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RISK ASSESSMENT OF ACCIDENTS DUE TO NATURAL FACTORS AT THE PASCUALES – CUENCA MULTIPLE-USE PIPELINE (ECUADOR)

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The natural aspects of the accident risk at the Pascuales – Cuenca multiple-use pipeline (Ecuador) are analysed in the paper. The Russian Methodological recommendations for the quantitative analysis of accident risks at hazardous production plants of oil trunk pipelines and oil product trunk pipelines issued in 2016 are used as a methodological framework due to relatively poorly defined evaluation mechanism for natural factors of accidents at oil trunk pipelines in the most widespread international accident risk assessment methodologies. The methodological recommendations were updated to meet the environmental conditions of oil pipelines of Latin America. It was found that the accidents due to natural factors make up approximately 15 % of cases at oil trunk pipelines in Ecuador. Natural geographical features of the areas surrounding the main Ecuadorian Pascuales–Cuenca oil trunk pipeline and its relatively short length allow defining three zones along the line in terms of the accident risk: lowland coastlines, high plateaus, and foothills. Calculations and analysis revealed that the maximum predicted specific frequency of accidents is characteristic of the lowland seaside area. The evidence showed that physical and chemical properties of soils and significant seismic activity are the root causes of failures.

***Key words*:** accident risk, oil trunk pipelines, natural factors of accident rate, risk assessment frameworks, physical and chemical properties of soils, overhead-line hardware, deformation monitoring

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Introduction. An accident risk assessment at any hazardous production facility is an essential element in ensuring operational safety [3, 5, 6]. At present, a number of methods and techniques allow quantitatively and qualitatively assessing the risk of emergencies at oil trunk pipelines [2]. The most popular and in-demand methods for analyzing the accident risk in the world are Check-List, What-If, HAZID, PHA, QRA, ETA, FTA, FMECA, and HAZOP.

Each of the existing methods has advantages: from the simplicity of the questionnaire estimation, conditioned by the expert perception of the oil pipeline condition (Check-List and What-If methods), to the use of high-precision sensors of various parameters of facility operation with the automated input of appropriate corrections in case of uncertainty (HAZOP method). However, all these methods have one common drawback that is the lack of a full-fledged possibility of estimating proportions of accident factors having fundamentally different origin: anthropogenic, natural, structural, technological, etc.

A certain success was achieved in solving this methodological issue in 2016. Researchers of the Russian Federal Service for the Supervision of Environment, Technology and Nuclear Management developed and published the Methodological recommendations for the quantitative analysis of accident risks at hazardous production plants of oil trunk pipelines and oil product trunk pipelines [1]. This regulating document describes the analysis sequence that complements existing methods for assessing accident risks and can be adapted not only to the Russian operating conditions of oil trunk pipelines but also to the industrial safety management of any other country.

Formulation of the problem. The natural environment is one of the key factors determining the probability of emergency situations at oil trunk pipelines. This factor is especially significant in the territories having substantial deviations from the average statistical parameters in conditions of extremely low or high temperatures, high humidity, exceptionally unstable soils [9], elevation difference, and the presence of a developed river basin.

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Virtually all the factors complicating the operation of oil pipelines can be found in the Republic of Ecuador. The small country area (283,560 km^2) includes coastal lowlands adjacent to the Pacific Ocean, highlands of the Andes (with elevations of up to 6,000 m), and low-lying areas that are part of the natural geographical region of the Amazon [4, 12]. A significant difference in altitude creates a significant temperature difference (average annual temperatures from +30 °C in low parts and up to +3 °C on mountain peaks), the presence of natural relief barriers leads to fluctuations in the amount of precipitation (from 200 to 3500 mm) [8]. This, in turn, affects the geomorphological features and properties of soils [7].

The 205 km Pascuales – Cuenca multiple-use pipeline is the longest and most significant in volumes of transported oil and oil products amongst several oil trunk pipelines in Ecuador [10]. This pipeline stretches from the Pacific coastal zone near the largest Ecuadorian city of Guayaquil to the Cuenca terminal in the submountain region at an altitude above 2,500 m, where transported petroleum products and liquefied petroleum gas are stored. With this natural geographical features, the pipeline goes through three zones: lowland coastlines, high plateaus, and foothills, where accident risks were analysed. Assessment of an accident risk level due to natural geographical conditions along the whole Pascuales – Cuenca multiple-use pipeline and comparison of the numbers at different pipeline sectors is the major aim of the research.

