THE PROBABILITY APPROACH TO MODELLING OF AN OPTIMAL UNDERWATER PIPELINE ROUT UNDER IMPACT OF HUMMOCKS

Alexander T. Bekker and Olga A. Sabodash
Far-Eastern State National University, Vladivostok, Russia

ABSTRACT
Drifting hummocks are the major problem in achievement of sufficient reliability of pipelines in freezing seas because such hummocks may contact the sea bottom, as well as pipelines, during their movement. In this paper, the authors have considered the problems of track choice for an underwater pipeline offshore Sakhalin. For such purpose, there was applied a probabilistic approach to determination of spatial position (including bottom configuration) of the underwater pipeline track.

KEY WORDS: Drifting hummocks; Underwater pipeline rout; Probabilistic approach; Reliability; Sakhalin offshore.

INTRODUCTION
As a rule, pipeline transportation is the most economic kind of transportation for oil&gas during development of oil&gas fields, including those within the offshore of the Sea of Okhotsk. The Sakhalin offshore, which total area is almost 20 thou sq. km, is the most examined and promising part of the Russian Far-Eastern region concerning oil&gas. According to experts’ estimations, conditions of resources development on the Sakhalin offshore are very complicated. The sea within Piltun-Astokhskoe oil&gas field, where “Molikpaq” platform was installed in 1998, is 30-meters deep with ice cover for more than 6 months during a year. Thereby, we should take into consideration influence of the ice features, when designing or constructing the underwater pipelines or other structures on the Sakhalin offshore.

In the freezing seas, drifting hummocks are the main problem in achieving sufficient reliability of pipelines, because they may touch the sea bottom or the pipelines during movement. Such contact, if any, may destroy the pipeline that is confirmed by statistics data of averages on available pipelines. At the same time, deepening of pipelines into soils is the main and the most applicable way of pipeline protection from external impacts.
It is generally known that natural factors, which define strength and frequency of the drifting hummocks’ impacts on the sea bottom, possess spatial variability and inhomogeneity, and are subject to considerable seasonal-temporal variability, as well. In particular, such hummocks’ parameters as width of the bottom, depth of their keels, angulations of edges of the hummocks’ keels, height of hummock sail, and physic-mechanical features of the ice of hummocky formations, may vary to a considerable extent. Besides, the relief and the geomorphologic parameters of the sea bottom may re-form under influence of flows and waves.

Accordingly, the purpose of this study is to develop a procedure of optimization calculations of the underwater pipeline track attitude position taking into account its burial value and bottom relief of the sea area on the basis of probabilistic approach. At the same time, we consider the methodology of choice of the optimal pipeline track basing on theory of reliability, as well as on probabilistic simulation model of interaction between the drifting hummocks and the sea bottom. When developing this model we applied some well-known methods of numerical/statistic simulation, which have got intensive development in recent years.

In this paper, the authors represent the results of the following investigations: there was specified and investigated a new deterministic model of drifting hummocks’ effect on the sea bottom; there was implemented a statistical processing of data on natural observations of hummocks’ parameters offshore the north-eastern Sakhalin through the ice season; to receive probabilistic characteristics of parameters of the optimal track of the underwater pipeline there was specified a probabilistic simulation model of the drifting hummocks’ effect on the sea bottom and underwater pipelines; basing on developed procedure, there were implemented some optimization calculations of variants of spatial track of the underwater pipeline at Piltun-Astokhskoe oil&gas field located Sakhalin offshore.

MODEL OF THE DRIFTING HUMMOCKS’ EFFECT ON THE SEA BOTTOM AND UNDERWATER PIPELINES

Investigation of parameters of actual configuration of the hummock’s cross-section

Problems of choice of the underwater pipeline track offshore Sakhalin Island was considered in papers (Bekker et al, 2004; Surkov, 2000). On comparison of some natural factors, which affect the considered design solutions on several variants of underwater pipeline tracks from the Akutun-Dagi, Piltun-Astokhskoe and Chaivo oil&gas fields, there were given some recommendations on choice of a track and value of burial depth for the main variant of the underwater pipeline.

When choosing the pipeline burial depth, we used a procedure developed at SakhalinNIPImorneft. This technique has been based on simulation of the process of the hummock’s penetration into the bottom ground while taking into account real conditions offshore the northern Sakhalin (Surkov, 2000).

