Th)$. For the abovenamed dangers, the events listed below will act as threats:

- in earthquake case, the seismic wave will reach the site where object is located; and

- loss of the oil tank containment will cause the oil leak.

Vulnerability of SP to threat of this type is defined as the conditional probability in case of the affecting factor's impact on an object when the latter one will get a certain damage rate $P(DS_k|H)$, where k is an object damage rate.

If it is required to get more accurate description of danger of an extreme event, it should not be characterized by the point estimation of probability of occurrence of a dangerous event $P(Th)$ but by the distribution curve of danger intensity $p_{Th}(\Omega)$ or integral distribution function $P_{Th}(\Omega)$ presented in **Figure 7** (where Ω characterizes dangerous event intensity). In particular, the seismic hazard can be characterized by distribution of probabilities of potential earthquake intensity degree, while threat from loss of tank containment can be characterized by the distribution of probability of the effective opening area. At the same time, threats will be characterized by family of the conditional distribution functions $p_{H|Th}(w)$ corresponding to different intensity Ω of a dangerous event. Then the dangers of an earthquake and loss of containment mentioned above will correspond to the threats described by family of probabilistic distributions of amplitudes of vibration accelerations of soil on site of platform location at different earthquake magnitudes and family of probabilistic distributions of volume of leaked oil for different diameters of effective openings.

Vulnerability of an object relative to impact of the affecting factor with intensity w will be characterized by the vulnerability curve $V = P(DS|W = w)$, which defines the conditional probability of sustained damage of level DS with the proviso that a random value intensity $W_{\text{takes a certain value}}$ $(W = w)$.

When making decision on what physical parameter of impact of dangerous process on an object to select for threat intensity evaluation, it is necessary to consider vulnerability of an object relative to action of different components of such impact: for example, in case of seismic impact on the platform, some parts of the equipment and structures are the most sensitive impact from soil vibration accelerations, while the another to vibration amplitudes.

Within that narrative, the accident initiation on SP can be considered as the complex event occurring in case of occurrence of simultaneous random events cascade (**Figure 7a** or **b**):

1. danger: realization of the extreme initiating event $Th = p_{Th}(\Omega)$;

2. threat: impact of affecting factor of dangerous event on SP parts $H = p_{H|Th}(w)$; and

3. vulnerability: damage of SP's parts as a result of impact affecting factors of the initiating extreme event $V = p_{V|H}(w)$.

2.6 Damaging and affecting factors

SP operation is associated with production, storage and transportation of considerable volumes of dangerous materials, transformation of considerable volumes of energy, running of hazardous technological processes on the platform as well as with presence in areas of SPs' location of external sources of natural and

technogenic nature hazards which are resulting in extreme external impacts on the platform. Depending on the location of danger source (i.e., location of the place where the initiating event starts) outside or inside the platform boundaries, it should be taken into account the external and internal threats damaging and affecting factors. Risks $R(\tau)$ used in expressions (1)–(9) depend on them.

Internal threats for SP are initiated by dangerous process potential of the following [1–3]:

- mass and composition of chemically dangerous substances W which are on the platform; and

- amount of the reserved on the object energy E.

Among internal threats to SP are operational loads on parts and components of oil and gas production facility (OGPF), impact of harsh chemical environment, control system failures, etc. The considerable segment of internal threats range for OGPF is caused by human factor action (mistakes at a design stage, construction and operation of the platform, including violation of regulations, etc.).

Among external threats are affecting factors resulting from natural and technogenic events (processes) happening outside SP boundaries. Seismic impacts, hurricane, technogenic accident on the neighboring object, collision with the sea vessel, extreme weather conditions, etc. are between initiating events of the external type. Besides mentioned above, external threats include the events connected with interruptions in work of energy, telecommunication and transportation infrastructures which lead to breakdown of technological processes, damage of platform's control and supply systems and terrorist attacks which also can be classified as an external threat to the platform.

The probabilistic approaches usually are used for description of the initiating events and affecting factors [1–4]. The necessity to use the probabilistic methods is determined by lack of knowledge about comprehensive system "SP—the environment," on the one hand, and by stochastic nature of the processes occurring in a system and environment and by high uncertainty inherent to the examined system (uncertainty of system parameters, materials strength characteristics, external loads, etc. and also the uncertainty explained by limited knowledge of an object) on the other hand.

The threats (affecting factors) H(t) influencing SP (**Figure 8a**), in general, should be considered not only as the separate and determined processes (a) but also as random events (**Figure 8b**) and *stochastic processes* (**Figure 8c**). This is due to the fact that during analysis of the platforms' vulnerability relative to the prevailing threats, an essential role is played by damages' accumulation and fatigue mechanism of ultimate limit states reaching. Such approach necessitates review threats as dynamic task taking into account history of operational loads and dynamic and cyclic impacts of the affecting factors (external loads, influence of extreme temperatures, harsh environment, etc.).
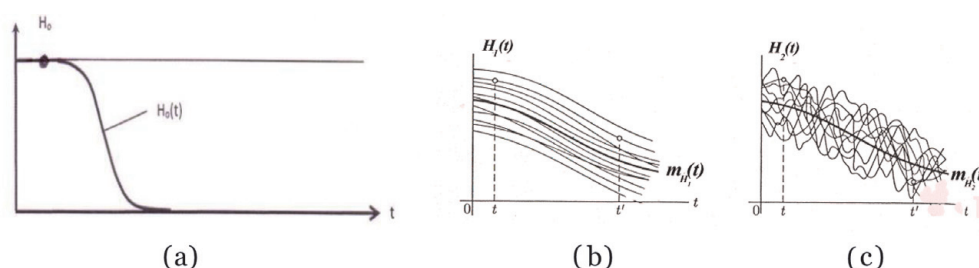

(a)   (b)   (c)

Figure 8.
Presentation of the threat as a random process.

In such problem formulation, the definition of threat for SP will be characterized by the random vector-process which is functional of a vector of internal and external force actions $\overline{Q}(t)$, temperature influences $T(t)$, fields of dangerous substances concentration $\overline{c}(t)$, radiations $\overline{\psi}(t)$ and information flows $\overline{I}(t)$.

$$\overline{H}(t) = F\big(\overline{Q}(t), T(t), \overline{c}(t), \overline{\psi}(t), \overline{I}(t)\big\} \tag{10}$$

Physical and chemical bases of the analysis of accidents occurrence and evolution conditions are defined both by work processes in technical SP systems, and by external impacts on these processes.

It is important to note that requirements to detailed level of this object threats' description are defined based on the used destruction mechanisms—external and internal types. The analysis of threats to SP has to be carried out in a manner to provide required data for further calculations of the following:

- stress, stiffness and withstandability (with use of material resistance methods);

- stress and cyclic life and life time (with use of methods of theory of high- and low-cycle fatigue);

- stress and life capability—life time (with use of methods of creep theory and creep-rupture strength theory);

- dynamic strength and life time (with use of methods of crash and fracture dynamics); and

- crack growth resistance (with use of methods of linear and nonlinear fracture dynamics).

If, on the contrary, the fatigue mechanism of destruction is used, the threat cannot be considered as a separate extreme event and has to be characterized by process of on-stream loading.

The quantitative description of development of accidents initiation on SP can be performed on the basis of fundamental mechanisms of disasters physics, chemistry and mechanics. At the same time, the stages of occurrence and development of emergencies can be characterized by various combinations of physical, chemical and the mechanical affecting and damaging factors.

Analysis of the majority of accidents of technogenic and natural-technogenic nature occurred on SP demonstrates that they are determined by three major dangerous factors according to equation (5):

- uncontrolled leak of dangerous substances W;

- uncontrolled hazardous energy E release (mechanical and thermal); and

- uncontrolled flows of diagnostic and controlled information of I.

If to take into account (**Figure 5**) the classification of accidents on critical infrastructure objects as well as parameters W, E, I mentioned above, then for classification of oil and gas production facility (OGPF), it is possible to set their critical states' limit areas (**Figure 9**). When talking about critical infrastructure objects, without no doubt, the off-shore oil- and gas production platforms (local—1,
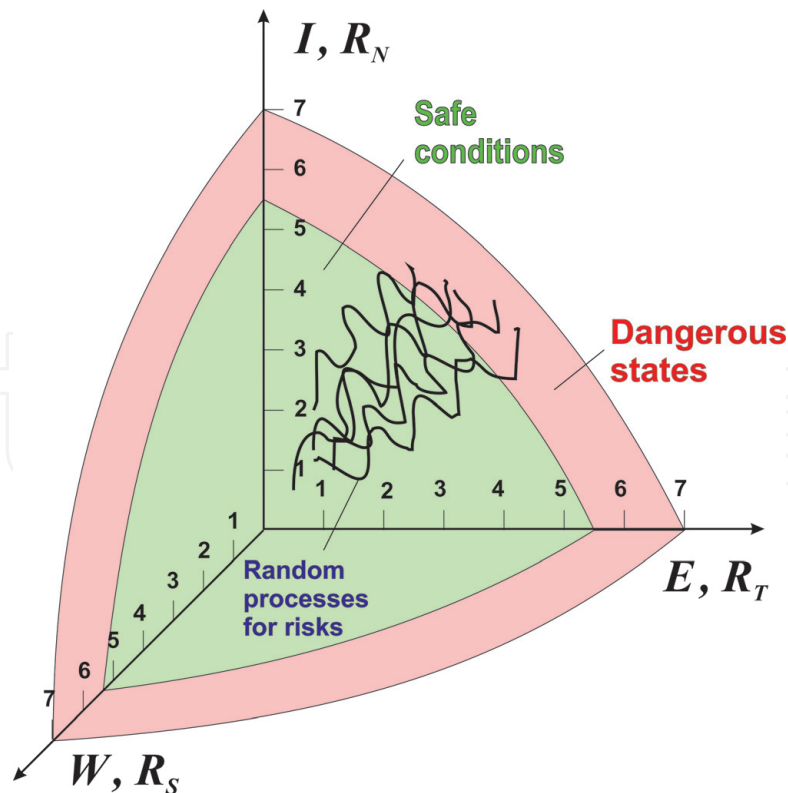
Figure 9.
Areas of dangerous and safe states of the system.

facility-based—2, domestic—3, regional—4, national (federal)—5, global (transboundary)—6, planetary—7) shall be included in the list of such objects.

Then, radius-vector in space of *W, E, I* will become a quantitative index of dangers to OGPF

$$|T_h| = \sqrt{\overline{W}^2 + \overline{E}^2 + \overline{I}^2}, |T_n| = \overline{W} \cdot \overline{E} \cdot \overline{I} \qquad (11)$$

where $\overline{W}, \overline{E}, \overline{I}$ is the hazard class of object for each of accidents classes (from 1 to 7). In the first case, the quantitative value of this hazard will vary from 1.73 to 12.2; and in the second case, it varies from 1 to 343.

The hazards related to external natural processes in the territory of OGPFs location are evaluated in another way and with use of other criteria (earthquakes intensity degree, force of winds, level of floods, extremeness of climatic temperatures, depths of holes, mass of landslides, volume of rainfall, etc.)

The equation (11) can be accepted as unified for different types of dangers: technogenic, natural and natural-technogenic.

In traditional formulation when performing analysis of threats to OGPD initiated by dangerous processes, the first stage of the analysis or problem solving is assessment of losses and risks relevant to accidents on OGPD objects. The solution of the inverse task making it possible to classify the threats to OGPD coming from known consequences of accident occurred on an (**Table 2**) is of interest.

At the solution of such tasks, the intensity of threats is subdivided into the following groups:

Group U1: the threats causing hypothetical accidents which can occur at the options and scenarios of development which are not predicted in advance, with

the greatest possible damages (total destruction of OGPD) and a large number of the victims.

Group U2 group: the threats causing the beyond-design-basis accidents which are followed by permanent damages of the SP critical components with high level of damages and fatalities.

Group U3: the threats causing the design accidents followed by standard outperformance with predictable and acceptable consequences.

Group U4: the threats causing the SP operating mode accidents followed by deviations from normal operation conditions while OGPD is operating in standard mode.

Group U5: the threats when an object operates in standard mode.

