Comparative Analysis on Artificial Freezing Design Scheme of Vertical Underground Garage

Zhang Ji-wei\textsuperscript{1,2}, Zhang Song\textsuperscript{1,2,3*}, Liu Shu-jie\textsuperscript{1,2,4} and Wang Hua\textsuperscript{1,2}

\textsuperscript{1} Shaft Branch, China Coal Research Institute, Beijing, 100013, China
\textsuperscript{2} Beijing China Coal Mine Engineering Co., Ltd., Beijing, 100013, China
\textsuperscript{3} School of Civil Engineering, Shijiazhuang Tiedao University, Hebei, 050043, China
\textsuperscript{4} University of Science and Technology Beijing, Beijing, 100083, China

*Corresponding author’s e-mail: 357102668@qq.com

Abstract. Based on 7m length×7m weight×50m depth vertical underground garage of old residence communities in Shanghai China, the new article ground freezing (AGF) method—Box-frozen method was studied. The elastic theory calculation and numerical simulation showed that the thickness of straight (h_q) and bottom (h_d) frozen wall are 2.8m and 10m respectively, which can meet load bearing and water insulation requirements. Three artificial freezing design schemes and parameters were proposed according to different freezing hole layout, namely, 1) double row holes and cutting bottom holes;2) double row holes and leave bottom holes;3) single row holes and leave bottom holes. Evolution law of temperature field of different Box-frozen design schemes was checked by numerical simulation. The results showed that, during maintenance freezing period, both of double row holes and cutting bottom holes and single row holes and leave bottom holes schemes appear thaw phenomenon at bottom of frozen wall while double row holes and leave bottom holes stops thaw tendency basically. Three Schemes are compared in four aspects including construction period, cost, excavation difficulty and risks, which prove that double row holes and leave bottom holes scheme are a most suitable article ground freezing method due to less construction period and low risk.

1. Introduction
Parking difficulties has been an urgent problem of large city as vehicle number gradually increasing year by year. Especially, there are inadequate space to build garage above ground in the older residential communities, so vertical underground garage (VUG) become a good option in this condition. VUG is one way of intensive parking, and its advantage including little space, large parking number and fast pick up speed [1]- [2].

Generally, the depth of VUG is 40–60m, and soil type of this layers are usually sludge and fine sand in south China. It is difficult to build VUG in older residential communities of south China because of high groundwater level stratum, complex and low strength soil and close to old building. Recently, shaft boring machine meets technical requirements of excavation and support, but this construction method is higher cost and may influence adjacent buildings.

Artificial ground freezing (AGF) can be employed as a special construction method to increase soil strength in soft strata such as alluvium and water-rich sand and to isolate groundwater in aquifers [3]- [4]. Therefore, VUG can be built by AGF method that can make a closed and continuous freezing wall around structure in order to isolated groundwater and ensure adjacent buildings will be not influenced...
by construction. However, the extension and application of AGF in VUG construction is hampered by small design depth (40~60m) because low permeability coefficient water-resisting layer hard to be found freezing depth range [5].

In this study, the Box-frozen method including straight frozen wall and bottom frozen wall was proposed to solve the problem of water-resisting layer loss. The designed thickness method of frozen wall was put forward and different freezing designs schemes were discussed to determine the optimum scheme. This enables us to elucidate how VUG can be built by AGF without water-resisting layer, and provide references for the further study.

![Fig.1 Box-frozen method of vertical underground garage.](image)

2. Frozen Wall Design and Bearing Capacity Calculation

As shown in Fig.1, the size of VUG is 7m length×7m width×50m depth and the stratum including silt, sandy silt and clay. There is no low permeability coefficient water-resisting layer within the scope of 80m. Therefore, the Box-frozen method is chosen to build VUG. The Box-frozen method including straight frozen wall and bottom frozen wall.