A procedure of calculation of the depth of the hummock’s penetration into soil according to deterministic model of interaction was studied in detail by (Surkov, 2000). From analysis of mathematic dependencies between penetration depth $H$, length $S$ and furrow width $B$ we may see, that the definition of these parameters (Figure 1) in the model has the following problems:
- taking into consideration actual configuration of side edges of the hummock’s keel;
- taking into consideration actual width of the hummock’s underwater part (that is length of
exaration furrow) when penetrating into sea bottom;
- development of calculation criteria for fracture of the hummock’s keel when penetrating into soil.

In this chapter, we represent a brief analysis of each raised problem. Said analysis served for specification of the model of drifting hummocks’ impact on the sea bottom, which had been developed by SakhalinNIPImorneft Institute (Surkov, 2000).

First of all, there is an issue of taking into account a configuration of the front edge of the hummock, which impacts the sea bottom. This issue is both general and less investigated than others.

In this study, we tried to approach a solution of the problem of interaction between a drifting hummock and substructure soil on the basis of natural observations over hummocks’ parameters offshore the northern Sakhalin. When defining depth of the hummocks’ penetration into bottom, such approach allowed rejecting simplified theoretical models of hummocks offered by various researchers (Bekker, 2000; Surkov, 2000). We accurately consider all the variety of actual configurations of hummocks, which may be actually observed in natural ice conditions within sea areas of the oil&gas fields.

The second problem (when solving the task of hummock’s formation impact on the sea bottom) concerns the choice of furrow width value.

According to a review of literature on this problem, it’s rather difficult to receive $B$ value by way of mapping. That’s why theoretical methods of calculation were widely developed in recent years. However, calculations on the furrow width and depth of the hummock’s keel exaration into sea bottom have considerable variations in results. When defining depth of the hummocks’ penetration into soil, the authors were solving this task by using in mathematics dependences of penetration value $H$ and length $S$ from real natural observations of the furrow width made by the hummocks in the sea bottom soils offshore the northern Sakhalin.

There were investigated 90 of actual hummocks on north-eastern part of the Sakhalin offshore. The following hummocks’ parameters were processed statistically: depth of the hummock’s keel $H_k$; width of the hummock’s bottom part $B$; angle of inclination of the hummock’s edges to the vertical line $\varepsilon$; height of hummock sail $H_s$.

All parameter data were distributed in lines in accordance with goodness measures and then statistically tested. The statistical testing showed that all the parameters distributed in accordance with the normal (Gaussian) distribution function (Table 1).

**Development of calculation criteria for the hummock’s keel fracture when penetrating into the sea bottom soil**

One of the least studied issues in special literature concerning the drifting hummocks’ impacts on the sea bottom or underwater pipelines is development of the calculation criteria for the hummock’s keel fracture when penetrating into the sea bottom soil under the influence of outer forces. It’s obvious that some calculation situations may arise when local strength of the sea bottom soil overcomes the strength of the hummock’s keel that causes shear fracture of the hummock’s keel over a surface. As a result, some hummocks’ keels will destruct on contact with the soil and, hence, we may not take into account parameters of such hummocks in optimization.
calculations of spatial situation of the underwater pipeline track. To develop criteria of the hummock’s keel fracture, the authors took the following assumptions:
- material of the hummock’s keel is considered as free-flowing/binder homogeneous medium;
- it is necessary to take into account geometrical specificity of the underwater keel of the hummock;
- strength of the soil of sea bottom and strength of the hummock’s keel are described by the equations of soil mechanics and by the theory of the ultimate stress condition.

Then we may consider the following condition as a criterion of the hummock’s keel material fracture (Figure 2):

\[ F_{\text{soil}} \geq F_{\text{keel}} \]

(1)

where \( F_{\text{soil}} \) is a passive resistance force of the sea bottom soil, kN; \( F_{\text{keel}} \) is a passive resistance force of a hummock’s keel material, kN.

To define passive resistance, we usually apply a calculation model of the boundary soil balance and solutions of the Coulomb's wedge theory or various approximate answers in terms of such model (SNiP, 1987).

Then the resultant force of soil passive resistance including the expressions will be defined as (SNiP, 1987):

\[ F_{\text{soil}} = \frac{1}{2} H \cdot (\gamma_i \cdot s \cdot H \cdot \lambda_{p,s} + c \cdot \lambda_{pc,s}) \]

(2)

where \( H \) is a maximum depth of the hummock’s keel penetration into the soil defined in the study (Surkov, 2000); \( \gamma_i \) is volume weight of soil; \( \lambda_{p,s} \) is coefficient of horizontal component of soil passive resistance defined including friction between medium and soil according to Coulomb's wedge theory; \( c \) is specific cohesion of soil; \( \lambda_{pc,s} \) is coefficient of the passive resistance from cohesion forces.