Research methodology. When assessing the probability of accidents at linear pipeline facilities, the following parameters were considered [6]:

- $\bar{\lambda}$, the specific frequency of accidents along the whole pipeline;
- λ_n, the specific frequency of accidents at certain sites of the pipeline;
- k_f, the index showing the difference between the specific frequency λ_n at certain sites and the statistically average value of $\bar{\lambda}$ along the whole pipeline; the factor is appraised by points.
- F_{ij}, a factor influencing failure rate at the pipeline;
- B_{ij}, a 10-point-scale of F_{ij} significance;
- B_n, a point-scale assessment of an n pipeline sector;
- B_{av}, an averaged point-scale assessment of the pipeline.

A rating of each studied factor was analysed according to the formula

$$k_f = \frac{B_n}{B_{av}},$$

provided that

$$B_n = \sum_{i=1}^{I} \sum_{j=1}^{J(i)} \rho_{ij} q_{ij} B_{ij};$$

$$B_{av} = \frac{1}{N} \sum_{n=1}^{N} B_n,$$

where N is the total number of sections of the oil trunk pipeline; q_{ij} is a share of a specific accident factor in the aggregated group of accident factors; ρ_{ij} is a share of the aggregated group of factors, e.g. a share of natural impact factors in the whole set of factors.

The values of ρ_{ij}, based on an expert assessment of the accident causes at all oil trunk pipelines of Ecuador over the past 25 years are shown below:

A group of factors	ρ_{ij}
External anthropogenic impacts	0.50
Corrosion	0.05
Natural effects	0.15
Structural and technological factors	0.10
Defects in a pipe body and welds	0.20

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Laying of oil pipelines over the water course in the region of Cuenca

The general mathematical relationship between the specific frequency of accidents along the whole pipeline and the specific frequency at certain sections is described as

$$\lambda_n = \bar{\lambda} k_f k_n k_l .$$

Where λ is applied to the conditions of Ecuador and calculated by the formula

$$\bar{\lambda} = \lambda_{av} k_D k_{reg} .$$

Where λ_{av} is an average accident rate at all oil trunk pipelines in the country over the last 5 years; k_D is a diametric ratio, the accident statistics dependent on the nominal diameter DN of the oil pipeline:

DN	1400	1200	1000	800	700	500	Less than 500
k_D	0.35	0.85	1.60	1.25	1.40	1.20	1.10

k_{reg} is a regional index; k_n is a strength ratio, i.e. the value reciprocal of the ratio between the effective factor of safety of an oil trunk pipeline at the certain sector and the reserve strength ratio, in the absence of data it is assumed to be 1; k_l is a ratio dependant on the method of pipeline laying [6], k_l = 0.1 after applying microtunneling technology at a site, k_l = 0.4 after controlled directional drilling, k_l = 0.6 after using the pipe-in-pipe system or concrete weight coated pipe, k_l = 1 at all the other sites.

Theoretical and field studies. Based on actual data on the parameters of the pipeline operation, natural geographical characteristics of the pipeline laying area, data on physical and chemical properties of soils in the adjacent territory [11], as well as visual and metrological analyses, the obtained results allow to implement the proposed method for analysing the accident risk caused by natural factors.

The natural accident factor of the oil trunk pipeline operation in Ecuador depends on potential negative mechanical impacts:

• damage to the oil pipeline caused by such soil deformations as rockfalls, landslides, mudflows, thermokarst, soil heaving, solifluction;

• uneven subsidence of the pipeline, typical of the ground nodes of the branched configuration, linear fittings, chambers of start-up and reception of cleaning devices, onshore combs and adjacent areas.

Failure to account for trench erosion on underwater crossings is the main difference from the basic methodology applied in the Russian conditions. This is due to the fact that all transitions at hydrographic network facilities are created overhead (Fig.).