### 2.1. Straight frozen wall design

The mechanics characteristic of straight frozen wall is similar to retaining wall that the back of the frozen wall is affected by external unfrozen soil, both sides of the frozen wall is bound by continuous frozen wall and the bottom of frozen wall is bound by soil. The mechanical calculation model can be treated as elastic plane plate, which boundary conditions is top and both sides simply supported, bottom fixed, external unfrozen soil pressure is simplified to lateral pressure. The thickness of straight frozen wall \( h_q \) can be calculated by Leeds method of elastic theory [6]. The thickness \( h_q \) is expressed as:

\[
h_q = \sqrt{\frac{2\rho H^4 (1-\mu^2)}{E \pi [u] \left[ 2 + \left( \frac{4}{3} - 2\mu \right) \left( \frac{\pi H}{L} \right)^2 + \frac{1}{10} \left( \frac{\pi H}{L} \right)^4 \right]}}
\]

where \( \rho \) is lateral pressure (MPa), \( H \) is frozen wall depth, \( \mu \) is Poisson's ratio, \( E \) is elasticity modulus, \([u]\) is allowed deformation, \( L \) is frozen wall span. The lateral pressure of frozen wall at 50m depth is 0.65MPa, the Poisson's ratio and elasticity modulus of -10°C frozen soil are 0.3 and 200MPa respectively, allowed deformation is 0.02m, and frozen wall span is equal to excavation height is 1m. The thickness of straight frozen wall \( h_q \) is 2.64m, so design value is 2.8m.
2.2. Straight and bottom frozen wall bearing capacity calculation

Following the city standard of the People's Republic of China, DBT29-251-2018, the thickness of bottom frozen wall can be estimate 10m due to the thickness of water-resisting layer should larger than 10m, and the average temperature of frozen soil is -10℃ [7]. Straight and bottom frozen wall bearing capacity are calculated by three-dimensional elastic numerical simulation to verify whether the mechanical properties of frozen wall meet the requirements.

The numerical model is the deepest excavation height (50m) of 1/2 VUG due to symmetry structure. The lateral pressure of frozen wall at 50m depth is 0.65MPa, and bottom water and soil pressure is 0.39MPa, the pressure stress, tensile stress, shearing stress and maximum displacement as shown in Table1. All of stress are much less than intensity index, and safety factor meet the test standard of frozen wall strength. Therefore, the thickness of straight ($h_q$) and bottom ($h_d$) frozen wall are 2.8m and 10m respectively, which can meet load bearing and water insulation requirements.

| Location                  | $\sigma_1$/MPa | $\sigma_3$/MPa | $\tau_{max}$/MPa | $U_{max}$/mm |
|---------------------------|----------------|----------------|-------------------|--------------|
| Border region of straight and bottom wall | 0.98           | 0.38           | 0.13              |              |
| Intensity index           | 3.6            | 2.0            | 1.5               | 19.8         |
| Safety factor                      | 3.67          | 5.26          | 11.5              |              |
| Central position of bottom wall |               |               |                   |              |

3. Box-frozen design scheme and parameters

Box-frozen design scheme including straight frozen wall and bottom frozen wall. Following the city standard of the People's Republic of China, DG/TJ08-902-2006, the freezing hole layout of straight frozen wall can be divided into single-row hole and double- row hole. The freezing hole layout of bottom frozen wall can be divided into leave partial bottom hole and cut off all of bottom hole. Three artificial freezing designs, namely, 1) double row holes and cutting bottom holes;2) double row holes and leave bottom holes;3) single row holes and leave bottom holes are proposed. The thickness of bottom ($h_d$) frozen wall is greater than 10m in consideration of defrost after cut off bottom hole.

1) Double row holes and cutting bottom holes scheme. As shown in Fig.2, row A (A1-A5) to row E (E1-E5) is bottom freezing holes, and its total length is 60m consists of heat preservation at the depth between 0 to 50m and freezing at the depth between 50 to 60m. Row A to Row E are cut off during excavation period. Row Z, Row S, Row Y and Row X are straight freezing hole and its total length is 60m, and adopt all deep-freezing method. The straight hole distance is 1.3m and row distance is 0.8m while the bottom hole distance is 1.5m. The diameter of freezing hole is 108mm. The freezing period is 110d including positive freezing period is 40d and maintenance freezing period is 70d.