Resultant force of the keel passive resistance is defined as (SNiP, 1987):

\[ F_{\text{keel}} = \frac{1}{2} H \cdot (\gamma_{hw,k} \cdot H \cdot \lambda_{p,k} + c_k \cdot \lambda_{pr,k}) \]

(3)

where \( \gamma_{hw,k} \) is a volume weight of the hummock’s keel in condition of hydrostatic weighing; \( \lambda_{p,k} \) is a coefficient of horizontal component of the hummock’s keel passive resistance defined including friction between hummock’s keel and the sea bottom soil according to Coulomb's wedge theory; \( c_k \) is a specific cohesion of the keel; \( \lambda_{pr,k} \) is a coefficient of the keel passive resistance from cohesion forces.

It is known from soil mechanics theory that passive resistance depends not only on structure’s characteristics but on physic and mechanical properties of environment and configuration of free surface of the soil, as well. Thereupon, in deterministic model of impacts of the drifting hummock on the sea bottom (Surkov, 2000) we consider the complicated geometry of the
underwater part of the hummock. This consideration makes a sufficient correction to the value of the hummock’s keel passive resistance. Thus, introduction into simulation modeling made by the SakhalinNIPInmorent Institute for criterion (1) of the hummock’s keel material fracture allows more accurate describing of the penetration process of drifting hummocks into bottom soil.

PROBABILISTIC SIMULATION MODEL

The optimization of the underwater pipeline route is carried out by two parameters: the accepted level of reliability of the pipeline and the distribution function of depths of drifting hummocks or icebergs penetration in a sea bottom.

The optimization criteria of choice of a space track of the pipeline will be defined by the following expression (Surkov, 2000):

\[ P_d \geq P_n , \]

(4)

where \( P_d \) is a level of reliability of the designed pipeline (the probability of lack of contact of the pipeline with hummocks for some time period can be accepted); \( P_n \) is a normalized reliability level.

The probability of lack of contact of the pipeline with a hummock for lifetime period in case of single intersection it of the pipeline route (a level of reliability) will be defined as (Surkov, 2000):

\[ P_d = \int_0^{h_d} p(h)dh , \]

(5)

where \( h_d \) is a pipeline burial depth; \( p(h) \) is function of density of distribution of penetration depths of drifting hummocks \( h \) in sea bottom.

Hence, for optimization calculations of a spatial track of the underwater pipeline it is necessary to determine of function of frequency distribution of depths of drifting hummocks or icebergs penetration in sea bottom \( p(h) \). It is possible to solve this problem only on base of a simulation modelling.

Main elements of the simulation model are probabilistic characteristics of initial parameters of the hummocks and the sea bottom topography.

In terms of deterministic model considered in (Bekker, 2000; Surkov, 2000), which allows to define the depth of the hummock’s penetration into soil \( H \) taking into account the hummock’s keel fracture criterion (1), we specified the block-diagram of the probabilistic simulation model of ice impacts on the sea bottom and underwater pipeline (Figure 3), which was offered by (Bekker et al, 2004).

Statistical modeling of probabilistic geometrical and kinematical parameters of hummocks (in accordance with specified functions of distribution of their probabilities) was implemented under method of Monte-Carlo as per especially developed algorithm and a program. Modeling of the sea bottom geometry by exchange of its real spatial geometry with calculated one was implemented on the basis of geoinformation computer systems (GIS).
When implementing the simulation model on computer with the help of specially developed algorithm, we finally made some optimization computations of spatial location of the buried-into-soil underwater pipeline taking into account specified level of its reliability, which was considered in detail by (Bekker et al, 2004).

**EXAMPLE OF CALCULATION FOR THE SAKHALIN CONDITIONS**

The offered procedure of probabilistic calculation for the optimal track of the underwater pipeline was applied by example of the Piltun-Astokhskoe oil&gas field. As shown in studies (Surkov, 2000), optimization of the underwater pipeline track was implemented by normalized reliability index (that is by tolerance probability of pipeline fracture by hummocks through life cycle of a structure). In the Table 1, we show main initial data necessary for probabilistic calculation of the optimal underwater pipeline track within Piltun-Astokhskoe oil&gas field.