2.7 Design loads

The loading on offshore ice-resistant oil and gas structures can be split in three groups: permanent, temporary and special loads [1, 2]. Among permanent loads are the loads of the structure weight $P_{s.w.}$ and self-weight of soil and soil pressure on fixed piles. The temporary loads are subdivided into long and short term, namely:

- Long-term load:

  - weight of equipment and drilling rig;

  - weight of liquids, bulk materials and stocks of drill pipes and tubing;

  - weight of warehouse equipment and tools; and

  - weight of drilling cuttings (bore mud, etc.).

- Short-term load:

  - load on drilling rig in and derrick table during drill string trip;

  - snow loads (used for design of bowl type helicopter deck);

Type of accident	Threat causing the accident	Type of threat
Hypothetical accidents (Type T1)	Combination of unknown, unlikely and the difficult to predict constructive, technological initiating events and affecting factors of huge intensity, including terrorist attacks.	U1
Beyond-design-basis accidents (Type T2)	The affecting factors, the initiating events and damages development are not known in full.	U2
Design accidents (Type T3)	The affecting factors are known and predictable.	U3
Operating mode accidents (deviations from standard conditions) (Type T4)	The affecting factors are studied and controlled.	U4
Normal (standard) operating conditions (Type T5)	The affecting factors are well understood and controlled.	U5

Table 2.
Accident and threat types.

○ due to structural icing;

○ wind loads P_{wind};

○ waves P_{wave} and current P_{curr} loads;

○ loads caused by sheet and hummocked ice P_{ice};

○ docking impact load; and

○ helicopter impact load.

The special loads are the seismic ones P_{seism} and those initiated by natural phenomena (structure base subsidence, additional dynamic loads due to impact of ice filed on the structure imbedded in ice); and ice load due to hummocked nature of ice fields (collision of the structure and iceberg). Seismic impacts are taken into account during design of stationary platforms constructed in different regions with seismic magnitude of 7, 8 and 9.

For definition of seismic loads, it is required to have data on seismological parameters of seismic zones: magnitudes, depths of earthquake sources, the epicentral distances, earthquakes frequency, seismicity of the site and spectral characteristics of seismic impacts depending on engineering-geological conditions on construction sites.

Various types of loads on ice-resistant stationary platforms are schematically presented in **Figure 10**.

When calculating the wind and wave loadings, it is expedient to accept load factor for one of loadings equal to 0.9, and for another equal to 1. This assumption is based on more realistic knowledge (from physical point of view) by reference to correlation between these processes. In the case of basic combination, the calculated values of short-term loadings (wind, wave and current) respectively refer to the reliability factor which is equal to 1. For special combinations, these loadings are calculated with factor 0.8, however, at the same time, as well as in the previous case, two possibilities of wind and wave impacts on ice-resistant structures are taken into consideration.
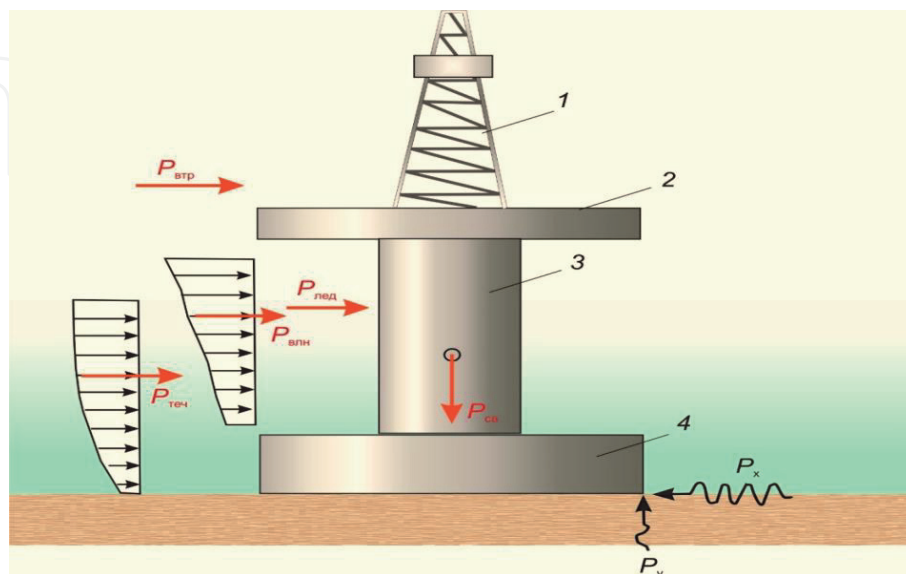

Figure 10.
Symbolic diagram of application of external loads on ice-resistant stationary platforms: 1—derrick; 2—deck; 3—jack structure; and 4—bottom module. For loads, the following symbols are used: P_{sw}—gravity force; and P_x, P_y—horizontal (shear) and vertical (transverse) reactions.

Types of calculated loads	Combinations					
	I	II	III	IV	V	VI
Dead loads	1.0	1.0	0.9	1.0	1.0	1.0
Long-term live loads	0.95	—	0.8	1.0	0.95	0.95
Short-term live loads:						
• *ice load* ($h = 0.8$ m);	—	—	0.8	—	—	1.0
• *wave load* (repeated once in 100 years);	1.0	1.0	—	—	—	—
• *wind load*;	0.9	0.9	0.8	1.0	0.8	0.9
• *current load*	0.9	0.9	0.8	—	0.8	0.9
Special loads:						
• *ice load* ($h = 2.5$ m);	—	—	—	—	1.0	—
• *seismic load*	—	—	1.0	—	—	—

Table 3.
Factors of loads combinations.

As an example of the case when simultaneous impact of the wide spectrum random loadings on ice-resistant structures for sea of Okhotsk conditions can use the approach based on factors of loads combination shown in **Table 3**.

In the given case, it is proposed to analyze the following loads combinations:

I. basic combination of loads during ice-free season;

II. combination of loads during construction and assembling works in ice-free season;

III. special combination allowing for seismic loads;

IV. combination for calculation of maximum efforts in structures of the topside facilities;

V. special combination allowing ice loads occurring during freeze-up period; and

VI. basic loads combination during freeze-up period depending on cycles' number.

In special combinations, the seismic load of calculated earthquake with magnitude 8 is accepted allowing the possible side dynamic effects: liquefaction of soil in the construction bottom and relevant subsidence, additional hydrodynamic loadings from ground shaking in case of open water and impact of ice fields on construction jacks during the winter period. However, depending on the earthquake source location, the specified side effects can happen with considerable time lag with respect to ground shake time, and summation of the caused by them dynamic impacts on a construction with seismic loads does not happen. Impact of the hummocky ice-fields can have very serious consequences for a construction; therefore, such case has to be separated as special loading and be analyzed in other special combination of loads.

In terms of (1)–(5), the total risk R of SP operation as mathematical expectation of incurred damages U should be presented as follows [3]:

$$R = \sum_{i=1}^{n} P(\mathrm{A}_i)U_i, (i = 1, \dots, n), \tag{12}$$

where $P(A_i)$ is the probability of causing damage U_i to a technological object and other objects, the population and the environment in case of the emergency scenario No. *I* and *n* is the number of possible outcomes of an emergency.

Generally, the probability *P* of occurrence of analyzed unfavorable event (or its components P_i) is defined as the function of function (functionality) depending on sources, corresponding affecting factors and objects subject to damage: person *N*, off-shore technosphere object *T* and environment *S*; taking into account (3), the probability will be defined by the formula:

$$P = F_p\{P_N(t), P_T(t), P_S(t)\} = \sum_i F_{P_i}(P_{N_i}(t), P_{T_i}(t), P_{S_i}(t)). \tag{13}$$

$P_N(t), P_T(t), P_S(t)$ are the probabilities of occurrence at time *t* of unfavorable (dangerous) event initiated correspondingly by human factor, technosphere or nature.

The general damage *U* or its components U_i defined by damages affected by the population *N*, objects of a technosphere *T* and the environment *S* as follows:

$$U = F_U\{U_N(t), U_T(t), U_S(t)\} = \sum_i F_{U_i}(U_{N_i}(t), U_{T_i}(t), U_{S_i}(t)). \tag{14}$$

$U_N(t), U_T(t), U_S(t)$ are damages caused by unfavorable (dangerous) events at time *t* from which suffered population *N*, objects of a technosphere *T* and the environment *S* correspondingly.

At the present stage of technical regulation, it is recommended to estimate the quantities of damages *U* and total risk *R* from unfavorable events by two indicators: economic—in dollars, rubles (conventional units) and in human losses (fatalities or non-fatal outcomes). Human losses should be estimated by the number of injured or probability of fatalities.

Taking into account expressions of (13) and (14), components of damages and probabilities of accidents can be calculated separately by use of various methods of risk assessment. Also from the expression of the risk (12) presenting the summation of risks of different emergencies, it becomes clear that to define the total risk, the various methods for definition of its components can be used, i.e., the combined approach is applied.

Combined risk analysis is based on the systematic approach that provides review of the system of interest in a formalized manner, i.e., by studying of subsystems' components by considering structural and functional features of this system at the same time.

The damages and losses *U* caused by technogenic accidents and disasters are defined by three basic components by taking into account expression (4):

$$U = U_T + U_S + U_N, \tag{15}$$

where U_T are damages to off-shore technosphere objects; U_S are environmental damages; and U_N are damages to the population (to the person and society).

Damages U_T are defined by summation of damages from destruction of industrial buildings and constructions of $U_{T\varPi}$ type; damages from destruction of civilian (residential) objects of $U_{T\varGamma}$ type; and damages from destruction of

infrastructure of $U_{TИ}$ type (transportation, energy, pipeline, telecommunication systems, etc.):

$$U_T = U_{TП} + U_{TГ} + U_{TИ}. \tag{16}$$

Environmental damages U_S defined by summation of damages to soil $U_{SП}$, aquatic U_{Sa}, air $U_{Sв}$ environment, flora U_{Sp} and fauna $U_{Sж}$ are as follows:

$$U_S = U_{SП} + U_{Sa} + U_{Sв} + U_{Sp} + U_{Sж}. \tag{17}$$

Damages to the personnel and population U_N are defined by summation of losses from fatalities $U_{Nб}$ and losses from injuries (permanent injuries and health damages) U_{Ny}, which are as follows:

$$U_N = U_{Nб} + U_{Ny}. \tag{18}$$

Damages and losses quantitatively are defined by two types of parameters:

- in physical units—scales (number of damaged objects and injured people, polluted and damaged territories by area); and

- in equivalent economic units (rubles, dollars).

In statistical estimation of the above damages, the summarized information about emergencies from the state reports of departments can be used.

In probabilistic estimation of damages, the data from simulation modeling, data on probable areas covered by the affecting factors, and probabilistic and statistical data on vulnerability of objects, the environment and the population at various emergencies are used.

In the analysis and risk assessment, various aspects of accidents and disasters occurrence and development including various dangerous processes, the factors initiating events, scenarios of development, objects and personnel pattern damage function, etc. can be considered.

The variety of issues to be studied in the analysis process and risk assessment requires application of various methods at various stages of the systems analysis of examined object safety, as well as their integrated application.

Some methods in nature are integral ones; for example, the logical-and-probabilistic method, which includes a graph method, a probabilistic method, a logical reasoning method, event tree analysis and fault tree analysis are probabilistic methods implementing the graph method.
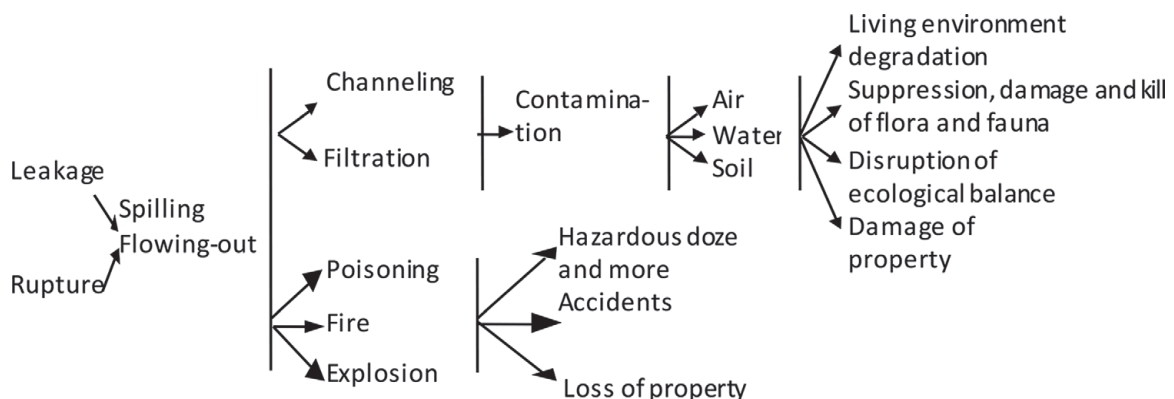

Figure 11.
Basic scenarious of accident development on sea platform (SP).

