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Structural Design of Frozen Ground Works For Shaft Sinking By Practicing Artificial Ground Freezing (Agf) Method in Khalashpir Coal Field

[1,] Atikul Haque Farazi [2,] Chowdhury Quamruzzaman
[1,] Environmental and Geospatial Solutions, Coordinator (Geophysical and Environmental Management Unit)
[2,] Associate Professor, Department of Geology, University of Dhaka, Dhaka-1000, Bangladesh

--Abstract--
Khalashpir coal field, the 3rd largest coal field of Bangladesh where proved reserve of about 143 million tons and probable reserve of about 685 million tons is estimated, has been decided for underground mining and artificial ground freezing (AGF) technique has been proposed as shaft sinking method after feasibility study. This method has been used in mining industry over the past 125 years for support of shaft sinking, tunneling and foundation excavation. To run the process brine solution is chilled between -25°C and -35°C in large refrigerant plant. The brine is then circulated through freezing tubes in required pattern to remove hit from the ground and thus freeze the soil to achieve soil strength and decrease the mobility of liquid water. This process results in a frozen earth barrier which gives strength to loose soil and bars water from inrushing excavation work for sinking a shaft. In this paper structural design of frozen ground works has been proposed to achieve a vertical cylindrical ice-wall for shaft sinking in Khalashpir coal field.

***Key Words**: shaft sinking, ice-wall, structural design, ice-wall thickness, freezing borehole.*

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I. Introduction

Constructional work below ground level is normally preceded by a ground investigation to establish the data sequence, soil/rock properties and hydrogeology of the site. Such exploration must be sufficiently deep and comprehensive to establish the long-term stability of the intended structure, and of any temporary works needed to effect the excavation within which the sub-surface permanent works can safely be constructed. The results of such investigations will identify the location and extent of weak and/or saturated strata, alert the designer to potential problems or difficulties, and indicate the need for preventive measures. The same data will enable a ground freezing engineering to prepare a scheme, but supplementary information may be needed before the design can be finalized. Site investigation boring is needed to know the lithology of the site and for collecting samples to know the geotechnical properties of the rocks to be frozen in laboratory. Moreover, pumping test should have to be done to get the hydrogeological condition of the area as — porosity, permeability, flow direction, flow rate, hydraulic gradient, volume of water etc. of the water bearing strata.Khalashpir coal field situated in the Rangpur Saddle of Bangladesh which again belongs to a half graben structure, has four stratigraphic units from top to bottom:

1. Barind Clay Formation (6m)
2. Dupitila Sandstone Formation (142.50m)
3. Jamalganj Formation (Surma Group equivalent, 184m)
4. Gondwana Formation (814m has been drilled)

[China Jinan Mining Development Corporation (2006) Techno-economic Feasibility Study of Khalaspir Coal Mine Project, Dhaka, Bangladesh (unpublished)] According to the pumping test and geotechnical data of borehole GTB-1 drilled in the proposed shaft location, structural design of the frozen wall has been proposed in this paper.As loose, friable and water bearing Dupitila Formation is the most vulnerable in sense of strength and water encroachment with unit inflow rate of 661.33 M^3/ day/ M and filtration coefficient 34.67 m/day, the whole unit has been considered for freezing vertically. [Dr. Yong Om Kil, Khlaspir Coal Mine Project, Pirjang, Rangpur (2005) Pumping Test Report of Exploration Boreholes on Khlaspir Coal Field (unpublished)].It should be mentioned that this water bearing, loose, low strength sand dominated formation is the major concern for the underground construction, threatened by caving and water ingress. According to this typical problem of shaft sinking through loose unstable soils (sands, silts and clays), the AGF method that is proved successful and best suit to serve the purpose in the aforementioned soil condition throughout the world, has been proposed to admit there for conducting underground works successfully by forming of frozen earth barrier to water and at the same time increasing compressive strength of soil remarkably. This method is environment friendly, safe, not limited to typical soil condition and has nearly no effect on water table and water condition.[Farazi A. H., Quamruzzaman C., Ferdous N. Mumin A., Mustahid F., Kabir A. K. M. F., (2012) Selection of Shaft Sinking Method for Underground Mining in Khalashpir Coal Field, Khalashpir, Rangpur, Bangladesh]Frozen ground works have been designed for a shaft of **3.9m** radius which would be enclosed by a ring shaped freezing wall. Total vertical length to be frozen has been estimated **162m** which includes 6m of Barind Formation, 144.50m of Dupitila Formation and 12.5m additional freezing for safety of the temporary structure. This paper is continuation of the previous one proposing AGF method for shaft sinking in the site. Values of the parameters in the used formulae were taken from the borehole GTB-1 data drilled by Korea South-South Cooperation Corporation which is situated at the shaft sinking location proposed by China Jinan Mining Development Corporation (2006). This paper is a continuation of our previous one suggesting AGF method for shaft sinking in the coal field, based on ground informations gathered which is the primary scheme of engineering design frozen ground works.

