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Optimization of pipeline design solutions for slope stability in Sakhalin region, Russia

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Abstract The article discusses the optimization of design solutions for stabilizing landslide prone slopes on the main pipeline route on the Sakhalin Island, Russia. The calculations of slope stability for various areas located in difficult engineering and geological conditions reveal the possibility of significantly reducing the length of bored piles.

Keywords: pipelines on landslide prone slopes, safety factor, sensitivity analysis, retaining wall, landslide protection measures.

The territory description

In terms of geological structure, Sakhalin Island and the adjacent waters of the Japan Sea and the Okhotsk Sea are part of a transitional zone from the continent to the ocean and belong to the northwest segment of the Pacific mobile belt. The island's territory is part of the Hokkaido-Sakhalin geosyncline fold system. The pipeline route passes through a hilly, dissected area, composed of Cretaceous and Neogene deposits (fig. 1, 2), represented by siltstones, mudstones and sandstones. The area can be characterized by active tectonics: presence of faults, intrusions (neogene diorites and quartz diorites), and high seismicity.

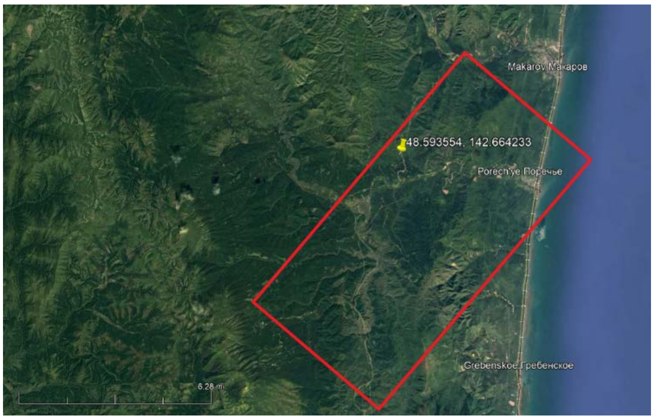

Figure 1 Study area location

The slope heights along the route varies from 15 to 25 meters, with average angles of 25-35°. Field observations on the route reveals the signs of landslides on the slopes and the threat of the existing pipeline destruction.

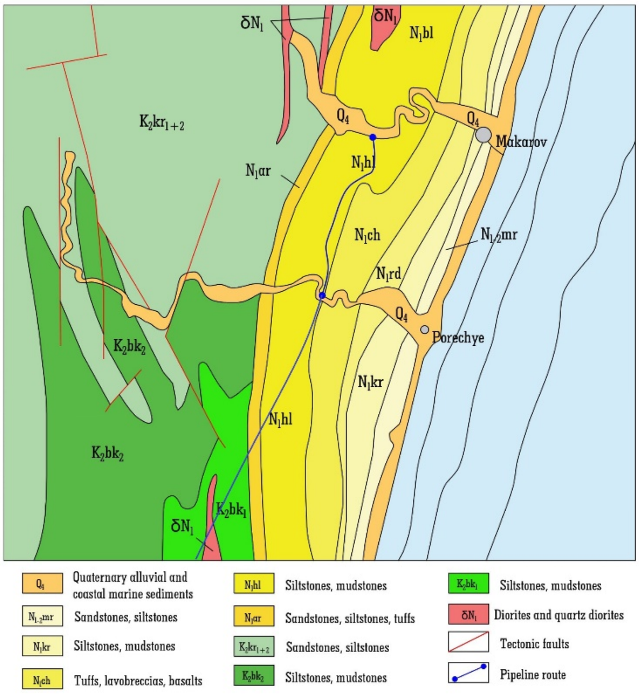

Figure 2 Geological map of the area of 1:200 000 scale.

The geological structure of the studied sections includes: artificial deposits represented by clayey deposits ranging from semi-solid to solid consistency (layer t1); modern eluvial and colluvial-deluvial deposits represented by clayey sandy and gravelly deposits ranging from semi-solid to solid consistency (layers 50, 51, 51a, 51b); deposits of Bykovskaya formation (K_2bk_2) of Santonian-Campanian stages represented by weakly fissured argillites (IGE 30).

Groundwater is prevalent in fissured siltstones of Cretaceous age and is located at depths ranging from 5 to 20 meters. They have sporadic distribution in coluvial-deluvial and eluvial clayey deposits and have not been encountered in the studied areas.

One of the most dangerous geological processes closely related to tectonic structure is seismic activity in the area. According to Russian codes of practice the seismicity of the area is rated 8 points on the MSK64 scale on map A (10%-possibility in 500-years' time period) and 9 points on map B (5%-possibility in 1000-years' time period).