The main possible events chains for scenarios of accidents on OGPF are presented in **Figure 11**. The main events (faults) causing accidents are the leak and rupture of technical pipelines. These faults cause development of accidents in various scenarios and corresponding damages. All these possible scenarios and corresponding damages have to be taken into account.

2.8 Consideration of ultimate limit states at risk assessment of SP condition

When forming a system of classification of ultimate limit states in routine operating conditions of objects and in case of occurrence of accidents and disasters in comprehensive technical systems, it is required to identify various combinations of states for five groups of situations [1, 2, 5]:

- ultimate limit states for regular service conditions;

- ultimate limit states for abnormal service conditions;

- ultimate limit states for designed accident;

- ultimate limit states for beyond-design-basis accident; and

- ultimate limit states for hypothetical accident.

Ultimate limit stress for normal service conditions have to be in full reflected in design codes of potentially hazardous objects, consider a set of design operating modes and proceed from all previous operating experience of similar objects.

In case of violation of normal (i.e., abnormal) service conditions (at any deviation from planned operating procedure causing the necessity to change operating mode or stop an object without necessity to activate or use all safety systems) the given above types of ultimate limit states can be used, or more extensive and wide. Such expansion is caused by the increase of number of work abnormalities and range of operation parameters changes.

When analyzing a design accident requiring the stop of an object and activation of safety systems, in addition to mentioned above types, it is necessary to consider those types of ultimate limit states which occur at increased mechanical, thermal, electromagnetic and other loads at scheduled stages of accident development.

For beyond-design-basis accidents followed by full activation of safety systems, it is not possible to exclude considerable damages of the most critical components and the equipment in general; in this case, the ultimate limit states include not only standard ones, but also new ultimate limit states that are object specific at broad variation of load conditions at all stages of accidents development.

The hypothetical accidents are most severe, hardly probable and poorly studied, and the worst combination of the affecting factors and that is why it is necessary not only to provide the analysis of the ultimate limit states stated above but also to analyze the states at which significant changes of conditions of working substances and structural and mechanical conditions of engineering materials are possible.

When accidents (explosions, destruction, fires, collisions, collapses, chemically dangerous substances release) are occurring in the load bearing structures, the corresponding ultimate limit states are arising. At different stages of accidents development, these limit states can change both in the direction of scaling up of consequences, and in the direction of localization and full stop of the accident development.

When determining safety of the most important objects, the following types of ultimate limit states have to be considered: plastic deformation and forming; short-duration elastic failure; delayed or fast brittle failure; long-term static fracture; cyclic (low- and multi-cycle) destruction; creep strain accumulation; cyclic strain accumulation; buckling; dangerous vibrations occurrence; coupled units wear; single loading cracks initiation and propagation; cyclic cracks initiation and propagation; corrosion, corrosion and mechanical, cavitation and erosive damages; leakages; and change of structures and a condition of the bearing components.

The ultimate limit states listed above identify methods, structure and criteria of safety analysis by integrated approaches of mechanics, physics and chemistry of disasters.

In the process of design of structure, its components and, at the bottom, the following groups of the ultimate limit states are taken into consideration. The first group with unacceptable plastic strain and damages includes ultimate limit states surpassing of which will cause total unusability of the structure or total (or partial) loss of supporting capacity of the platform substructure. The second group with damages accumulation and development includes the ultimate limit states where surpassing makes impossible the normal operation of the platform substructure.

It should be noted that the above-listed ultimate limit states were taken into account at design of the reinforced concrete support substructure of gravity type for offshore stationary platforms on the sites of the Sakhalin-II project for Piltun-Astokhsky (PA-B) and Lunsky (LUN-A) fields.

The design elements of the platform substructure can be split into criticality categories depending on the external impacts taken into account:

High criticality design elements—these are elements whose destruction can cause fatalities, serious damages to constructions and environment contamination.

Low criticality design elements—these are elements whose destruction will not cause fatalities, serious damages to constructions and environment contamination.

Between high criticality design elements, the following ones shall be listed:

- design elements of skirt and skirt interface with caisson bottom;

- column walls in areas of their connection with the bottom and top plates of overlapping of a caisson;

- parts of walls and columns overlapping subject to significant loads concentration;

- design elements contacting with ice;

- connection of deck with the column;

- outer walls, floor slabs and caisson bottom;

- internal waterproof walls;

- design elements of supporters of the critical and safety equipment including riser holders; and

- structures which damage and destruction will cause dramatic environment contamination including risers.

Between low criticality design elements, the following ones shall be listed:

- internal structure not involved in provision of general strength; and

- design elements of equipment supporter not identified as elements of critical importance.

2.9 Comprehensive assessment of risk, strength, in-service life, reliability and safety

Characterization of initial strength, in-service life, risk and safety of the bearing elements of the sea oil and gas production platform in terms of impact of a complex of loads (including such specific service conditions as collisions with the drifting ice floes, impact of storm and gale-force winds, existence of the corrosive environment, low-temperature embrittlement effects, etc.) is the comprehensive problem considering occurrence of the cyclic dynamic loads corresponding to these conditions and, consequently, nonlinear change in time of the kinetic fields of stresses and deformations in these elements of SP under the impact of irregular loads [1–4]. In this regard in zones of design concentration, the local stresses and deformations have the increased values and the processes of material damage run more intensively leading to appearance of local destructions zones (cracks) eventually developing into macrodestructions (loss of bearing capacity). In such conditions, depending on the nature of loading and the operational environment, various mechanisms of accumulation of damages and destruction are implemented.

For the analysis of operational load of SP (as well as on other objects of energy, transport, oil and gas chemistry) at all stages of the life cycle, curves of the parameters dependent on calculated or real force impact on the bearing elements of the oil and gas production platform (set in the specification or measured during operation) are plotted. Among these parameters are number of loading cycles N, time τ, temperature t as well as service forcing P, stress σ and deformation e. The curves of parameters P, t, σ and e as function of time (**Figure 12**) are plotted for all stages and operational phases.
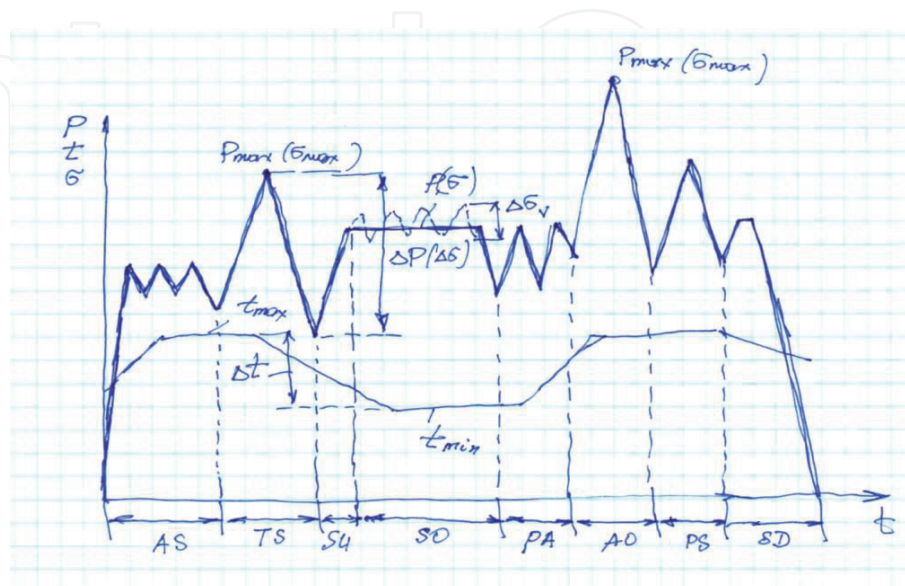

Figure 12.
Diagram of operational loads and their basic parameters.

These dependences are initial for the analysis of strength, in-service life, risk and safety of elements of engineering designs both for their initial states and for the damaged states. Values P, t and τ, are, as a rule, set by the modes of operation and can be registered by instrumentation and control diagnostic systems or by monitoring equipment.

At the same time, σ and e parameters of the general and local stress-deformed states can be obtained with the help of calculation based on the values of parameters *P, t* and τ or purposely measured by means of full-scale strain gauging and thermometry.

In **Figure 12** where a block of external and internal technological operational loadings are presented, the following standard modes of loading of the SP elements are highlighted: assembling (*AS*), tests (*TS*), start-up (*SU*), stationary the mode with maintenance of set operating parameters (*SO*), basic parameters adjustment (*PA*), accident occurrence (*AO*) (including those after of earthquakes), protection systems actuation (*PS*) and shut-down after planned or fault situation (*SD*).

When analyzing the initial and residual strength, service-life, survivability, risk and safety of the oil and gas production platform, the key phase is decomposition of SP and selection and identification of its potentially dangerous critical components, defining the greatest risks of accidents and disasters occurrence. The critical zones of SP components and critical points in them are identified on the basis of experimental and computational studies of stress-deformed and ultimate limit states. In such zones and points, as a rule, processes of local destructions are initiated followed by tramline destructions. At the same time for further experimental and computational evaluations of initial and residual strength, service-life, survivability, risk and safety, the following characteristics of history of loading (**Figure 12**) are accepted:

- maximum rated load P_{max};

- maximum (minimum) rated temperature $t_{\mathrm{max}}(t_{\mathrm{min}})$;

- time of standard load conditions τ_i and total time pf all modes and blocks of modes τ_Σ (life capacity).

With the help of this history of loading set are additional design parameters:

- peak-to-peak range of forcing ΔP and forcing amplitude;

- peak-to-peak range of temperature variations Δt; and

- peak-to-peak range of vibration loads ΔP_B (dual- or multi-frequency) loads.

From the analysis of all *i* modes according to standard calculation, the most adverse combinations of *P* and *t* are identified: (P_{max}, t_{max})—for heavy loadings and areas of increased temperatures impacts, and (P_{min}, t_{min})—for heavy loadings and low temperatures (including cryogenic). A set of such combinations is defined by taking into account the number and geometrical shape of the designed details or elements and number of critically dangerous zones, sections and points in them.

For quantitative evaluation of static and cyclic strength, as well as in-service life [1, 2, 5], experimental and computational diagram in coordinates of "σ_a-N" (**Figure 13**) is used.

$$\sigma_{\mathrm{a}} = \mathrm{e}_{\mathrm{a}} \cdot \mathrm{E} = F\{N, r_\sigma, \sigma_{\mathrm{T}}, \sigma_{\mathrm{B}}\}, \qquad (19)$$
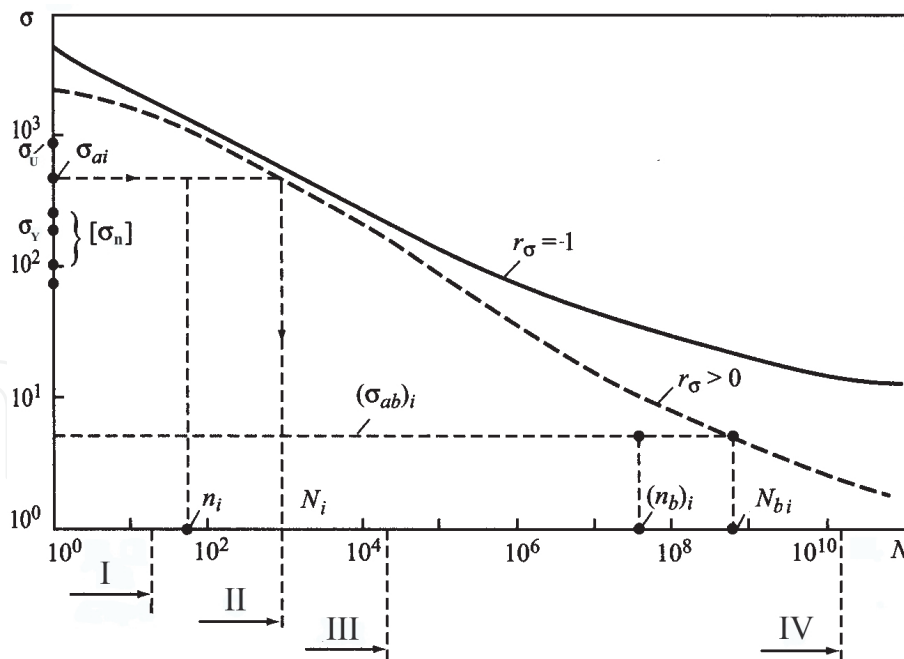
Figure 13.
Diagram that is used for identification of static, cyclic and long-term initial strength and in-service life parameters: I—AS, SU, TS, PS, SD; II—SO; III—PA; and IV—V (vibration $\Delta\sigma_v-$).

where σ_a, e_a are strength and deformation amplitudes; E is the elasticity modulus; N is the number of cycles prior to destruction; r_σ is the stress ratio; σ_m, σ_6 are yield and ultimate stress limits of the structural material.