Thus, the natural factors affecting oil trunk pipelines are as follows:

An impact factor	q_{ij}
Probability of soil movement	0.20
Carrying capacity of soil	0.15
Presence of linear reinforcement, aboveground technological pipelines on the site	0.15
Taking of preventive actions	0.50

When analysing the data on topography and tectonics of Ecuador, it is obvious that the whole of its territory belongs to zones with a high or medium probability of soil movements. The landscapes of Ecuador are typical of a sharp drop in altitude, high seismic activity in the foothill zone, manifested by active volcanoes, as well as the dynamic geological activity of the ocean.

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The point-scale assessment of the 'Probability of soil movement' factor is determined in accordance with the probability of soil movement:

Probability of soil movement	B_1
High. Ground movement is a common occurrence, regular shifts and discontinuities of soil, landslides, subsidence, rockfalls, and heaves are observed. Zones of dangerous seismic processes, mining, and mountains	10
Average. Topography and soil types do not exclude the possibility of soil movements, but significant soil deformations are rare. No damages or unacceptable position changes of oil trunk pipelines were registered for this reason. Zones of low-risk seismic processes	5
Low. Soil movements are rare. Displacements and damages of oil trunk pipelines are practically excluded. The site is located out of seismically hazardous areas	1
No signs indicating a potential threat associated with ground movements	0

So, $B_1 = 10$ for the lowland coastlines, $B_1 = 5$ for the high plateaus, and $B_1 = 10$ for the foothills.

Soil composition determines its bearing capacity, affecting stability of the design position of an oil trunk pipeline axis, and, consequently, the probability of its integrity violation. Accordingly, the higher is soil load-bearing capacity, the more stable is the position of an oil trunk pipeline and the less likely is the occurrence of unacceptable stresses in the wall of the pipe, which can lead to its depressurization. The point-scale assessment of this factor in relation to the physicochemical and petrographic properties of Ecuadorian soils is given below:

Soil bearing capacity	B_2
Low (marsh zones, silty sands with inclusions of pebbles, gravel and boulders)	10
Medium (loam with gravel and pebbles inclusions)	5
Normal (shale schists with quartz veins, pebble soils and sandy loams with inclusions of gravel and pebbles)	2

The averaged analysis of soil properties by geomorphological and geological maps of Ecuador allows to conclude that $B_2 = 10$ for the lowland coastlines with predominating soils of aeolian alluvial origin; $B_2 = 5$ for the high plateaus composed mainly of eluvial loamy deposits; and $B_2 = 2$ for the foothills where generally eluvial and illuvial sandy loam sediments include a large number of hard pebble and basaltic inclusions.

The 'Presence of linear reinforcement, aboveground technological pipelines on the site' factor takes into account an additional impact of heavy ground fittings of the oil trunk pipeline on the probability of significant stresses and deformations of pipeline bending sections adjacent to the above-ground nodes and, consequently, on the probability of its destruction with seasonal temperature fluctuations and uneven ground subsidence. A scoring of this factor is given below:

Presence of linear reinforcement, aboveground technological pipelines on the site	B_3
Presence of aboveground nodes with complex strapping and reinforcement without foundation	10
Presence of complex aboveground nodes with reinforcement on the foundation; frame construction is designed taking into account recommendations of modern regulatory documents	5
Presence of linear reinforcement without foundation	7
Presence of linear reinforcement is present on the foundation	3
No aboveground structures	0

Associated engineering structures on the oil trunk pipelines of Ecuador are not particularly complicated (a typical version of the supporting reinforcement is shown in the figure). An indispensable condition for using such a reinforcement is its installation on a rigid cement foundation with at least 1 m depth of the reference well. It should be noted that there are no specific regional differences in the use of such reinforcement, therefore, $B_3 = 3$ for all three study areas, the lowland coastlines, the high plateaus, and the foothills.

The 'Taking of preventive actions' factor evaluates the following measures:

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• providing physical protection or stress relaxation at the trunk pipeline: laying of the pipeline below the depth of soil deformation, the shift of a line section, designing of retaining walls on the slopes, installation of expansion joints, ground discharge of the pipeline using a device of parallel trenches;

• change in soil properties, for example, soil dehumidification by drainage systems;

• monitoring of soil deformations and pipeline movements.