II. Structural Design

The design of a successful 'ice-wall' for an AGF scheme requires thermal and structural calculation [Harris J.S. Ground Freezing in Practice, 1995]. After selection 'structural design' is the second sequence of AGF events. It should be kept in mind that excessively thick or too thin ice-wall is not desirable for its cost and time consumption or breakage. Another important factor for designer is that ice should not encroach into the excavation area which causes time killing and costing as well.When building the underground construction by an open-cast method with the freezing method of rock, the ice-wall carries out the function of support wall. The most common ice-wall configuration is based on the circle since, in the ideal case; this is the only shape which offers uniform compressive stress and minimal tensile stress in the ice-wall during its working life. Thus circular constructions are the simplest to design to construct. [Harris J.S. (1995)) Ground Freezing In Practice]. For Khalashpir coal field circular shaped ice-wall has been proposed and designed accordingly in this paper.Determination of the thickness of unlined frozen ground barrier according to loads of surrounding ground is the most important of the design procedure. After this, the diameter of the borehole arrangement circumference and number of boreholes is calculated. When the necessary geotechnical properties of the ground are known, this engineering design is nothing but replacing parameters of the formulae by values and calculation.

III. Calculation

Calculation of Overburden Pressure

The thickness of ice-wall is determined in consideration of the shape and size of the shaft, technical processes of mine construction, rock pressure and static-hydraulic pressure of water. Overburden pressure is an important parameter of the equation regarding ice-wall thickness. So, it is mandatory to calculate overburden pressure on frozen wall to designing a sustainable frozen barrier. In soft rock, the rock pressure P_r can be determined by the following formula.

$$Pr = r_g QHtg^2\left(45^\circ - {}^{\emptyset}/_{2}\right) \text{ .... } (1)$$

= 688.12 KPa.

Where r_g = volume weight or density of the formation= 1.99 t/m^3, Q = acceleration of gravity= 10, H is the height as shown in the Fig. 2 = 162m and Ø = internal frictional angle of the seam= 24^o When deciding rock pressure in water saturated rock seam below the underground water level , the static hydraulic pressure of water P_h is determined as the following formula in consideration of the density of water.

$$P_h = r_w qh \text{ .... } (2)$$

= 760 KPa

Where, r_w = density of water= 1t/m^3 and h is the head of water= (82-6) m = 76m (from Fig ??)

The whole load which acts on ice-wall is determined by addition of rock and water pressure. So the overburden load P_o is:

$$P_o = P_r + P_h \text{ .... } (3)$$

= 1.448 Mpa

[Sin K.C. & Young J. (1998) Driving and Mining (Kim Chaek University of Technology)]

IV. Calculation Of Ice-Wall Thickness

The thickness of the ice-wall is one of the main parameters of deciding the economical rationality of using the freezing method. The excessive or too thin thickness of ice-wall might have enormous volume to be frozen or breakdown of ice-wall or explosion of underground water. Based on the taken thickness of the freezing wall, all the heat-engineering and technological calculation of refrigerating processes is realized. To determine the thickness of the ice-wall is a very complex problem in technological view. This complexity is that the ice-wall has not got lawfulness of elastic body and has the changing property clearly and its characteristics depend on the rock type, freezing temperature and time for forming the ice-wall. Besides, depending on the thickness of the ice-wall, it has the elastic characteristics of different strength and its change law depends on the law of heat field change in the ice-wall.