On **Figure 13**: σ_{ai}, $(\sigma_{a6})_i$ is the amplitude of basic and vibratory stresses for i-mode; n_i, $(n_6)_i$ is the number of cycles for basic and vibratory loads; N_i, N_{6i} is the number of destructive cycles; σ_m, σ_6 are yield and strength limits; $[\sigma_a^*]$, $[N]$ are acceptable tensions amplitudes $[\sigma_a]$ and endurance capability $[N]$ are defined on the basis of traditional calculations with consideration of ultimate factor of safety n_σ and marginal life n_N

$$[\sigma] = \frac{\sigma}{n_\sigma}, [N] = \frac{N}{n_N}. \tag{20}$$

When making stress assessment, the characteristics σ_B and σ_T have to be set with taking into account service conditions—impact of loading cycling, temperatures and operating environment.

2.10 Criteria of strength, in-service life, safety and protection level (security)

As it was noted above, the solution of fundamental problems of provision of safety, risks and security of critically and strategically important infrastructure facilities is based on the analysis and development of fundamental scientific approaches to issues relevant to strength and in-service life, development of engineering methods of calculations and tests, creation of norms and rules regulating design and fabrication of objects of offshore technosphere, ensuring their functioning within identified limits of the design and beyond-design modes and parameters. Nowadays, the analysis and development of all components of the criterial sequence "Strength → rigidity → consistency → in-service life → reliability → survivability → safety → risk → protection level (security)" became the basic ones, step by step raising requirements imposed on their routine (normal) functioning and ensuring realization of design parameters at all stages of life cycle.

The specified requirements implemented in this knowledge area are imposed on operability of critical structures and expressed by means of the corresponding characteristic parameters of criteria dependences for the above sequence.

A "pyramid" of provision of technosphere objects' operability according to the main criteria (**Figure 14**) was constructed based on requirements and parameters providing safe operation conditions of these objects.

From **Figure 14**, it is clear that every element located above the other one is supported by the lower elements, i.e., it is laid on it as on foundation. It eventually means that the solution of the task of security, risk and safety provision has to rest upon the solution of problems of "survivability → reliability → in-service life → rigidity → consistency → strength" with passing through traditional stages of their interaction I → VIII. Fundamental results of identification and provision of strength (stage I) were obtained in the beginning of the nineteenth century and it took a long time, while complete analysis of rigidity and resistance (consistency) (stage II) came to the end by the end of this century. In the twentieth century, the theory and practice of provision of "in-service life → reliability → survivability" (stages III, IV, V) were formed. At the end of the last century, the fundamental problem of the analysis and safety and risk provision (stage VI) was formulated for all potentially hazardous civilian and defense objects with transition to management (stage VII) of safety and security according to risks criteria. At these stages, safety and security requirements were formulated like governing, and this provoked development of the new line where consequence "VII → I" becomes the basis for the future technosphere development. At the beginning of this century, the new task (stage VIII) was formulated and this is provision of safety and security of crucial objects based on anti-accidents and anti-disasters of technogenic, natural and anthropogenic character performance.

According to abovementioned and expressions (1)–(9) and **Figure 14**, the proofness of SP is the function of function (functional) Fz of the basic change in time τ parameters

$$Z_\kappa(\tau) = F_z \{R_\sigma(\tau), R_{N\tau}(\tau), L_{ld}(\tau), P_{PR}(\tau), S(\tau)\}, \qquad (21)$$

where Z_κ is the proofness determined by the ability of an object to resist to accidents occurrence and development of adverse situations in normal and abnormal conditions; R_σ is the strength determined by resistance of the bearing object elements to destruction under normal and emergency impacts; $R_{N\tau}$ is the in-service life (endurance capability) determined by time τ or cycles number N prior to
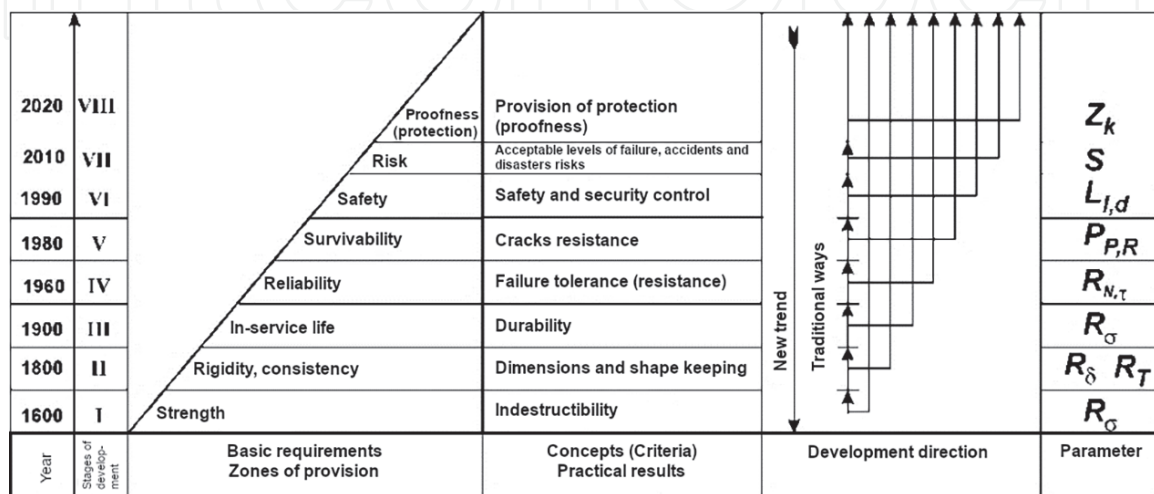

Figure 14.
General structure of provision of technosphere objects operability.

destructions or instability; L_{ld} is the survivability determined by ability of an object to perform limited functions at damages d and dimensions of defects l that are inadmissible according to norms; P_{PR} is the reliability determined by ability of an object to perform specified functions in the known or defected state at specified loadings P or service-life $R_{N\tau}$; and S is the safety determined by the ability of an object not to pass into a catastrophic state causing significant damages to the person, the technosphere and the environment.

As it was already mentioned, operational conditions of loads of SP are characterized by a significant amount of various factors and parameters; among them are loading conditions and levels of static and dynamic mechanical loads (**Figure 15a**) and impact of corrosive environment, of external factors, etc. These factors taken together and each one individually can cause significant change of nature of behavior of material, its mechanical properties, ability to resist cyclic deformation in comparison with standard design loading specifications (stationary application of cyclic load, room temperature, etc.) at which standard experiments are usually conducted to define the corresponding characteristics. They also may contribute changes in the corresponding patterns of damages accumulation in the material of the equipment components experiencing their influence when in operation.

Cyclic loading waveform of random operating modes as a rule has more sophisticated nature than widely used in experimental practice sinusoidal or triangular waveforms of cyclic loadings.

In some cases, it is obviously possible to schematize and replace actual conditions of loadings by more simple, single-frequency modes. However, generally, the patterns of change of the loadings influencing the structural elements have random nature (**Figure 15b**).

The actual loading modes are schematized (**Figure 15c,e**) in the process of the loading history tracking (**Figure 15e**). Approximation of simulated loading conditions of the equipment as accurate, in respect to reality, as possible for each factor occurring during equipment operation and taking into consideration of impact of these factor on parameters of the characteristic equations and equations describing damages accumulation process is an effective step for adjustment of applied methods for calculations of strength, endurance capability and reliability of the oil and gas production platform components' and hence to identification of really grounded and justified their safe in-service life.

Cyclic strength σ and endurance capacity N are defined by the use of the stress-cycle relationship and the equation

$$e_a = \frac{1}{2 \cdot (4N)^{m_p}} ln \frac{100}{100 - \psi_K} + \frac{1}{(4N)^{m_e}} \cdot \frac{S_K}{E\left(1 + \frac{1+2}{1-2}\right)}, \qquad (22)$$

where ψ_K is the limit plastic yield of contraction, S_K is the rupture strength of contraction and E is the elasticity modulus defined in the process of standard tests of static tension. Value of index of plastic m_p and elastic m_e components of deformation e_a in the absence of direct data on their values can be determined with the help of material yield stress and ultimate stress values, which are as follows

$$m_p = 0,36 + 2 \cdot 10^{-4}\sigma_B, m_e = 0,132 \cdot lg(S_K/\sigma_{-1}), \qquad (23)$$

where value of fatigue limit σ_{-1} can be defined as $\sigma_{-1} \cong 0,45\sigma_B$, and rupture strength of contraction S_K, dependent on ultimate stress limit σ_B and relative narrowing of contraction ψ_K, correspondingly comes from relation $S_K = \sigma_B(1 + 1,4 \cdot \psi_K)$. Parameters $\sigma_\epsilon, \psi_K, S_K$ in general case are dependent on time τ, operational temperature and full size cross-sections of SP bearing elements.
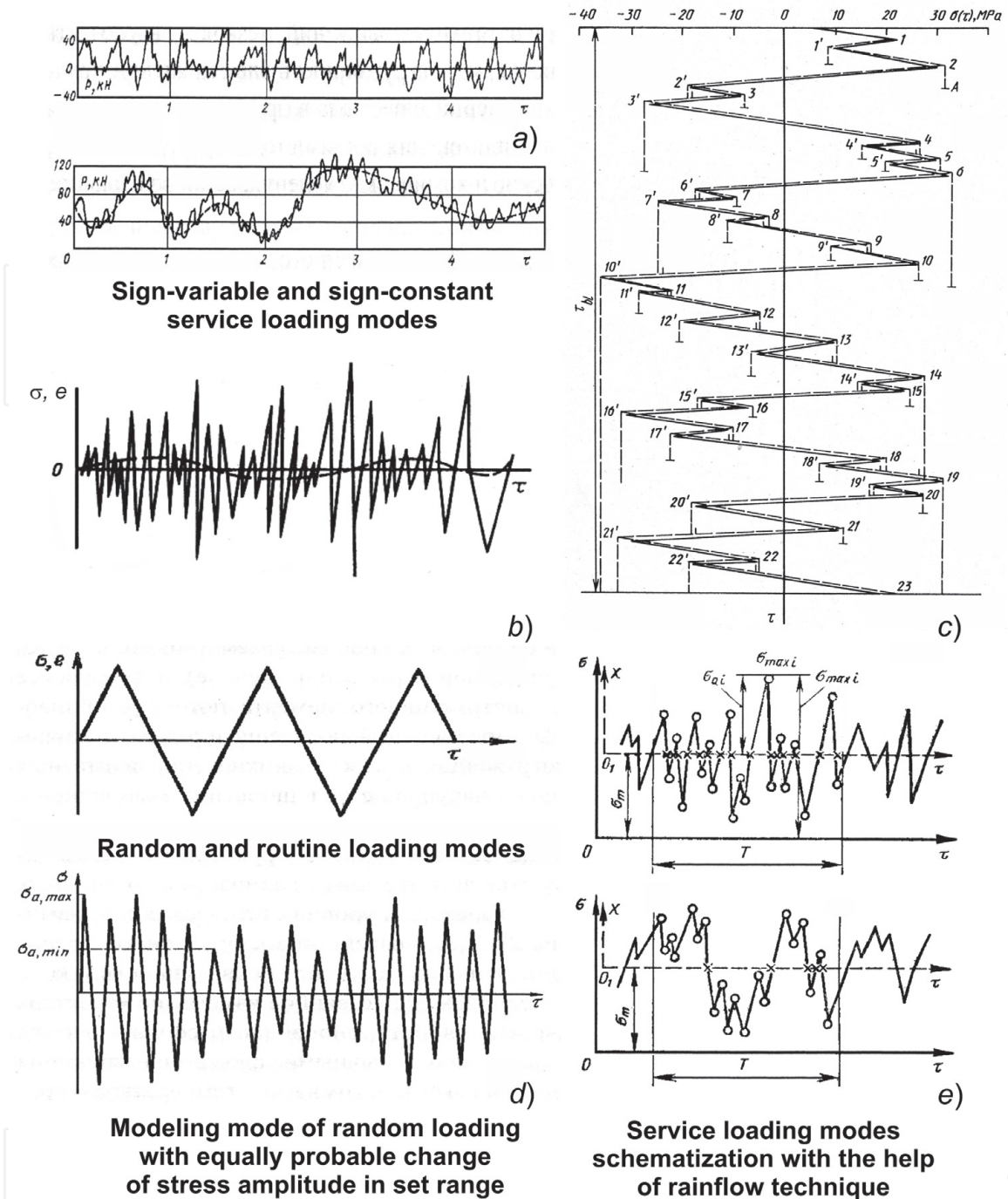
Figure 15.
Methods of schematization of operational modes of loads. a) Sign-variable and sign-constant service loading mode. b) Random and routine loading modes. c) Service loading modes schematization. d) Modeling mode of random loading with equally probable change of stress amplitude in set range. e) Rainflow technique.