The score depends on the presence or absence of preventive measures on the analysed section of the pipeline, conducted whenever necessary. The score is calculated as the sum of the scores of the three components. Information on the conduct of preventive measures:

Taking of preventive actions		$B_4(m)$
Measures to reduce stresses in the trunk pipeline	Taken or not required	0
	Not taken or inadequate	2
Measures to change soil properties	Taken or not required	0
	Not taken or inadequate	1.5
Monitoring of soil deformations and pipeline movements	Carried out constantly by means of engineering seismometric stations and surveying services	0
	Carried out visually twice a year by means of fixed benchmarks on the track	1
	Not carried out or rarely done	3
	Stress-strain state is controlled by automated diagnostic tools	0

Throughout the length of the Pascuales – Cuenca multiple-use pipeline, various retaining walls are present (especially at sharp relief drops), in some areas pipeline sections are shifted, the pipeline is laid below the depth of soil deformation in flat areas. Accordingly, $B_4(m_1) = 0$ at all three sites. Measures to change soil properties are taken on a wetland foothill, where precipitation is much higher than on the other two sections; the number of drainage channels can be estimated as insufficient. So $B_4(m_2) = 0$ for the lowland coastlines and the high plateaus; $B_4(m_2) = 1.5$ for the foothills.

Thus, summing the values obtained, $B_4 = 0$ for the lowland coastlines and the high plateaus, and $B_4 = 1.5$ for the foothills.

Evaluation of results. Based on the proposed methodology for point-scale assessment of the accident rate due to natural factors at the Pascuales – Cuenca multiple-use pipeline for three investigated sites, the following results were obtained:

• $B_n = 0.6$ for the lowland coastlines;

• $B_n = 0.33$ for the high plateaus;

• $B_n = 0.525$ for the foothills.

The average score $B_{av} = 0.485$ for the whole Pascuales – Cuenca multiple-use pipeline accident rate due to natural factors.

The influence index of the natural factor:

• $k_f = 1.24$ for the lowland coastlines;

• $k_f = 0.68$ for the high plateaus;

• $k_f = 1.08$ for the foothills.

Based on statistical data on the average accident rate at oil trunk pipelines in Ecuador, $\lambda_{av} = 0.13$ accidents per year per 1000 km.

The technical documentation establishes the nominal diameter of the pipe $DN = 609$ mm. Accordingly, the diametric coefficient $k_D = 1.4$.

Due to the fact that the area of Ecuador is 283,560 km^2, the pipeline length is small, the areas surrounding the pipeline do not differ significantly in socio-economic development, the regional k_{reg} index can be neglected and considered equal to one. Respectively, the specific frequency of accidents along the whole pipeline $\bar{\lambda} = 0.18$.

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Since there are no precise data on strength parameters of the trunk pipeline in open sources, the strength ratio $k_n = 1$.

The way of the laying of the Pascuales – Cuenca pipeline combines various approaches that cannot be unequivocally attributed to any of the options offered by the methodology. So the ratio dependant on the method of pipeline laying $k_l = 1$.

In this way, the specific frequency of accidents at certain sites of the Pascuales – Cuenca pipeline due to natural factors is:

- $\lambda_n = 0.22$ for the lowland coastlines;
- $\lambda_n = 0.12$ for the high plateaus;
- $\lambda_n = 0.19$ for the foothills.

Thus, the greatest accident potential, due to the complex natural impact falls on the initial, lowland coastline area.

Conclusions. The results of the natural accident risk study at the Pascuales – Cuenca multiple-use pipeline show:

1. Approximately 15 % of accident cases on the trunk pipelines in Ecuador account for the natural factor.

2. Analysis and calculation of the main accident parameters related to natural effects are carried out both for the Pascuales – Cuenca multiple-use pipeline as a whole, and for its separate sections in accordance with the Methodological recommendations for the quantitative analysis of accident risks at hazardous production plants of oil trunk pipelines and oil product trunk pipelines, modified for the conditions of Ecuador.

3. It is found that the greatest potential for accident rate caused by a natural factor is characteristic of the lowland coastlines, which is associated with the peculiarities of physical and chemical properties of soils and the constant seismic activity.

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