The characteristic load and stress patterns are illustrated in Figs 1, 2 and 3 which clarify the formulae used here.

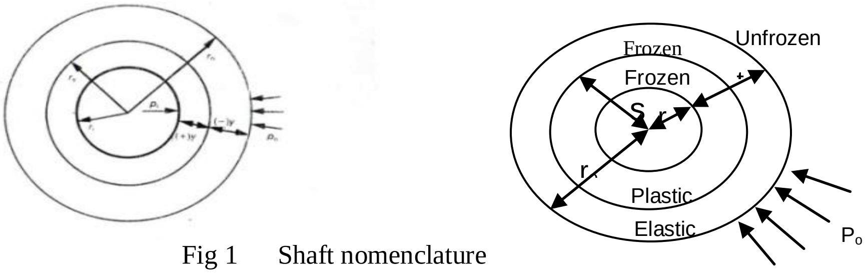


Fig 1 Shaft nomenclature

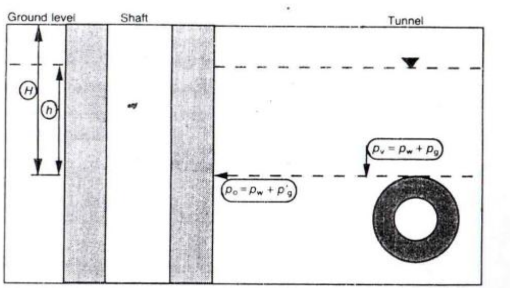


Fig 2 Load nomenclature (cross section)

Fig 3 Shaft load nomenclature (plan view); where $P = P_o + P_1$, $P_1 = P_l/2(1 + \cos 2Ø)$ and $P_l = 0.0013H$, i.e.

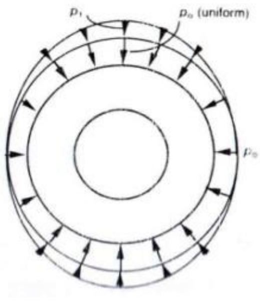
0.13 × hydrostatic pressure from the surface [Link et al (1976)].
[Harris J.S. (1995) Ground Freezing In Practice (Thomas Telford Services Ltd, London]
Many formulae have been developed based on different elasto-palstic properties of ice-wall. The thickness of frozen support wall **t** has been determined by the following formula here:

$$t = r\left[0.56\frac{P_o}{q} + 1.33\left(\frac{P_o}{q}\right)^2\right] \text{............... (4)}$$

= 1.5 m

where, q is unconfined compressive strength in frozen state= 4MP (for saturated sand at less then -10^{o}C), R= radius of shaft.

Fig. 4 Characteristic ice-wall formation pattern led by equation (4), where r is radius of shaft, r_o is outer



radius of ice-wall and s = $\sqrt{r r_0}$

This formula was, proposed by Shangdong Mining College and others to take account inter alia of plastic deformation of the ice-wall. Serious creep deformation and basal heave is reported to have occurred at 257m depth, together with associated freeze tube breakages, suggesting that in this case the design gave a factor of safety approximating to 1 at that depth. The formula used here is yields thickness is both adequate and generally less than that which is generated by the usual range of spacing between freeze-tubes.
[Harris J.S. (1995) Ground Freezing In Practice (Thomas Telford Services Ltd, London]

Verticality of freezing boreholes

The drilling of vertical freezing is one of the most difficult and long time processes when freezing rock. The period drilling boreholes takes 30 ~ 65% of the whole time to be required in freezing the rock according to the depth of borehole. The Final diameter of borehole should be a little larger than the diameter of the connecting bushing of the freezing pipe and its diameter should be less than 150 ~ 170mm. When the depth of freezing the rock is very big (500 ~ 700m), final diameter of the freezing borehole is about 200 ~ 250mm.

The depth of the borehole should be 5 ~ 20m deeper than designed of level of the rock freezing. In the borehole, the freezing pipe of given diameter should be moved in and out freely. The borehole variation about given diameter should be minimum. When the depth of shaft reaches 500m level, the maximum variation of borehole is as follows.