2.11 Probabilistic analysis of strength, in-service life and risks

Because SP is functioning in the conditions of the high level of uncertainty concerning external impacts during operation period and bearing capacity level changing due to structures degradation, the criteria in expressions (21)–(23) have to be probabilistic [2–6].

Let function of ultimate limit states for the considered platform element is defined by a ratio of bearing capacity and loading l. Generally, function of ultimate limit states
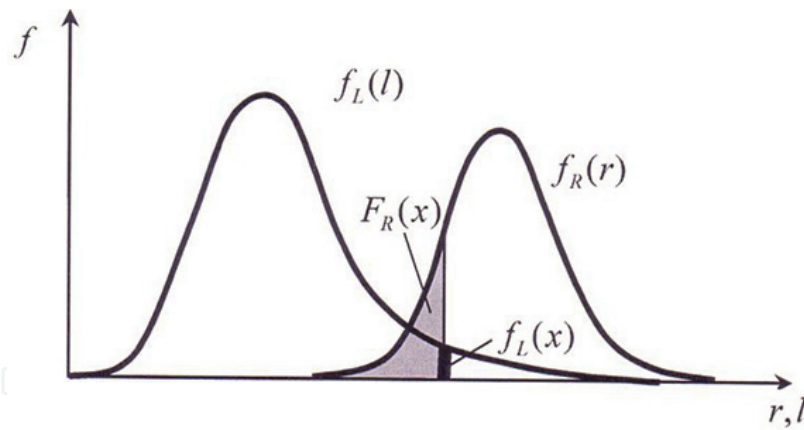
$$g(r,l) = r - l \qquad (24)$$

Figure 16.
Probability density functions for bearing capacity and loading. Probability curves for design parameters at assessment of chances of failure.

is written as $g(x)$, where $x = (x_1, x_2, \cdots, x_n)$ is the vector of variables describing the element state. Then the element failure can be generally described as follows (**Figure 16**)

$$F = \{x | g(x) \leq 0\} \tag{25}$$

Conditional probability of failure in case when the element is under load $L = l$ is defined by function $F_R(x)$ (this is due to the fact that $F_R(x) = P(R < l)$). Then, using the theorem of total probability, it is possible to write expression for the probability of element failure as follows:

$$P(F) = \int_{-\infty}^{\infty} F_R(x) f_L(x) dx, \tag{26}$$

where R is the bearing capacity and $x = l$ is the load.

Let us consider the random variable of margin of safety, in-service life and proofness (safety) $M = R - L$ equal to excess of bearing capacity over load. As R and L are random variables, M is also the random variable with mathematical expectation μ_M and rms deviation σ_M. They can be calculated from mathematical expectation and rms deviation of values R и L:

$$\mu_M = \mu_R - \mu_L$$
$$\sigma_M = \sqrt{\sigma_R^2 + \sigma_L^2 + 2\rho_{RL}\sigma_R\sigma_L} \tag{27}$$

The probability of system failure which is equal to the probability of value M be less or equal to 0.

$$P(F) = P(M \leq 0) = \Phi\left(-\frac{\mu_M}{\sigma_M}\right) = \Phi(-\beta), \tag{28}$$

where β is the proofness (safety) index (this variable sometimes is called reliability index) of the element analyzed upon its ultimate limit state $g(x)$. Value β characterizes the distance of the ultimate limit state surface and can be treated as safety (proofness or security) characteristics of element relative to analyzed failure mechanism.

If the destruction mechanism relative to excess of maximum permissible load is considered, then equation of the surface of ultimate limit states takes the form

$$g_U(\mathbf{x}) = R - L, \tag{29}$$

where R is the strength (bearing capacity) of the element and L is the maximal load during the analyzed period.

Safety (proofness or security) upon the criterion of exceed of maximal permissible load will be presented by the expression:

$$\beta_U = \frac{\mu_R - \mu_L}{\sqrt{\sigma_R^2 + \sigma_L^2 + 2\rho_{RL}\sigma_R\sigma_L}}. \tag{30}$$

If to talk about the fatigue mechanism of element destruction, then equation of the surface of ultimate limit states takes the form $g_F(x) = N - n$ where N is the number of cycles prior to destruction at the set level of stresses range and n is the number of cycles to which the element is exposed during use. Then the proofness of element upon criterion of fatigue failure will look as follows:

$$\beta_F = \frac{\mu_N - \mu_K}{\sqrt{\sigma_N^2 + \sigma_K^2 - 2\rho_{NK}\sigma_N\sigma_K}}. \tag{31}$$

Because of hostile environment influence on the OGPF elements and relevant degradation processes in them, the function of element ultimate limit states has to depend on time. In the considered statement, the proofness (safety or security) reserve of a critical element is estimated in the form of $M = R\text{-}L$, where R is the bearing capacity in critical cross-section and L is the loading in the same cross-section. If to consider that both random variables of R and L in real systems can depend on time, then the bearing capacity can change because of degradation of material properties (corrosion, fatigue, etc.); loading, in its turn, can change due to change of service conditions, of external environment, etc. At that their mathematical expectations $\mu_R(t)$ $\mu_L(t)$ and rms deviations $\sigma_R(t)$ $\sigma_L(t)$ will change as well. Then the margins of bearing capacity can be written as follows:
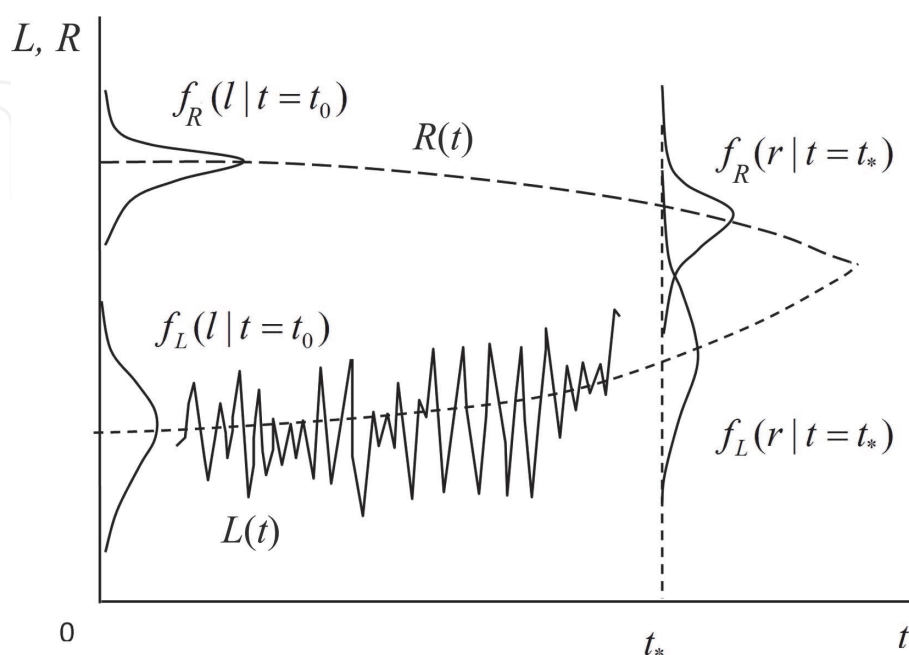
$$M(t) = R(t) - L(t). \tag{32}$$

Figure 17.
Load and bearing capacity changing in time.

In this case, the probability of failure becomes the function of time:

$$P_f(t) = P\{R(t) \leq L(t)\} = P\{g(X(t)) \leq 0\}, \qquad (33)$$

where $g(X(t)) = M(t)$, depending on time proofness margins as per bearing capacity. The probability of system failure is

$$P_f(t) = \int_{g(X(t)) \leq 0} f_{X(t)} \boldsymbol{x}(t) d\boldsymbol{x}(t). \qquad (34)$$

The identification of time moment t_* when loading $L(t)$ for the first time will exceed the bearing capacity of an element $R(t)$ is an important task (**Figure 17**).

2.12 Engineering justification of strength, in-service life and safety

As it was noted above, continuously raising requirements to regular (normal) and abnormal functioning are imposed on modern SP. In modern conditions of the analysis and provision of safe operation of technosphere objects, the new task about identification and safety and security provision upon criteria of actual $R(\tau)$ and acceptable $[R(\tau)]$ bearing capacities are used in expressions (7) and (9). Within that narrative [1–4, 7], only characteristics of safety with the set levels of risks give justification to acceptance (or rejection) of decisions on permission of new projects realization or permission to operate running offshore objects.

Operational impacts on the SP elements in general (periodically arising ice loadings, service, wind and seismic loads) are characterized by the following parameters, in particular numbers of loading cycles N, time of loading τ and ambient temperature t. At the same time, N and τ define in-service life of the examined object, while t defines its cold brittleness. The imperfection of bearing structures is defined by the sizes of cracks of l, their shape and location. Sizes l are initial for determination of objects survivability. Characteristic of flexibility, rigidity, stability λ of the bearing component of the analyzed element depends on a shape and dimensions of cross section, length and type of supporting. It defines his stability.

External routine and abnormal impacts (including accidents and catastrophic) generate in the analyzed element design stress level σ and deformations e; they depend on the applied loads (mechanical, temperature, aero hydrodynamic, seismic, etc.), a way of their application, the sizes and shapes of cross-sections. If these impacts increase, then at some point in the bearing elements, the ultimate state limits (critical) are achieved, and these elements are destructed, losing stability and getting inadmissible deformations. Stresses and deformations at this moment achieve extreme (critical) values σ_f, e_f.

Values of characteristics σ_f, e_f according to **Figures 12–14** depend on values N, τ, l, t, λ. Based on these dependences and upon experimental and laboratory studies of the construction materials, the following are plotted:

- fatigue curves (live curve) for stresses "σ–N" and deformations "e–N";

- stress rupture curves for stresses "σ–τ" and deformations "e–τ";

- crack resistance curve (survivability) for stresses "σ–l" and deformations "e–l";

- temperature resistance curve (cold- and heat resistance) in coordinates of stresses "σ–t" and deformations "e–t"; and

- stability curves (general or local) in coordinates of stresses "σ–λ" and deformations "e–λ."

At relatively low levels of external routine impacts when occurring deformations are elastic, the calculations relevant to stresses and deformations have identical results. At the increased abnormal and stress impacts when occurred are general and local plastic deformations, the calculations made with respect to stresses σ and deformations e are divergent—the values of stresses σ_f happen to be insensitive to N, τ, l, λ variation. This fact predetermines the importance of transition from the traditional determined calculations in terms of stresses σ_f to probabilistic calculations in terms of deformations e_f [2, 5, 7–9].

In case of the integral analysis of strength, in-service life and safety, the deformation curve in true coordinates (the true stress σ and true deformations e) is presented as follows

$$\sigma = \sigma_T \, (e/e_T)^m, \tag{35}$$

$$m = lg(S_k/\sigma_T)/lg(e_k/e_T), \tag{36}$$

where σ_T is the yield stress; m is the work hardening exponent ($0 \leq m \leq 0.3$); S_k is the tension strength; $e_T = \sigma_{T/E}$; $e_k = S_{k/E}$; and E is the elasticity modulus.