2) Double row holes and leave bottom holes scheme. As shown in Fig.2, several bottom freezing holes is left during excavation period including A2、A4、B1、D1、E2、E4、B5、D5、C3, and other freezing holes is cut off. The freezing hole layout parameters is similar to double row holes and cutting bottom holes scheme.

3) Single row holes and leave bottom holes scheme. As shown in Fig.3, row A (A1-A5) to row E (E1-E5) also is bottom freezing holes, which heat preservation at the depth between 0 to 50m and freezing at the depth between 50 to 60m. The bottom freezing hole namely A2、A4、B1、D1、E2、E4、B5、D5、C3 are left during excavation period. The straight hole distance is 1.1m and the bottom hole distance is 1.45m. The freezing period is 130d including positive freezing period is 60d and maintenance freezing period is 70d.

The salt water average temperature of double row holes and single row holes must lower than -28℃ and -30℃ respectively during positive freezing period, while -25℃ and -28℃ during maintenance freezing period. The temperature difference of inlet and discharging salt water lower than 2℃, and average temperature of frozen wall lower than -10℃.
4. Evolution law of temperature field of Box-frozen design scheme

4.1. Establishment of model

The temperature field of 1/4 freezing zone are calculated by numerical simulation due to symmetry freezing hole layout [8]-[9]. As shown in Fig.4 (a), the region is 10m length, 10m wide and 25m height, consisting of 10m straight freezing region, 10m straight and bottom freezing region, 5m unfrozen region from top to bottom.

Table 2. Thermo-physical properties of soil.

| Item          | Density (kg/m³) | Heat capacity (kJ/kg·℃) | Thermal conductivity (kJ/kg·℃) |
|--------------|-----------------|-------------------------|-------------------------------|
| Frozen soil  | 2240            | 0.968                   | 1.58                          |
| Unfrozen soil| 2240            | 1.287                   | 1.84                          |

According to the Box-frozen design scheme, the numerical simulation can be divided into two stages [10]-[12]: 1) In the positive freezing period, the temperature field and frozen wall thickness should be predicted. 2) In the maintain freezing period (excavation period), the law of natural thaw of frozen wall after cut off bottom freezing hole should be grasped. As shown in Fig.4 (b), Line 1, begin at (10,10,0), can reveal the variation of temperature of bottom freezing wall. Line 2, begin at (0,0,22), can reflect the change of temperature of straight freezing wall. Plane 1 locate at 5m height can reveal the thaw law of bottom freezing wall.
4.2. The variation of temperature during positive freezing period

As shown in Fig.5, the straight wall temperature of double row holes scheme is similar to single row holes scheme, but the bottom wall temperature of double row holes scheme is higher than single row holes scheme. The main reason is positive freezing period of double row holes (40d) is shorter than single row holes (60d). The soil can be treated as frozen soil when the temperature below 0℃. The straight frozen wall thickness of double and single row holes scheme is 2.83m, and bottom frozen wall thickness are 11.3m and 11.9m respectively. The straight frozen wall average temperature of double and single row holes scheme is -12.4℃, and bottom frozen wall average temperature are -19.89℃and -23.17℃. Obviously, both of frozen wall thickness and average temperature meet above design requirement and can start to excavate.

4.3. The thaw law of bottom frozen wall during maintain freezing period

The bottom frozen wall gradually thaws after cut off bottom holes during maintain freezing period due to excavation. Therefore, the thaw law of bottom frozen wall is a key problem during maintain freezing period.
4.3.1. Double row holes and cutting bottom holes scheme

As shown in Fig. 6, the temperature contour near central axis is sharply offset upward at bottom of frozen wall in 110d. Obviously, bottom frozen wall gradually thaws after cut off bottom holes though straight freezing hole keep cooling. The temperature of bottom frozen wall is around $-1.414 \sim -6.37^\circ C$ in the middle area at 5m (Fig.6 (b)), which indicates bottom frozen wall at 5m cannot meet the design requirement due to freezing wall thaw.

