PROBLEMS OF INTERACTION BETWEEN STRUCTURES AND PERMAFROST: 
THE EXAMPLE OF HEADFRAME FOUNDATIONS

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Abstract

The problem of foundation construction for heavy tower headframes, located in a talik zone adjacent to a shaft, is discussed for various permafrost-soil conditions. Previously known and design variants of headframe foundations are analyzed, their advantages and disadvantages are compared, and the conditions for the use of different types of foundations are described. A general flow-chart is proposed for solving the problem of foundation construction for headgear buildings that depends on the industrial technology of the shaft-headframe complex with respect to specific engineering-geological situations in the shaft mouth zone.

Problem description

In permafrost areas, industrial enterprises characterized by the interaction of adjacent, but different structures at the same site, e.g., of great weight and heat emitting, involving wet technology and excavations, with dynamic loads and of considerable height, can create practically insurmountable design and construction difficulties under certain permafrost-soil conditions. Since the present construction codes in Russia allow only a single principle of foundation construction at the same site (SNiP, 1990), structures which interact with permafrost in a variety of ways require nonstandard designs.

In the current paper, foundation construction for tower headframes is described. The special characteristics of these structures is that a vertical talik forms along the whole depth of the excavation under the headframe buildings due to the warming effect of the shaft. If the soils at the headframe base are weakened or highly compressible upon melting, then according to SNiP they should be preserved in a frozen state, since this guarantees the stability of the base. However, such a requirement, considering the inevitability of the formation of the near-shaft talik, means that the standard approach is unrealistic.

As a result of interaction between the two opposite (assigned and required) technical challenges, universal solution to this problem is needed as it is one of the most urgent and widespread in industrial construction in the North.

Characteristics of headframe buildings

As a result of the increase in depth of the underground mines in the past few decades, a transition to multi-cable lifting machines has taken place in world mining practice. These are usually placed directly on a headframe with the result that the headframe is transformed into a tower of a fairly strict shape. Tower headframes are economically preferable with mine depths of more than 700-800 m. Presently, more than 1000 tower headframes are operated in the world providing ore uplift from depths of about 3.4 km. Headframes have even been designed for a 4.8 km deep mine.

A tower headframe, as a separate structure or part of the headgear block, is structurally independent from other structures on the mine surface. In turn, blocking of headframes themselves is possible above closely located shafts. Thus, cylindrical coupled headframes are applied in Swedish mines (Andreev, 1970), and even a unique linear headframe has been erected above nine shafts passed along one axis (Naydenko and Belyy, 1979). However, practically all tower headframes operated in Germany, USA, Canada, Great Britain, Sweden, Finland and South Africa are point structures up to 100 m high, with round, rectangular or multiangular cross-sections. Tower headframe buildings range between 11200 and 62500 m$^3$ with a mass from 2000 to 20,000 tons.

Headframe foundations - strip, slab, box, pile as well as columns, are usually constructed of reinforced concrete and can be constructed in the lowering shaft. Foundation cost can reach 40% of the cost of a headframe. There are also examples of headframes without
their own foundations, resting on timbering at the shaft mouth.

Experience of headframe foundation construction on permafrost

Dozens of tower headframes, both frame and poured-in-place, have been built on permafrost in the Russian North. In Norilsk, the mine plant is situated in an area of bedrock outcrops, so construction of foundations for headframes was not a problem. Dangerous fissuring and associated ice within rocks at the base of headframe were stabilized by cementing after preliminary thawing (Kim, 1962). On the Pechorskiy coal field, loose Quaternary deposits of considerable thickness are widespread. Their physical-mechanical properties depend on the temperature and ice content, and abruptly change when thawed. Therefore, mine builders of Vorkuta had to construct the foundations for headgear buildings under complicated permafrost-geological conditions.

The stability of headgear buildings on permafrost, thawed under the effect of the adjacent shaft talik was ensured using a number of structural methods (Figure 1). Separation of foundation supports beyond the limits of the thaw bulb with the headframe hanging from beams or bridge supports (scheme I in Figure 1), despite some successful applications, is considered to be uneconomical because of the increase in construction cost, weight of structures and increase in building cost in general. To localize adjacent to a shaft talik, special timbering near the journal of the shaft with a ventilated collar of the front shaft type has been applied (scheme II in Figure 1) (Novikov, 1959). However, the small radius of soil freezing behind the timbering did not pre-vent surface water drainage along the shaft through the active layer, and refrigerated front shafts were not successful.