The strength-duration curves $\sigma_{B\tau}^t$ and ductility property $\psi_{k\tau}^t$ for time τ are the basic ones in case of long-term loading at increased temperature

$$\sigma_{B\tau}^t = \sigma_B^t \, (\tau_o/\tau)^m{}_B, \psi_{k\tau}^t = \psi_k^t (\tau_o/\tau)^{m_\psi} \tag{37}$$

where τ_0 is the time of short-time tests ($\tau_0 \approx 0.05$ h); and m_B, m_ψ are the material characteristics depending on temperature t and yield stress σ_T^t ($0 \leq m_в \leq 0.08$, $0 \leq m_\psi \leq 0.15$). Then, it is possible to obtain the cyclic stress curve "σ^* - N" as per parameter τ.

In estimating the effect of temperatures t, different from room temperature t_0 = 20°C (both in the range of low climatic temperatures 20°C $\geq t \geq -60$°C, including cryogenic range -60°C $\geq t \geq -270$°C and elevated 20°C $\leq t \leq 350$°C and high temperatures 350°C $\leq t \leq 1000$°C), standard tests are carried out in thermocryocameras. In the absence of such tests' results, the estimated dependences of mechanical properties on temperature of t °C or T °K ($T = t + 273$) T are plotted

$$\{\sigma_m^t, \sigma_в^t\} = \{\sigma_m, \sigma_в\} \cdot \{\beta_m, \beta_в\} \left(\frac{1}{T} - \frac{1}{T_o}\right) \tag{38}$$

where T is the temperature in Kelvin degrees ($T = t^o + 273$); and β_T and β_B are designed material characteristics dependent on σ_T. Limiting yielding is calculated via $\psi_к$, σ_T and σ_B at room temperature.

For dynamically loaded components of the SP, the values of β_T decrease from 120 to 50 with σ_T changing from 300 to 700 MPa, and at increased deformation velocities $\dot{e} = de/d\tau$ (10^0 c$^{-1} \leq \dot{e} \leq 10^3$ c^{-1}), there is increase of yield stress and ultimate stress limit defined experimentally or calculated with the help of polynomial equation

$$\sigma_B^{\dot{e}} = \sigma_в(\dot{e}/\dot{e}_0)^{m_{ев}}, \sigma_T^{\dot{e}} = \sigma_т(\dot{e}/\dot{e}_0)^{m_T} \tag{39}$$

Dynamic plasticity performance calculation is done via $\psi_к$, σ_T and σ_B, with the help of the same relations that are used for temperature effects description. Eqs. (37)–(39) provide possibility to calculate work-hardening index m in Eq. (36).

The entire system of experimentally defined (E, σ_T, σ_B, ψ_κ) and designed (m, S_κ, m_p, m_e, m_B, m_ψ, β_T, β_B, $n_B^{\acute{e}}$, $n_T^{\acute{e}}$) characteristics is identified with regard to results of mechanical tests of smooth standard samples.

The real bearing SP components have various zones of concentration and various sizes of cross-sections. Performance of the mechanical tests for assessment of sensitivity to a factor of tension concentration (in elastic and inelastic areas) and size factor represents essential methodical difficulties and is time-consuming.

For big group of constructive metal materials due to use of the modified analytical decisions (of Neuber type), it is possible to receive correlation of tension concentration factor K_σ and deformations K_e in elastoplastic domain with theoretical concentration factor α_σ in elastic domain, taking into account the relative level of the effective stress σ/σ_T and work-hardening index m

$$\{K_\sigma, K_e\} = F_k\{\alpha_\sigma, \sigma/\sigma_T, m\}. \tag{40}$$

For existing offshore structures $1 \le \alpha_\sigma \le 5$, $1 \le K_\sigma \le \alpha_\sigma$, $\alpha_\sigma < K_e \le \alpha_\sigma^2$.

For experimental evaluation of size facto impact (sizes F of transverse cross-section) on mechanical properties of large-size SP components a set of polynomial equations is recommended:

$$\sigma_T^F = \sigma_T(F_0/F)^{m_{TF}}, \sigma_B^F = \sigma_B(F_0/F)^{m_{BF}}, \psi_k^F = \psi_k(F_0/F)^{m_{\psi F}}, \tag{41}$$

where m_{TF}, m_{BF}, $m_{\psi F}$ –characteristics not separate steels, but their groups (as per the stress level and doping level ($m_{TF} \approx m_{BF} = 0.013$, $m_{\psi F} = 0.024$–0.04).

For assessment of survivability characteristics based on crack resistance criteria in presence in the SP bearing structures of cracks like defects, the standard, unified and special tests with variation of cracks sizes l, cross-sections F and loads technique Q shall be conducted. The critical value of the stress intensity factor within the frameworks of the linear fracture mechanics is generally viewed as fundamental characteristic of crack resistance at cyclic loading

$$K_{Ic} = \sigma_c\sqrt{\pi l \cdot F\{l, F, Q\}}, \tag{42}$$

where σ_c is the failure stress for the sample with limitation $\sigma_c \le (0.9$–$1.0)\sigma_T$.

At the same time, by numerous experiments, it was shown that at change of l, F, Q, and temperature t, time τ, deformation velocity and stress voluminosity I_σ, D_e the basic characteristic K_{Ic} changes (in the same manner as change other basic design characteristics σ_T, σ_B, ψ_κ.).

As the first assumption in technical practice use is made of minimal values of K_{Ic} depending on the temperature t as this not always is counted as safety factor. The most acceptable in comprehensive assessment of strength, in-service life and safety of the SP components is the use of the minimum values defined on cylindrical samples with a circular crack with further calculation of K_{Ic} value as per basic characteristics σ_T, m, e_κ with regard to changes caused by variation of parameters l, F, Q, t, τ, I_σ, D_e. In more general case when conditions of linear mechanics of destruction are not satisfied and there are considerable deformations of plasticity and creep, instead of the standard characteristics K_{Ic} (or critical integral J_c and critical cracks opening δ_c), the deformation criterion of K_{Iec} is developed and implemented, where K_{Iec} is the critical factor of deformations intensity [5–7]. Factually this factor plays the same role as deformations concentration factor K_e in (41) upon condition of similarity of α_σ and K_I. At the same time, the modified analytical solution with regard to (4.14) type gives dependence

$$\overline{K}_{Ie} = \overline{K}_I^{p_{ke}}, \tag{43}$$

where $\overline{K}_I = \frac{K_I}{\sigma_m}$; $\overline{\sigma}_n = \overline{\sigma}_n / \sigma_\tau$; σ_m is the yield stress; $P_{ke} = \frac{2-n(1-m)(1-\overline{\sigma}_n)}{1+m}$ is the generalized parameter depending on work-hardening index m and relative level of rated stresses; m is the work-hardening index for deformation curve; and n is the characteristic of structural material type $n \approx 0.5$.

The value of stress intensity factor in terms of operation at stress σ_n with regard t0 (4.14) equals to

$$\overline{K}_I = \overline{\sigma}_n \sqrt{\pi l} \cdot F\{l, F, Q\}. \tag{44}$$

Expressions (41) and (44) make it possible to get conditions of local destruction—crack formation (41) and its development according to (43).

In presence of cracks and use of local criterion obtained is expression to plot the fracture diagram connecting increment of the crack length Δl with the rated stress value and designed parameters of mechanical properties

$$\Delta l = \frac{1}{2\pi} \left(\frac{\overline{K}_{Ie}}{\overline{e}_f} \right). \tag{45}$$

where $\overline{e}_f = \frac{1}{e_\tau}(e_k)$.

If loading process is cyclic, the value Δl is equivalent to crack increment in preplanned cycle $\Delta l = \frac{dl}{dN}$, and the main parameter of loading appears to be the peak-to-peak range of deformations intensity factor $\Delta K_{Ie}^{(N)}$ in this very loading cycle N with a variable work-hardening index $m = m(N)$. The value $m = m(N)$ depends on cyclic properties of materials that can be as follows:

- cyclically stable—$m(N)$ does not change depending on number of half-cycles of N;

- cyclically hardening—$m(N)$ increases with growth of N; and

- cyclically softening—$m(N)$ decreases with growth of N. Then

$$\frac{dl}{dN} = \frac{1}{2\pi} \left(\frac{\Delta \overline{K}_{Ie}^{(k)}}{\overline{e}_f} \right)^2 = \frac{1}{2\pi \overline{e}_f^2} \left(\Delta \overline{K}_{Ie}^{(k)} \right)^2 = C_e \left(\Delta \overline{K}_I \right)^{m^e}. \tag{46}$$

Expression (46) with regard to expressions (43), (44) is similar to known Paris-Erdogan equation when C and m_k are material constants; however, in expression (46), the values C and m are variables and are calculated. Mechanical tests for identification of $\overline{K}_{Ie}, \overline{K}_{Iec}, dl/dN$ within the frames of nonlinear destruction mechanics are more comprehensive than those in linear destruction mechanics when identified are values of K_{Ic} and dl/dN. In non-routine events, emergency and catastrophic situations in nonlinear setting of the problem analyzed are the following essential effects of redistribution of the local plastic deformations and creep deformations depending on $m, t, \tau, N, F, I_\sigma, D_e$ in case of probabilistic approach. Noted complexity is overcome within deformation destruction criteria at setting of the general problems of strength, in-service life, reliability, survivability, risks, safety and SP equipment protection.

Theoretical and practical solutions of the considered problems of strength, in-service life, reliability, crack resistance were already performed for such high-risk objects as nuclear reactors, hydraulic and thermal power stations, aircraft, main pipelines and unique engineering constructions.

The ground for the analysis and risk management directed to quantitative evaluation of critical and acceptable risks is based on the matrix of risks. Qualitative and quantitative risk assessment is based on the standard matrices of criticality determined by probabilities of adverse events occurrence (destructions, failures, etc.) and consequences of these events. However, within risk matrixes, the mechanisms of material and the bearing SP components degradation relevant to the erosion and corrosion processes are considered.

The listed above approaches, methods, criteria, design schemes and calculation dependences give the chance to carry out assessment of SP technical condition and risks monitoring.

3. Development of methods of calculations and justification of strength, in-service life and safety

3.1 Techniques of provision and enhancement of strength, in-service life and safety

Taking into account a possibility of reaching in time of the ultimate limit states in the wide range of loading parameters, further it is required to define the following groups of situations occurring during SP functioning as presented in **Table 2**.

Each class of situations corresponds to diminution of safety level of the analyzed objects while diminution of safety level can be estimated on expressions (1)–(9) as per values of risks $R_i^{\ni}(t)$ of objects operation on a specified time interval of operation. Quantitative values of risks $R_i^{\ni}(t)$ are calculated as product of the probability of occurrence of each of the specified situation i - $P_i^{\ni}(t)$ by economic losses values as per analyzed situation $U_i^{\ni}(t)$. At the same time, the condition of safety provision takes the following form $n_R = R_c(t)/R_t^{\ni}(t)$ where $R_c(t)$ is critical (inadmissible, unacceptable risk), $R_t^{\ni}(t)$ is designed risk for the moment of operation t for mode i and n_R is the safety margin as per risks.

According to **Table 2**, the last three abovementioned groups of the situations (T5, T4, T3) occurring during objects functioning can be referred to a kind of the risks which are monotonously increasing up to critical values. Such risks, mainly, are caused by the controlled processes of damages and degradations of physical-mechanical properties of material relevant to its aging. The first two groups (T2, T1) correspond to the occurrence of the most dangerous situations with extreme impact parameters (earthquakes, tsunami, acts of terrorism and military actions). These cases require use of the most difficult calculations, tests, modeling, diagnostics, monitoring and protection. In this case, classic methods of a material consumption justification, constructability and efficiency are insufficient. In such statement, the approaches presented in clauses 2.9–2.12 have to be implemented.