The pipeline track has been calculated by the GIS-system of the analysis of the spatial data. This system allows finding at the given reliability level $P_n$ the shortest spatial path between points of a burial depth of the pipeline in each $i$-th square of modeled sea bottom. Thus, hummock penetration depth $h$ in each $i$-th square is the random value with parameters of mean and standard deviation (Figure 4). This parameter was calculated on the base of model of the hummock’s penetration into soil according to deterministic model of interaction, studied in detail by (Surkov, 2000). In given paper such assumptions are the optimization technique of calculation of underwater pipeline track.

At the first stage of calculations, there was carried out an exchange of actually investigated sea bottom configuration for the calculated one. For such purpose, we divided the sea bottom topography into regular $i$-squares, which made up a coordinate grid with 100x100-meter mesh. On such division, the quantity of formed squares was $n=700$ (Bekker et al, 2004).

In the computed version, the model of the sea bottom topography was represented by grid surfaces. On their basis there were built 2-meter long isobathic lines, which were used then to form output geospatial data. For the whole area of oil&gas field plans of depths and horizontal distances were dimensioned like 1:500.

Then we made simulation modeling of the process of hummocks’ penetration into soil within Piltun-Astokhskoe oil&gas field in accordance with special algorithm discussed in the study and with program of statistical modeling of hummocks’ parameters by method of Monte-Carlo. At each stage of modeling for every $i$-square of the sea bottom we changed (by random-number generator) such parameters as width of the bottom part of hummock keel $B(l)$, depth of the hummock keel $H_k(J)$, tilt angle of hummock keel edges to the vertical line $\varepsilon(K)$, hummocks’ drift velocity $V(P)$, and hummock sail height $H_s(L)$. Number of members of generated series was $N=2000$.

At that the angle $\alpha$ is characterized the inclination of sea bottom shape to horizontal plane in a place of a hummock indentation into a bottom. In each $i$-th square of water area the angle $\alpha$ was calculated under known geometrical formulas and accepted for a constant value.

At definition of the angle between a direction of drift hummocks and a track of the prospective underwater pipeline the statistical data of ice drift in the given area of the Sea of Okhotsk were used. The data on ice drift and velocities are submitted in previous paper of authors (Bekker at al,
In the program at modelling of hummocks’ drift velocity \( V(P) \) all directions and angles between a hummocks and pipeline track (including from coast) were considered. These parameters had the different value of probability, that taken into account at calculations.

For every \( j \)-set of geometric and kinematical parameters of hummocks in \( i \)-square of the sea bottom, probabilistic features of furrow (i.e. functions of density for distribution of depths of drifting hummocks’ penetration into soil \( f(h) \) and parameters of distribution) were calculated in accordance with specified mathematic model of hummock penetration into soil as per the block-scheme of the simulation model (Figure 3) and especially developed algorithm.

For example, Figure 4 shows a histogram of hummocks’ depths penetration into soil within the \( i \)-square with average sea depth \( H_{ave}=20.4 \) m, sea bottom angle \( \tan \alpha=0.01 \), and quantity of hummocks in the square \( N_{hum}=493 \).

On the base of investigations and publications of (Surkov, 2000) we suggest, that natural shape of bottom may have local bottom banks, so called bars, which protect parts of bottom behind them from impact of drifting hummocks coming from sea side (“shadow zones”).

In terms of optimization calculations of value of underwater pipeline burial into soil \( h_d \) in \( i \)-th square, there were obtained various versions of underwater pipeline track. Minimum value of pipeline track burial depth \( h_d \) was as follows (Figure 5):

a) (excluding shadow zone) minimal value was 0 m, average value was 1.18 m, and maximum value was 2.05 m; and

b) (including shadow zone) minimal value was 0 m, average value was 1.06 m, and maximum value was 2.05 m.

CONCLUSIONS

Main scientific and practical results of investigations carried out in this study are as follows provisions:

1. There was specified and investigated a deterministic model of drifting hummocks’ impacts on the sea bottom, and there was offered a criterion of hummock keel fracture during penetration into sea bottom soil.

2. There was implemented a statistical processing of data from natural observations over hummocks’ parameters offshore the north-eastern Sakhalin during one ice season.

3. To obtain probabilistic features of parameters for optimal underwater pipeline track, there was specified a probabilistic simulation model of drifting hummocks’ impact on the sea bottom and underwater pipelines.