The presence of rocks at depths of 20-50 m allowed the design of the tower headframes resting on four hollow reinforced concrete foundation piles 3.5-4 m in diameter (Markizov, 1974) for a number of mines in Vorkuta region. The depth of supports was 22-62 m or not less than half of the headframe height (scheme III in Figure 1). Despite the fact that the foundation costs constituted 37% of the total cost of the building due to narrow face and poor mechanization of tunneling, the foundations were efficient because of their independence from the thermal effect of the shaft and, correspondingly, they are reliable in operation.

Design research on selection of headframe foundation

Two principles of construction have been established for tower headframes and their foundations on permafrost for new underground mines (e.g., "Internatsionalnyy" mine) in Western Yakutia, based on experience gained elsewhere. The first principle allows soil to thaw at the base of the headframe, and this requires only measures to strengthen the foundation. The second principle, which involves preservation of the frozen state of the soil, involves not only constructive but also special technological decisions (Guryanov, 1988a).

Schemes IV-VI, shown in Figure 2, correspond to principle I, while schemes VII-IX in Figure 3 illustrate principle II. Schemes I-III (Figure 1) show positive experiences from the Vorkuta mine construction and have
been used only for comparison because they can lead to rather heavy structures.

DESIGNS WHICH ALLOW PERMAFROST TO THAW

Schemes IV-VI represent the development of a constructive decision, adopted for a pyramidal headframe with the use of bearing capacity of timbering (Bulychev and Abramson, 1978). This decision involves transferring a load from the machine and the adjacent rooms to standing timbering with supporting rows of crossbeams in stable rocks at a depth of some tens of metres. Technological lifting loads and their moments are transferred to external struts supporting the headframe head. Such load distribution is excluded for tower headframes because an external bearing frame is a constructive feature of pyramidal headframes. Transferring the full weight of the headframe and all operation loads to timbering fundamentally changes the work of the timbers used to construct the shaft.

Resting a headframe on timbering, which allows thawing of the soil at the base of headframe and of the near-shaft mass, requires an additional analysis of the resistive properties of soils of the shaft thaw bulb (Guryanov, 1983), as well as various calculations of the timbering stability of the vertical shaft. Studies have shown that bending stresses in timbering attenuate considerably with depth, and in a similar fashion for bearing rows of crossbeams at a depth of more than 100 m (scheme IV) or entirely self-bearing timbering (scheme V). Consequently, maximum headframe heelings and deflections do not exceed allowable values, and the timbering structure does not require any strengthening (Guryanov, 1984). A headframe foundation (transition structure between the headframe and the timbering) in this case is the most economical solution. However, this choice is possible only with reinforced concrete self-bearing timbering, while the structure of shaft timbering is selected based on different reasons and is the assigned one for mine surface structures. Therefore, with light headframes, the shaft mouth timbering can be designed as poured-in-place concrete, capable to handling the additional linear load.

Scheme VI (Figure 2) involves cooled underground rooms along the entire perimeter of the headframe, which create horizontal support of the top of timbering decreasing the momentary loads from the headframe and minimizing its horizontal deflection. Scheme VI can be constructed for a headframe of any mass.

DESIGNS WHICH PRESERVE PERMAFROST

Schemes VII and IX (Figure 3) have been worked out at the Yakutniiproalmaz Institute for mine technical designs.

The first variant (scheme VII) includes cooling the ground and resting the mine headframe on pile foundations 12-15 m deep, protected from the side of the shaft (proposition of Shakhtspetsststroy trust) by 25 m deep freezing columns with a brine-ammonia refrigeration plant. A ring consisting of 27 columns had a 11 m diameter with the average inside shaft diameter of 6 m.

According to the second variant (scheme IX), the warm underground rooms of the mouth zone were preserved (clearing, adjoining air ducts to a shaft), and resulting from this, deepened foundations were required that provided cooling of the adjoining soils. Box foundations met this requirement as a single structure being deepened to a depth of 7-8 m and covering the warm underground rooms, isolating them from the soil. Box foundations have high spatial rigidity and a permanently frozen state of the soil at the base can be guaranteed due to their high thermal inertia combined with ventilation of the foundation box during winter with outside air (Guryanov and Demchenko, 1984; Guryanov, 1990). The efficiency of foundations is based on corresponding calculations (Guryanov, 1988b).