3.2 Risk-based inspections

In case of use of foreign and domestic safety standards for risk analysis, the approaches given in [1, 2, 10, 11] can be rather efficient:
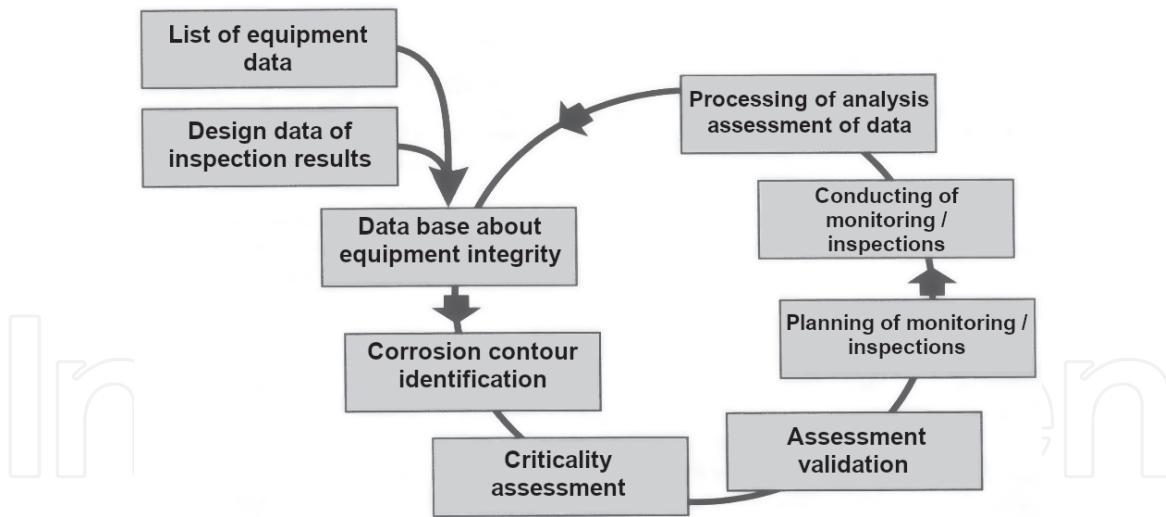
Figure 18.
Basic diagram of implementation risk based inspections technique.

- flow chart and fault-tree construction techniques (**Figure 11**);

- probabilistic modeling technique (**Figures 7** and **8**); and

- risk-based inspection (RBI) technique developed by Shell Global Solutions International company for residual life evaluation and planning of the objects' high-pressure equipment health monitoring frequency with consideration of risks-analysis (**Figure 18**). Inspections and tests planning is performed upon analysis of data about current technical condition of specified equipment item.

In the approach (**Figure 19**) presented above by analogy with **Figure 4**, the classes and categories of criticality, consequences of damages from accidents and accidents can be assessed in a similar way to **Figure 4**.

The risks analysis technique is based on information about scenarios of dangerous situations and probabilities of their occurrence received a priory. It is possible for SP for which design and operation experiences are accumulated already. In engineering design performed according to clauses 2.9–2.12, the inspections frequency can be obtained upon calculations as per expressions (18)–(41).

		RBI StF	IPF DR	RCM ETBF	Class of criticality of risks and reliability management				
Probability class	H	High	0-0.5 year		No need in additional monitoring of technological process	Not applicable for fracture mechanism not related to ageing			
	M	Medium	0.5-4 year						
	L	Low	4-20 year			L	M	MH	H
	In	Insign.	>20 year				L	M	MH
Consequences category		Economical (USD)			No / Minor loss <10 Thd.	Minor loss 10-100 Thd.	Local loss 0.1-1 mln	Severe damage 1-10 mln.	Widespread damage >10 mln.
		For safety and health			No / minor injuries	Moderate injuries	Serious injuries	Isolated cases of injury followed by fatality	Multiple fatalities
		For environment			No / minor consequences	Moderate consequences	Local consequences	Serious consequences	Severe consequences
Class of consequences					Minor	Low	Medium	High	Extreme

Figure 19.
Criticality and risks matrix.

3.3 Monitoring and seismic protection of offshore platforms

One essentially important question in the problem of protection of objects of offshore and land infrastructures is provision of SP seismic stability; this can be achieved with the help of developed scientific bases of design of self-lubricating, and self-adjusting sliding supports with reverse motion used as seismic-insulators for bridges, industrial and civil constructions. These works are also used for oil and gas offshore platforms on the continental shelf of the Russian Federation on the Sakhalin Island [1, 2, 17, 18].

It was proposed offshore structures protection against earthquakes to use the friction pendulum bearings (FPB) as the seismic-insulators [1, 12–14]. A calculation method for the service life of a FPB and the method of assessment of friction coefficient were experimentally developed [17, 18].

The real possibility of pendulum sliding supports use as efficient mean for absorption of energy from external force appeared in the last 30–40 years thanks to development of new technologies (in particular in connection with development of space research works in the USSR and the USA) and to introduction of new tribotechnical materials (such as the antifriction self-lubricant weaved fibrous materials).

In the SP pendulum bearings used are pendulum characteristics, providing increase of the natural oscillations (vibrations) period of the isolated structure in a manner to avoid the maximal forces occurring at an earthquake. During an earthquake, the articulation slide block in the bearing moves (slides) along a stainless steel concave surface, forcing a support to move within small pendulum displacements. The schematic view of the bearing is presented in **Figure 20**. The plate with a spherical concave surface is mounted on the top as viewed from the deck; this is done to arrange convenient operation. At such location of a concave plate, the grease does not get on the slide face. The lower plate of the case is mounted on the jack structure.

If forces occurring during an earthquake do not exceed the level of friction forces, then the structure supported by the bearing corresponds to the standard structure lying on the jack and has its own oscillation (vibration) period without insulator. As soon as the level of friction forces is exceeded, the structure starts oscillate with designed period; at that the dynamic response and damping are defined by bearing properties.

The hemispherical design of the articulation slide block allows getting relatively uniform distribution of pressure under the slide block and this reduces the movement judder and prevents occurrence of high local pressure in the bearing.
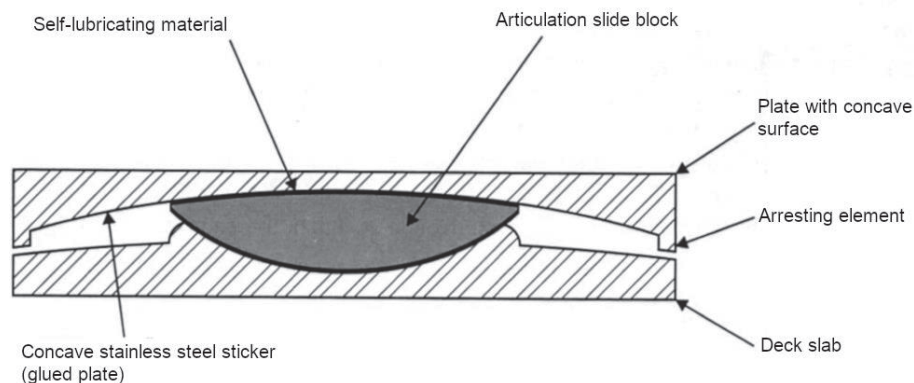

Figure 20.
Bearing structure diagram.

Platform component	a	b
Deck	0.24	0.73
Deck, level (+)27 m	0.31	0.65
Deck, level (+)38 m	0.25	0.74
Deck, level (+)47 m	0.31	0.84
Flare unit	2.00	4.37
Drilling module	0.61	1.22
Crane on the North side	0.82	1.74
Crane on the South side	1.46	2.27

Table 4.
Average side accelerations $\partial(m/sec^2)$ of the oil and gas platform components when pendulum bearings are used (a) and without such bearings (b).

As the displacements caused by an earthquake initially occur in bearings that are seismic-insulators, the side loadings and vibration motions transferred to a construction drop significantly.

In **Table 4**, the mean peak accelerations are presented, influencing, at designed earthquake, on the components of the oil and gas platform Lun-A for cases when friction pendulum bearings are in use and are not in use.

Accelerations drop is at 1.5–3 times that leads to significant reduction of wear of bearings and the antifriction self-lubricant film.

Development of oil and gas fields, as a rule, is carried out in the seismically active areas (their activity reaches magnitude 8–9 on 1–9 scale), and this is one of the main difficulties to be overcome in the process of such developments execution.

Sea platforms "Lun–A" and "PA-B" of the Sakhalin-II project are installed on the shelf of the Sakhalin Island in 2007. The weight of the gravity based structure is: for the"Lun–A" platform—103 thousand tons and for the "PA-B" platform—106 thousand tons. The weight of the topsides of "Lun–A" is 28 thousand tons and of "PA-B"—34 thousand tons. Service life of sea platforms "Lun–A" and "PA-B" is 30 years. Their design shall provide operation of equipment without damages and failures and resist loads occurred in the process of earthquake with probable repeatability once in 200 years and keep running without serious damages after impact upon such seldom earthquake that may occur once in 3000 years.

For the first time in world practice on "Sakhalin-II" project were installed frictional pendulum sliding supports (**Figure 21**) to provide seismic insulation between sea platform concrete gravity based structure and topside.

Such FPB previously were used for construction of highways, bridges and airports never before they were used in sea platforms.

Four bearings—seismic insulators installed in the catwalk of four concrete supports provide damping of extreme horizontal loadings due to isolation of the topside buildings from the most destructive pushes and due to reduction of loads on the topside buildings caused by impact of daily temperature changes, pressure of ice and waves.

3.4 Comprehensive on-line diagnostics, monitoring and the automated protection

Comprehensive on-line diagnostics and monitoring of sophisticated constructive components of SP equipment as per strength criteria, in-service life and crack resistance takes on greater and greater importance in the course of studies and

works with regard to technogenic safety [1, 2, 4, 5, 7, 15, 16]. So far, the solution of these tasks is difficult because of absence of enough nomenclature and number of means for multi-parameter and multi-factor diagnostics of the damaged SP elements with taking into account scenarios of accidents. When looking for methods and diagnostic means and monitoring performance, it is necessary to apply the system concept providing umbrella approach for: the preliminary analysis of the stress-deformed states by analytical and numerical methods; identification of the most loaded and dangerous zones; nondestructive testing and diagnostics at all stages of equipment life cycle; and development of a system of diagnostic data collection and exchange between design offices, manufacturers and operators.

Only based on this understanding, it is possible to provide high system reliability, sufficient depth and validity of diagnosing.

3.5 New offshore subsea technology solution for shelf development

Along with expert evaluation of above-water and above-ice technologies, the feasibility studies and assessment of basic features of subsea systems, including issues of energy security, were carried out. This analysis is made by the community of the specialized sea organizations: RNTs "Kurchatov institute" and Institute of machine science named after A.A. Blagonravov RAS (Moscow) with participation of the National laboratory Sandia (USA).

As a solution acceptable from the economical and technical point of view of above task is related to the transition to the system of underwater and under-ice technology of exploration, production, treatment and transportation of hydrocarbons (oil and liquefied natural gas—LNG (**Figure 22**) that so far is not available. Higher price of such underwater and under-ice system is compensated by the reduction of the subsequent costs required to provide safety and physical protection. Estimates show that the possible losses caused by technogenic accidents of above-water natural threats and terrorist impacts on the objects of a underwater technologies complex is 10 times less, than from impact of similar risk factors for traditional above-water technologies. The appraisals done by the specialized organizations show the technical capability of Russia to develop for the Arctic shelf the underwater and under-ice atomic technologies (**Figure 22**).