The main factors contributing to the development of landslide processes and determining the slope stability in some chosen sections are seismic effects, as well as actively occurring erosion processes (fig. 3).

Figure 3 Landslides and erosion processes on the pipeline route.

To prevent further development of landslide processes, a project was developed for the construction of a deep-seated retaining wall in the form of a single-row pile embankment with a wall on the embankment.

The goal of the research work was to develop recommendations for adjusting the design solutions for landslide protection structures to optimize the overall project cost.

Used calculation method

Currently, there are many methods for calculating slope stability. The type of landslide process and the mechanism of possible displacement primarily determine the choice of specific methods.

In the calculations we use the limit equilibrium method, represented by the Morgenstern-Price method, the simplified Bishop method, and the generalized Janbu method. The Bishop and Morgenstern-Price methods are considered accepted methods for slope stability calculations according to Russian regulatory documents (section 4.2.11 of SP 11-105-97, Part II)

Seismic effects, when assessing the stability of landslide-prone slopes, can be considered by the pseudo-static analysis.

In this approach introducing an additional force models the earthquake effect. The force F is determined as follows:

$$F = \frac{aW}{g} - kW, \qquad [1]$$

where a – is horizontal seismic acceleration; g – gravitational acceleration, W – the weight of the block; k – seismicity coefficient.

When calculating the stability of a slope to justify landslide protection structures, in accordance with the recommendations of regulatory documents the seismic acceleration value was taken with K1=0.5. Thus, the calculated seismic coefficient for period of 500 years is 0.2.

Normative safety factor should be calculated by the formula:

$$[Fs] = \frac{\gamma_n \psi}{\gamma_d}, \qquad [2]$$

where γ_n= 1.21 is the reliability coefficient for the responsibility of the pipeline;

ψ – load combination factor = 0.90 – for a special combination of loads, consisting of permanent, long-term, short-term and one of the special loads (seismicity).

γ_d – coefficient of operating conditions of the pipeline system = 0.99.

The value of the standard stability coefficient is:

For the main load combination:

$$[Fs] = \frac{1{,}21 \times 1}{0{,}99} = 1{,}22 \qquad [3]$$

For the special load combination:

$$[Fs] = \frac{1{,}21 \times 0{,}90}{0{,}99} = 1{,}1 \qquad [4]$$

Construction of a geomechanical model and calculation methods

The design solution involves the placement of a deep foundation retaining wall in the form of a single-row pile raft with a wall on the raft. The piles are designed with a diameter of 630 mm, a length of 17.5 m, and a spacing of 1.6 m on axes (fig. 4). Driven piles were taken into account in the calculations using specialized software support tools (Pile/Micro Pile) in the Rocscience complex. The piles are designed for a shear strength of 200 kN, and the pile driving spacing of 1.6 m is also considered. The retaining wall with the raft was accounted for by adding a new material to the model - reinforced concrete, its characteristics are specified in Table 1.

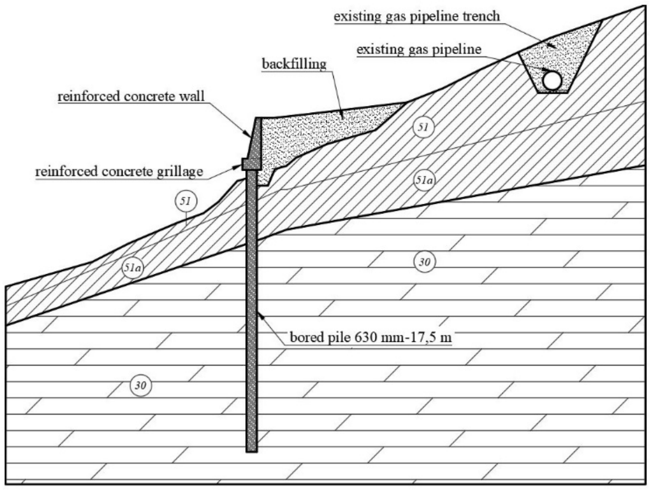

Figure 4 The scheme of retaining wall construction.

Calculations for the selected profiles were carried out for two scenarios:

1) slope stability calculation considering the adopted design solutions (without seismic effects);

2) calculation of the predicted stability considering the adopted design solutions and a special combination of loads (considering seismic effects). The adopted horizontal seismic coefficient = 0.2.

The model takes into account the groundwater level obtained from engineering-geological surveys.

The physical-mechanical properties of the soils used are provided in Table 1.

Table 1. Used properties of soils and concrete.