The designs showed that when the headframe weighs 173 MN, the estimated cost of foundations according to scheme IX is 3.4 times lower than scheme VII, with decreased operation expenses at 10% of the foundation cost, while with a headframe weight of 53 MN, pile foundations are only 7% more expensive. This is explained by the fact that the box foundation of a big headframe has considerable reserves of volume, and pile foundations with ventilated space under the building require the outlet to the surface of the underground rooms and an additional increase in the total construction volume. A small headframe has smaller underground rooms, and the volume of foundation box is not enough for the base cooling and requires its development in plan (Guryanov, 1988a). Based on the
technical and economic comparisons, the design was adopted as a working variant according to scheme IX.

Recently, the Dneprogiproshakht Institute has developed a variant of pile foundations for the Internatsyonalny mine headframes with built-in cooling systems (scheme VIII), however, their ability to compensate for the thermal effect of shafts has not been proven.

From the variants discussed, preference is given to the foundations designed according to schemes VI and IX, which have the highest margin of operation safety. When a headframe weight is about 70 MN, including operation loads, shaft timbering is recommended as a headframe support, and when it is heavier, then a ventilated box foundation is recommended.

Method to arrive at the solution to the problem

Taking into account the discussed approaches and the variants studied, the problem of foundations for tower headframes on permafrost can be solved by successive analysis of the different conditions, i.e., the geocryological-geological, the volumetric-construction and the calculated ones following the principles of selection of foundation type and their structural stability. The logic of the decision-making process, corresponding to
positive or negative response to each condition, can be evaluated using a single algorithm, as shown in Figure 4. The algorithm allows independent studies of issues and includes the decisions in a logical decision structure for the problem.

The first level conditions represent determination of possible real engineering-geological situation complicated by the formation of a talik adjacent to the shaft (block 2). A positive condition 2, if soils are strong enough and low-compressibility after thaw (rock and semirock), leads to decisions on the type of headframe foundations, which do not differ from those used on unfrozen soils (block 3). If the natural base when thawed is unstable, then the construction possibility (the third level conditions) of a headframe resting on a shaft timbering is considered (block 5). The bearing timbering, accepting the loads from a headframe, is checked according to condition 6 along the whole depth (block 7) or only in the upper part (block 8). When a headframe rests on timbering, an external fixing structure is recommended (bearing rows of crossbeams for timbering) not deeper than 100-200 m.

Principle I with a headframe resting on rocks or timbering, does not limit the development of a talik adjacent to a shaft. Therefore, detention of surface water is necessary in a shaft mouth zone (block 4). In cases of inadmissible headframe heeling or shaft deflections (block 9), horizontal supports of the top of timbering are constructed (block 10). If conditions 2 and 5 are not fulfilled, the required stability of the base can be achieved by ground freezing, i.e., using principle II.

Variations within principle II start from the second level conditions, which determine the position of the mine sluice (block 11). When the cage is unloaded on the marks close to the ground surface, an underground sluice is preserved and the warm headframe basement rooms are isolated from a frozen base by means of a cold box foundation (block 12). If the warm shaft and the headframe are taken out to the surface due to the impossibility of foundation pit works or because of high marks of skip relief, then the preferable configuration is a frozen base (block 13).

The variants of foundation structure or the third-level conditions predetermine the methods of ground cooling. With the possibility of horizontal cooling (block 14), a reinforced concrete slab is acceptable under the entire headframe, separated from the base overlap by ventilated space (block 15). If borehole cooling devices are used - air, liquid or vapor-liquid of different depth (block 16) - then column or pile foundations are used (blocks 17, 18).

As part of the development of the problem, dynamic calculations for the headframe are necessary, and the results of these depend on the foundation structures and predetermine the operational reliability of the building and the base (block 19). These results together with technical and economic estimates of the materials and labour associated with the construction technology (block 20) allow the best decisions to be made for a given set of criteria.

Conclusions

For the complex of structures discussed, a tower headframe and mine shaft timbering - a structure of timbering as a variant of headframe foundation (the third level conditions) predetermines variation in the principles of the foundation type selection (the first level conditions). In addition, the volumetric-design decisions for a shaft mouth (the second level conditions) predetermine variants within the frames of the principle of configuration of the cooled zone of the base and type of foundation (the first and third level conditions). Only the concluding stage - the design of foundations - is practically the same for separate structures and their complexes.

The above shows that solutions of the problem of foundation construction for technologically interrelated but unlike structures at the same site in permafrost is quite possible, but requires consideration of the specific characteristics of the complex and the engineering-geological conditions, as well as the specific industrial and construction task. The logical structure of the solution can be shown by a flow-chart (Figure 4).

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References