4. In terms of a developed procedure there were implemented some optimization calculations of versions of spatial underwater pipeline track within Piltun-Astokhskoe oil&gas field offshore the north-eastern Sakhalin. Minimum value of pipeline track burial \( h_d \) was as follows:

a) (excluding shadow zone) minimal value was 0 m, average value was 1.18 m, and maximum value was 2.05 m; and

b) (including shadow zone) minimal value was 0 m, average value was 1.06 m, and maximum
value was 2.05 m.

REFERENCES


Figure 1. Design scheme of drift hummock indentation in a sea bottom (Surkov, 2000).

Figure 2. The scheme of loads over the hummock’s keel during penetration into the sea bottom.
ENTRANCE OF STATISTICAL HUMMOKS’ PARAMETERS AND DETERMINISTIC STRENGTH PARAMETERS OF SEA BED SOIL AND ICE

NUMERICAL SIMULATION OF GEOMETRIC AND KINEMATIC PARAMETERS OF HUMMOKS BY MONTE-CARLO METHOD

SIMULATION OF REAL SEA BED TOPOGRAPHY BY THE REGULAR UNIFORM GRID SYSTEM

DETERMINATION OF PROBABILISTIC CRITERIA FOR COMING OF SIMULATED HUMMOKS INTO I-SQUARE OF THE SEA BED GRID

VERIFICATION OF DESIGN CRITERION OF THE HUMMOCK’S BACK FRACTURE AT IMPACT ON THE SEA BED: \( F_s > F_k \)

DEFINITION OF VALUE OF PIPELINE BURIAL INTO SOIL BY FUNCTION OF BURIAL DEPTH DISTRIBUTION TAKING INTO ACCOUNT STANDARD PIPELINE RELIABILITY AND ICE DRIFT DIRECTION IN THE I-SQUARE

END

Figure 3. General block-diagram of simulation model of hummocks’ impacts on the sea bottom and underwater pipeline.

Figure 4. Histogram of hummock penetration depth \( (H) \) at average sea depth in \( i \)-square \( H_{ave}=20.4 \) m (average value \( m=1.235 \) m, standard deviation \( \sigma=0.163 \)).
Table 1.
Initial data for calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Q-ty of terms in generated series</td>
<td>N</td>
<td>2000</td>
<td>-</td>
</tr>
<tr>
<td>2. Hummock sail height</td>
<td>$H_h$</td>
<td>1.72</td>
<td>1.29</td>
</tr>
<tr>
<td>3. Depth of hummock’s keel</td>
<td>$H_k$</td>
<td>8.62</td>
<td>6.45</td>
</tr>
<tr>
<td>4. Width of the hummock’s underwater part</td>
<td>$B_k$</td>
<td>32.75</td>
<td>24.52</td>
</tr>
<tr>
<td>5. Angle of inclination of the hummock’s edges to the vertical line</td>
<td>$\varepsilon$</td>
<td>42</td>
<td>23.3</td>
</tr>
<tr>
<td>6. Weight of hummock</td>
<td>$M_t$</td>
<td>27536.74</td>
<td>-</td>
</tr>
<tr>
<td>7. Specific cohesion of the hummock’s keel</td>
<td>$C$</td>
<td>40</td>
<td>kPa</td>
</tr>
<tr>
<td>8. Hummock’s drifting velocity</td>
<td>$V$</td>
<td>0.493</td>
<td>0.219</td>
</tr>
<tr>
<td>9. Angle of internal friction of the hummock’s keel</td>
<td>$\varphi_k$</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>10. Ice friction angle</td>
<td>$\delta$</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>11. Angle of internal friction of bottom soil</td>
<td>$\varphi_s$</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>12. Square length of grid of the underwater bottom topography</td>
<td>$L$</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>13. Sea depth within the oil&amp;gas field</td>
<td>$H$</td>
<td>0÷30</td>
<td>m</td>
</tr>
<tr>
<td>14. Underwater pipeline diameter</td>
<td>$D$</td>
<td>0.500</td>
<td>-</td>
</tr>
<tr>
<td>15. Normal level of reliability of pipeline</td>
<td>$P_r$</td>
<td>0.9999</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5. The plan of sea bottom with underwater pipeline track according to optimization calculation technique for Piltun-Astokhske oil&gas field:
- without taking into account the ice drift direction (top line) and
- with accounting the ice drift direction (lower line).
The scale of plan is 1:500.