As shown in Fig. 7, the variation of Line 1 temperature of double row holes and cutting bottom holes can be divided into three stages: 1) Rapid natural thaw period of bottom frozen wall (40d~50d). The temperature of bottom frozen wall significantly increases within 4.5m~15.5m after cut off bottom freezing holes. The thickness of bottom frozen wall reduces from 11.3m to 10.75m and average temperature increases from $-19.89^\circ C$ to $-15.57^\circ C$. 2) Slow natural thaw period of bottom frozen wall (50d~90d). The thickness of bottom frozen wall reduces from 10.75m to 10.65m and average temperature increases from $-15.57^\circ C$ to $-13.68^\circ C$. 3) Strength growth period of bottom frozen wall (90d~110d). The average temperature of bottom frozen wall decreases from $-13.68^\circ C$ to $-13.95^\circ C$, and its thickness is 10.65m. The thickness and average temperature can meet requirement during maintain freezing period but the frozen wall easy to be influenced by high seepage due to thaw phenomenon.

4.3.2. Double row holes and leave bottom holes scheme

As shown in Fig.8, the temperature contour near central axis is minor offset upward at bottom of frozen wall in 110d. Therefore, bottom frozen wall scarcely thaws due to straight and residual bottom freezing hole keep cooling. The temperature of bottom frozen wall basically unchanged, within the range of $-12.048^\circ C$ to $-17.366^\circ C$ (Fig.8 (b)). The frozen soil strength at 5m can meet design requirement.

As shown in Fig.9, The average temperature of bottom frozen wall only increases 0.06$^\circ C$ within 40d~50d while decline slightly 0.03$^\circ C$ within 50d~110d. The average temperature is less than $-19.86^\circ C$ and thickness within 10.6~11m. It indicates that leave a little bottom freezing hole can stop thaw tendency of bottom frozen wall basically during the maintain freezing period. So, this design scheme is the safest one and can avoid many risks such as project postponed and high seepage etc.
4.3.3. Single row holes and leave bottom holes

As shown in Fig.10, the temperature contour near central axis is minor offset upward at bottom of frozen wall in 130d but offset upward tendency larger than double row holes and leave bottom holes scheme. The temperature of bottom frozen wall has an annular thaw area within 1~3m from the central axis and its temperature range is around -6.802℃ (Fig.10 (b)), which indicates bottom frozen wall at 5m also have thaw area.

As shown in Fig.11, The variation of Line 1 temperature of single row holes and leave bottom holes can be divided into two stages: 1) Slow natural thaw period of bottom frozen wall (60d~90d), the average temperature of bottom frozen wall slightly increased within 4m to 16m. The average temperature increase to -21.12℃ and thickness reduce to 11.9m. 2) Strength growth period of bottom frozen wall (90d~130d). The average temperature of bottom frozen wall remains unchanged at -21.13℃, and its thickness is 11.9m. The thickness and average temperature can meet requirement during maintain freezing period.

5. Schemes comparative analysis

Three Schemes are compared in different aspects which is listed in Table 2. The results as follow: 1) Double row holes and cutting bottom holes scheme is higher cost, less construction period and easier to excavate than other two schemes. However, this scheme appears thaw phenomenon at bottom of frozen wall and may be influenced by high seepage, so it is a high-risk scheme. 2) Double row holes
and leave bottom holes scheme is fundamentally the same as above scheme on cost and construction period aspect but it is harder to excavate than scheme I. The bottom frozen wall stops thaw tendency basically during the main freezing period, so this scheme is low risk scheme.3) Single row holes and leave bottom holes scheme is lower cost, more construction period and harder to excavate than cut off bottom freezing hole scheme. The thaw area of bottom frozen wall is annular shape and single row holes freezing method easier to be influenced by hole deflection and high seepage, so this scheme is medium risk scheme [13]. Overall, double row holes and leave bottom holes scheme have the advantage of less construction period and low risk, so it is a most suitable method.  

Table 3. Comparison analysis of three schemes.

| Comparative item      | I     | II    | III   |
|-----------------------|-------|-------|-------|
| Construction period(d)| 127   | 127   | 145   |
| Cost (Ten thousand RMB)| 542.2 | 542.2 | 529.3 |
| Excavation difficulties| Easier| Harder| Harder|
| Risk                  | High  | Low   | Medium|

6. Conclusions

We draw the following conclusions from this study of artificial ground freezing design scheme of vertical underground garage:

(a) The new article ground freezing (AGF) method of vertical underground garage, Box-frozen method including straight frozen wall and bottom frozen wall, was studied. The elastic theory calculation and numerical simulation showed that the thickness of straight ($h_0$) and bottom ($h_d$) frozen wall are 2.8m and 10m respectively, which can meet load bearing and water insulation requirements.