Layer	Color in model	Unit weight (kN/m^3)	Strength criterion	Cohesion (kPa)	Int. friction angle(degrees)
t1		19.6	Mohr-Coulomb	41.6	22.7
50		18.8	Mohr-Coulomb	57	18
51		19.4	Mohr-Coulomb	24	26
51a		19.6	Mohr-Coulomb	35.3	21.6
30		21.4	Mohr-Coulomb	30.5	63
concrete		25	Mohr-Coulomb	250	55

The results of modelling are on figures 5 and 6.
After performing the standard slope stability analysis, stability calculations were carried out with various pile lengths - from 2.5 m to the design length. The dependence of the safety factor on pile length is on the plots (fig. 8, 9). The article presents an example of stability calculation for one analyzed section, with results for other calculated sections summarized in the conclusion.

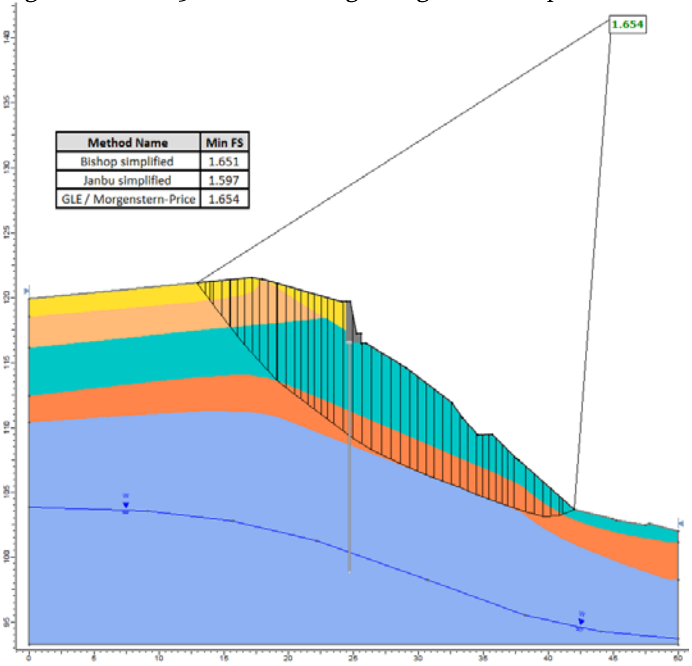

Figure 5 Modeling results without considering of seismic effects.

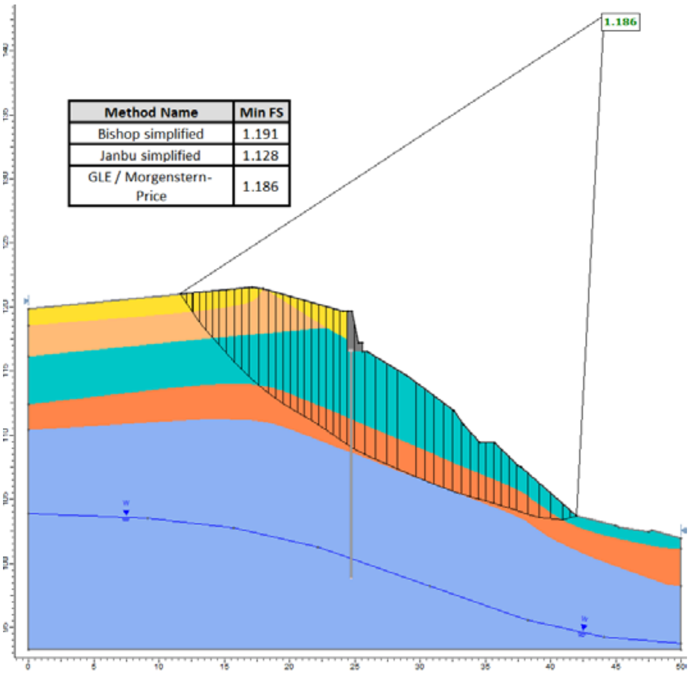

Figure 6 Sliding surface considering of seismic effects.

Calculation results

According to the calculation results, the analyzed slope with the preliminary protection measures decisions is in a stable state, both considering seismic effects and without them.

Additionally, a sensitivity plot of the safety factor (Fs) to the shear strength of the pile is shown on figure 7 considering seismic effects (in the worst-case scenario). It is worth noting that safety factor significantly decreases with increasing seismic effects.