$\mathbf{a = 0.5 + 0.002H}$,m **…………… (5)**

Where H — depth of borehole, m.

a=1 has been considered here in calculation here for designing of this shallow structure.

In case the borehole has some variation against vertical direction, its value is compared with the allowable standard or the borehole should be drilled again. When freezing rock, additional freezing boreholes are drilled less than 10% of the whole boreholes in case the depth is 100m, and 15% in case of 200m, and 20% in case of 400m. The percussive drilling, rotary drilling and their combination are used in drilling the freezing borehole.[Sin K.C. & Young J. (1998) Driving and Mining (Kim Chaek University of Technology)].

V. Calculation For Freezing Borehole Arrangement

The boreholes are arranged around the shaft along its circumference direction. This time the diameter of the circumference is decreased as small as possible and the number of the boreholes decreased as well. The area, which is necessary for the drilling and assembling works, should be reduced. However, excessive approximation of borehole near the shaft outline may incur damage to the ice-wall. When freezing rock, the ice-wall may be formed disproportionally according to the arrangement of boreholes. The ice-wall grows rapidly forward to the shaft center. The thickness **t** is divided as follows in response to the diameter of the borehole arrangement. That is it is divide into the thickness **0.6t** in the inside direction of shaft and thickness **0.11t** in the outside direction of shaft. Therefore, when designing the freezing process, the arrangement circle diameter of boreholes is as follows:

$\mathbf{D = D_s + 2 \cdot 0.6t + 2a}$**…………………….. (6)**

$= 12$m

Where D_s = sinking diameter of shaft= 7.8m, a = allowable variation of borehole against vertical direction= 1m

The number **n** of boreholes arranged along the circumferences is divided as the following formula.

$\boldsymbol{n = \pi D / l}$ **……………………………. (7)**

$= 31$

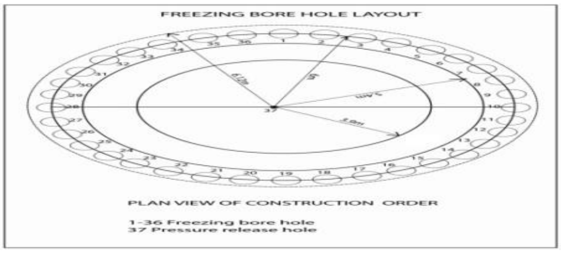
Where l: interval between boreholes, which is taken as 1.1 ~ 1.8m

The interval between boreholes, is mostly taken as 1.2m and so is used in this equation.

Additional boreholes for 162m required = (15% of 31) = 5

So, the total number of boreholes, **N** = 31 + 5 = 36

[Sin K.C. & Young J. (1998) Driving and Mining (Kim Chaek University of Technology)]



VI. Proposed Design

Ice-wall formation pattern and freezing borehole arrangement found from above calculation regarding structural design of frozen ground works is shown in Fig. 5.

Fig. 5 Schematic diagram showing freezing borehole layout designed for Khalashpir coal field.

The above figure shows 1.5m spacing between inner radius of ice-wall and radius of shaft. This spacing should be maintained to prevent unwanted ice encroachment into the excavation area in case of over freezing or erotic thermal design. Because encroachment of ice into the excavation area would make conventional excavation difficult, consequently insisting to introduce blasting that will increase cost and time consumption as well, affecting the overall project target.

6.1 Determination of Ice-wall Stresses for Shallow Shafts (Unstable Ground)

Ice-walls for shafts of shallow depth in soft ground may be designed on elastic criteria. When the relationships can be expressed in the following equations:

Axial stresses [after Link et al. (1976)]

$$\boldsymbol{\sigma_1} = \frac{p_o r_o}{t \times I}\left(1 + \frac{y}{r_s}\right) \text{ .... } \mathbf{(8)}$$

= 37041.006 KPa

$$\boldsymbol{\sigma_2^*} = \frac{p_l r_o}{2 \times t \times I}\left(1 + \frac{y}{r_s}\right) \text{ .... } \mathbf{(9)}$$

= 819.80 KPa

Where $\boldsymbol{\sigma}_1$ = axial stresses due to uniform load p_o (Fig. 3), $\boldsymbol{\sigma}^*_2$ = axial stress due to non-uniform load p_l, r_o = external radius of ice-wall = 6.17m, r_s = radius to centroid of ice-wall = 5.42m, y as in Fig 2, p_l = 0.13 × hydrostatic pressure= 98.8 KPa.