Calculations done with taking into account information from clause 2 make it possible to obtain the risks values for both traditional (on-land and above-water sea) technologies and for new (underwater) technologies. The following risks'
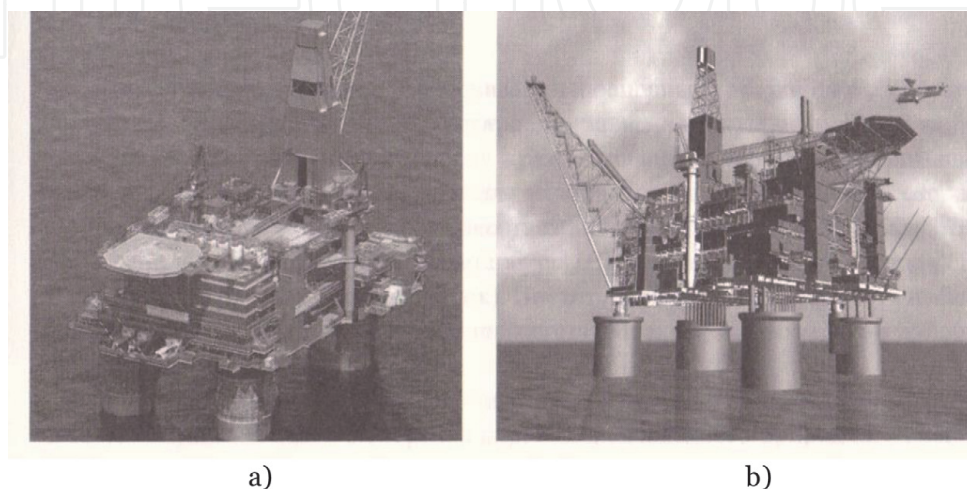

a)   b)

Figure 21.
Use of frictional pendulum bearings (sliding supports) on sea oil platforms installed in the top part of four concrete jacks. a) PA-B Platform; b) Lun-A Platform.
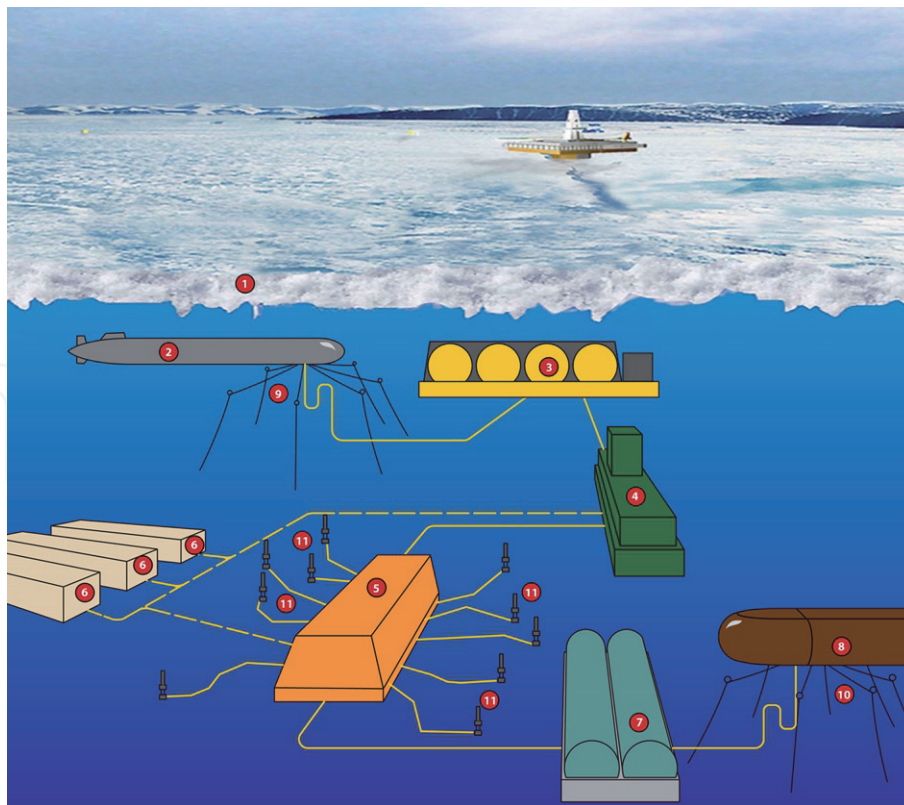
Figure 22.
Scheme of under-water and under-ice technological complex: 1—ice coverage on the sea surface; 2—underwater LNG carrier or tanker; 3—subsea oil and LNG tank; 4—subsea natural gas liquefaction and oil unit; 5—Field processing unit; 6—subsea power generation unit; 7—subsea condensate storage facility; 8—subsea condensate carrier; 9—LNG terminal; and 10—subsea well.

Types of risks	R	R_*	$R(t)$	$R_*(t)$	$R_{US}(t)$	$R_{US^*}(t)$
1. Risks for on-land infrastructures R^{H}	48.3	48.9	71.5	72.4	59.9	60.6
2. Risks of above-water sea transportation R^{M}	4.1	4.13	6.1	6.2	5.08	5.12
3. Risks of on-land and above water technologies R^{HM}	52.4	53.0	77.6	78.6	64.0	65.7
4. Risks of terrorist attacks on on-land infrastructures R_T^H	6.0	6.1	55.1	56.1	46.2	46.4
5. Risks of terrorist attacks in case of above-water sea transportation R_T^M	0.8	2.15	3.1	8.29	2.46	6.4
6. Risks of terrorist attacks on land infrastructures and on sea transportation R_T^{HM}	6.8	8.25	58.2	64.4	48.7	52.8

Table 5.
Risks of the traditional LNG technologies (million dollars per year).

characteristics are given in **Table 5**: R—risks estimates currently for on-land, above-water and under-water technologies without loss of LNG and oil at accidents and disasters; R^*—the same risks, but taking into account losses; $R(t)$—expected risks in 10 years at growth of LNG production, transportation and consumption rate in 4% without LNG loss; $R^*(t)$—the same risks taking into account LNG loss; $R_{US}(t)$—expected risks for LNG and oil transportation in the USA without LNG losses; and $R_{US^*}(t)$—expected risks for the USA taking into account loss of LNG and oil.

The estimated cost efficiency of new underwater technologies (liquefaction and transportation) increases in comparison with the traditional (on-land and above-water) technologies. Risks of new technologies at an initial stage are $(8.6–10.1)\cdot10^6$ of dollars/year; and for traditional ones $(59.2–61.3)\cdot10^6$ dollars/year.
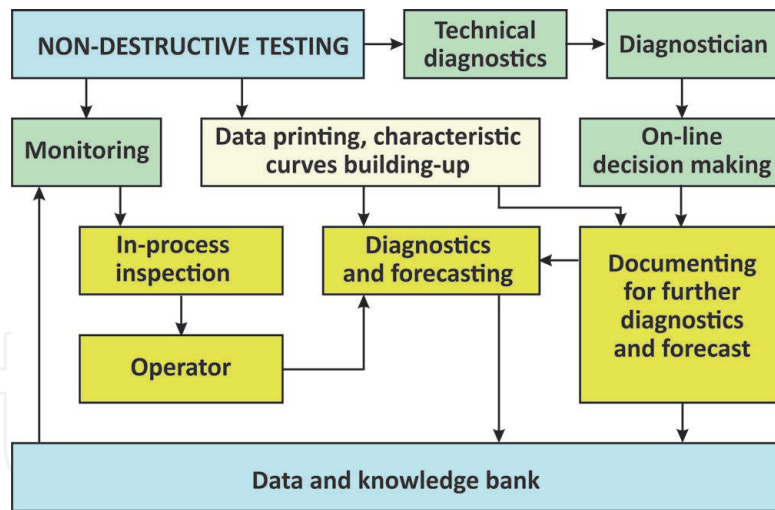
Figure 23.
Diagnostics and monitoring procedure chart.

These risks have to be considered at stage of economic assessment of all newly created technologies related to shelf developments.

The person (operator) or an automatic system, when conducting diagnostics and monitoring (**Figure 23**), closely follow change of parameters and use their abilities to identify and forecast the processes and the phenomena., most actively joins in control processes. The software provides comprehensive processing of the obtained information and active assistance to the operator by performing additional data processing and presenting upon operator's request necessary information recorded in the computing system memory.

A set of the principles, methods and means of defects finding and detection or, in another words, arranging of diagnostic assurance of crack resistance of equipment elements during production and in service, forms the basis for accidents prevention, actuation of the automated protection and safety enhancement.

Such approach was implemented during Sakhalin-II projects execution for protection of SP from earthquakes and tsunami.

4. Conclusion

Issues of development of the world and Russian continental shelf for exploration, drilling, production, treatment, storage and transportation of hydrocarbons become more and more important socioeconomically and in scientific and technical aspects. Unique sea platforms for a temperate and Arctic climate, undoubtedly, fall into group of critically and strategically important objects of infrastructures of life activity and life support. The fundamental studies and applied research works in the field of provision of strength, in-service life, survivability and risks play key role in comprehensive solution of issues relevant to the sea platforms safety, security and protection from accidents and disasters.

Their implementation is focused on scientific justification of classification of continental shelf technosphere objects, classification of routine and abnormal situations, development of methods and systems of diagnostic, monitoring and protection.

In the future-oriented technologies for safe continental shelf development, the results of advanced scientific theoretical and experimental developments in such industries as nuclear, airspace and transport will be used. The specified

research works and development have both clearly expressed national and general international character.

Author details

Gennady Yu. Shmal[1], Vladimir A. Nadein[2*], Nikolay A. Makhutov[3], Pavel A. Truskov[4] and Viktor I. Osipov[5]

1 Academy of Mining Sciences, The Union of Oil and Gas Producers of Russia, Russia

2 Member of the Society of Petroleum Engineers, LLC, Oil and Gas Safety—Energodiagnostika, Russia

3 Engineering Sciences, RAS, Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAN), The Pipeline Transport Institute (PTI, LLC), Russia

4 Engineering Sciences, The "Sakhalin Energy Investment Company Ltd.", Russia

5 Geological Faculty of the MSU, Department of Geo-Engineering and Protection of Geological Environment, RAS, Geological and Mineralogical Sciences, Russia

*Address all correspondence to: vladimir_nadein@ogsed.ru

IntechOpen

References

[1] Safety and Security of Russia. Basis of Safety of Continental Shelf Development. Moscow: MGOF Znanie; 2013. 768p

[2] Safety and Security of Russia. Justification of Strength and Safety of the Continental Shelf Objects. Moscow: MGOF Znanie; 2015. 668p

[3] Safety and Security of Russia. Fundamental and Applied Problems of Integrated Safety and Security. Moscow: MGOF Znanie; 2017. 992p

[4] Kostoqryzov A, editor. Probalistic Modelinq in System Engineering. London: IntechOpen; 2018. 278p

[5] Makhutov NA. Strength and Safety. Fundamental and Applied Studies. Novosibirsk: Nauka; 2008. 528p

[6] Safety and Security of Russia. Risks Analysis and Safety and Securities Issues. Parts I-IV. Bases of the Analysis and Safety Regulation. Moscow: MGOF Znanie; 2006. Part I—p. 639; Part II—p. 752; Part III—p. 800; Part IV—p. 857

[7] Makhutov NA. Safety and Risks. Systems Studies and Development. Novosibirsk: Nauka; 2017. 714p

[8] Strength Calculation Norms for Equipment and Piping of Nuclear Power Units (PNAE G-7-002-86). Gosatomnadzor of the USSR. Moscow: Energoatomizdat; 1989. 525p

[9] Alekseev Yu N, Afanasiev VP, Litonov OE, Mansurov MN, Panov VV, Truskov PA. Ice-Engineering Aspects of Oil and Gas Offshore Field Developments. St-Petersburg: Hydrometeoizdat; 2001. 356 p

[10] Risk Based Inspection Methodology. API Recommended practice 581. 3rd edition. April 2016. Addendum 1, April 2019

[11] Guidelines on Risk Based Inspection. OP 04-30260. Netherlands: SGS; 2009

[12] Lee DE. The base isolation of Koeberg nuclear power station 14 years after installation. In: Proceedings of the Post-SMiRT Conference Seminar on Isolation, Energy Dissipation and Control of Vibrations of Structures; Capri, Italy; 1993

[13] Clarke CSJ, Buchanan R, Efthimiou M, Shaw C. Structural platform solution for seismic arctic environments— Sakhalin II offshore facilities. In: 2005 Offshore Technology Conference – 17378; 2005. p. 21

[14] Drozdov YN, Pavlov VG, Puchkov VN. Friction and Wear in Extreme Conditions. Moscow: Mashinostroenie; 1986. 223p

[15] Drozdov YN, Nadein VA, Puchkov VN. Tribological characteristics of friction, pendulum type seismic-insulators. Friction and Wear. 2007;**28** (2):119-127 (in Russian)

[16] Makhutov NA, Gadenin MM. In: Kyuev VV, editor. Technical Diagnostics of Residual Life and Safety. Study Guides. Moscow: Spektr; 2011. 187p. (Diagnostics of safety)

[17] Nadein VA, Drozdov Yu. N, Puchkov VN, Puchkov MV. Characteristics of Mendulum Sliding Bearings—Seismic Insulators Vestnik Mashinostroeniya, 2. Moscow. 2007. p. 47–53 (in Russian)

[18] Safety and Security of Russia. Safety of Means for Storage and Transportation of Energy. Moscow: MGOF Znanie; 2019. 928p