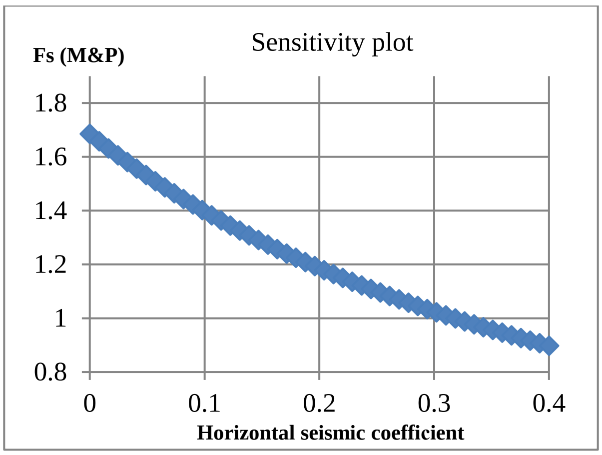

Figure 7 Safety factor dependence on seismic effects.

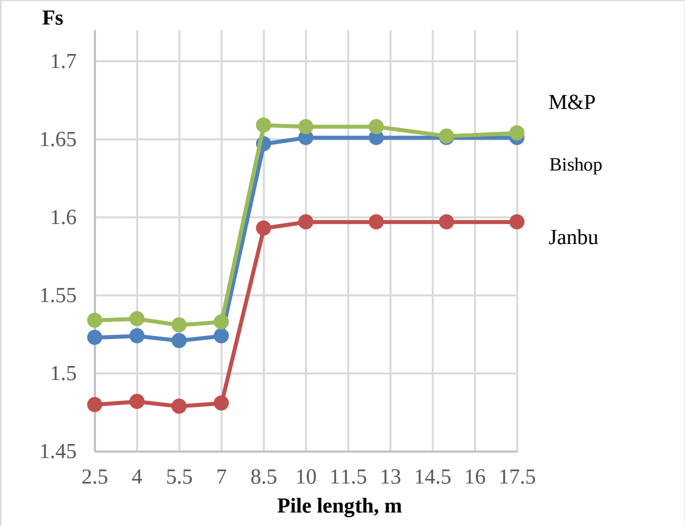

Figure 8 Safety factor on pile length dependence plot (not considering seismic effect)

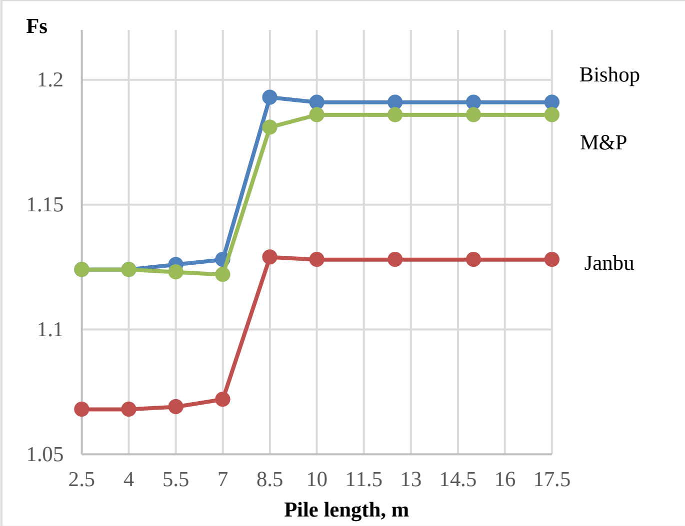

Figure 9 Safety factor on pile length dependence plot (considering seismic effect)

From the graphs, it can be seen that for pile depths up to 7 meters, the stability coefficient is below the normative value (Yanbu method), but in the range of 7-8.5 meters, there is a sharp increase in the stability coefficient. Beyond that, the coefficient remains within a consistent range.

Conclusion

The calculations analysis allows us to conclude that on one of the sections of the pipeline route considered, the designed length of piles can be reduced to 10-11 meters. Embedding piles into the underlying mudstones by an additional 2 meters is presumed to provide a sufficient margin for safe operation.

Using the method mentioned above, calculations were also performed for six other sections located along the pipeline route. Similar conclusions were drawn regarding the possibility of reducing the designed pile length while maintaining the safety of the structure's operation. Considering the piles embedding for 2 more meters, the pile length on the considered sections can range from 9 to 12.5 meters, which is significantly less than the designed pile length of 17 meters.

It is worth noting that an increase in the seismic coefficient entails a sharp drop in the stability coefficient. To ensure greater reliability of calculations, data on seismic microzoning of the study area is required.

The calculations performed justify the safety of the landslide protection structures with a possible reduction in the length of the piles, which will significantly reduce the cost of design work.

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