Bending stresses due to non-uniform load [after Link et al. (1976)]

$$\boldsymbol{\sigma_2^{**}} = \pm \frac{p_l r_o}{6 \times t \times I}\left(1 + \frac{6r_s}{t}\right)\frac{X}{(X-1)} \ \theta=0 \text{ and } \theta=90^\circ \text{...}\mathbf{(10)}$$

$$\text{with } \boldsymbol{X} = \frac{3E_f I}{p_o r_o r_s^2} \text{ .... } \mathbf{(11)}$$

= 6.5×10^{-6} KPa

Where E_f = Young’s modulus (frozen ground) =2,

$I = t^3/12 = = \frac{1.5^3}{12} = 0.28$

So, it is obvious that

$$\boldsymbol{\sigma_1 + \sigma_2^* > \sigma_2^{**}}$$

$\boldsymbol{\sigma_1} + \boldsymbol{\sigma_2}^*$ must always be greater than $\boldsymbol{\sigma}_2^{**}$ otherwise tensile stresses will develop.

Combined stresses

$$\boldsymbol{\sigma = \sigma_1 + \sigma_2^* \pm \sigma_2^{**}} \text{ .... } \mathbf{(12)}$$

= 37.861 MPa

Allowable stress:

$$\boldsymbol{\sigma_a} = \frac{\sigma}{\mathit{Factor\ of\ Safety}} \text{ .... } \mathbf{(13)}$$

= 114.730 MPa

The above calculation shows

$$\boldsymbol{\sigma_a > \sigma}$$

[Harris J.S, 1995, Ground Freezing In Practice (Thomas Telford Services Ltd, London, 1995]

For any engineering design of a structure against stress condition should be as such it withstands surrounding stresses. Allowable stress should be greater than the combined surrounding stresses to ensure its sustainability. While designing, designer have to ensure allowable pressure in an amount that can compromise erotic design or any mistaken build up of the structure or failure resulting from unwanted natural condition.

VII. Conclusions

A cost effective and sustainable ice-wall ring formation for sinking a 3.9m shaft in Khalashpir coal field, freezing works should follow the structural design proposed below:

- The 162m long cylindrical ice-wall should be at least 1.5m in thickness
- To achieve this 36 equally spaced freeze tubes should be arranged within 12 m diameter
- Allowable stress greater than stresses acting on the ice-wall considering safety factor less than 1 shows the lawfulness of the design.

It should, however, be kept in mind that the estimates obtained from this design are highly approximate and as such, should be taken as guidelines for decision making processes. These estimates do not replace site specific detailed analysis and monitoring. Thermal design of the AGF method for shaft sinking in Khalashpir coal field would be proposed in the next paper.

Notations

The following symbols are used in this paper:
a ─ verticality of shaft
D ─ borehole arrangement diameter
D_s ─ diameter of shaft
E_f ─ Young's modulus
H ─ depth to be frozen
H ─ head of water
l ─ borehole spacing
r_g ─ volume weight of formation
P_o ─ overburden pressure
P_h ─ static hydraulic pressure
P_r ─ rock pressure
Q ─ acceleration of gravity
q ─ unconfined compressive strength
$r_{\circ}$ ─external radius of ice-walls
r_s ─ radius to centroid of ice-wall
r_w ─ density of water
t ─ thickness of ice-wall
$\boldsymbol{\sigma}$ — combined stresses
$\boldsymbol{\sigma}_1$ ─ axial stresses due to uniform load
$\boldsymbol{\sigma}_2^{*}$ ─ axial stress due to non-uniform load
$\boldsymbol{\sigma}_2^{**}$ — bending stresses due to non-uniform load
$\boldsymbol{\sigma}_a$ — allowable stress
Ø ─ internal frictional angle of seam

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