(b) Three Box-frozen design scheme, namely, 1) double row holes and cutting bottom holes;2) double row holes and leave bottom holes;3) single row holes and leave bottom holes are proposed based on different freezing hole layout.

(c) Base on the method of numerical simulation, during maintenance freezing period, both of double row holes and cutting bottom holes scheme and single row holes and leave bottom holes scheme appear thaw phenomenon while Double row holes and leave bottom holes scheme nearly stop thaw tendency.

(d) Three Schemes are compared in four aspects including construction period, cost, excavation difficulty and risks, which prove that double row holes and leave bottom holes scheme are a most suitable article ground freezing method due to less construction period and low risk.

Acknowledgments

The research was financially supported by the National Natural Science Foundation of China (grant No. 51804157; 5177040737; 51604114), the National Key Research and Development Plan of China (grant No. 2016YFC0600904), the China Scholarship Council (grant No. 201909110045), the Science and Technology Innovation Fund of TianDi science and technology co., LTD (2018-TD-QN008; 2019-TD-QN009), the Science Innovation Fund of China Coal Research Institute (2016ZYQN002), which are all gratefully acknowledged.

References

[1] Ye Zhi-an, Wang Chang-wei. (2017) Parking Problem: A Major Bottleneck of City Development. Shanghai Urban Management, 26 (01) pp. 6-9.

[2] Song Cheng. (2017) Public parking equipment to solve the problems of the urban parking Commercial development model. Shanghai Construction Science & Technology, 25(01) pp. 65-69.

[3] Armaghani, D.J., Amin, M.F.M., Yagiz, S., Faradonbeh, R.S., Abdullah, R.A., (2016). Prediction of the uniaxial compressive strength of sandstone using various modeling techniques. Int. J. Rock Mech. Mining Sci. 85, pp. 174–186.
[4] Vitel, M., Rouabhi, A., Tijani, M., & Guérin, F.,(2016). Thermo-hydraulic modeling of artificial ground freezing: Application to an underground mine in fractured sandstone. Computers and Geotechnics, 75 pp.80-92.

[5] Wang yue, Xu Bing-zhuang, Wang xiang, Zhang ji-wei. (2016) Analysis of freezing curtain design and freezing effects on deep-buried pump station. Urban Mass Transit,19 (03) pp.109-113.

[6] Yang ping. (1997) Theory analysis of flat frozen soil wall deformation calculation. Journal of fuxin mining institute (natural science edition),9 (04) pp.499-503.

[7] Zhang Ming, Lin Hong-bao, etc. (2010) Adopting the horizontal freezing method frozen wall design and calculation. Journal of Glaciology and Geocryology,32 (04) pp.773-777.

[8] Li Ning. (2017) Numerical Calculation and Analysis of Freezing and Natural Thawing Temperature Field of Hetaoyu Auxiliary Shaft. Coal technology,36 (02) pp. 91-93.

[9] Hu Xiang-dong.(2009) The Influencing Factor of the Temperature Field of Cross-passage Construction by Freezing Method in Double-Deck Road Tunnels. Chinese Journal of Underground Space and Engineering, 5(01) pp.7-12.

[10] Chen Honglei, Gao Wei, Li Ning, et al. (2015) Analysis of weak interface between the actual holes in deep frozen shaft temperature field. Journal of Glaciology and Geocryology, 37(2) pp.434-439.

[11] Wang Hui, Li Da-yong, etc. (2011) Analysis of 3D Numerical Simulation in Ground Freezing Method for a Cross Passage of the Subway. Chinese Journal of Underground Space and Engineering, S2 pp.1589-1593.

[12] Yang Geng-she, Rong Teng-long, etc. (2016) Numerical Simulation Analysis on the Evolution Laws of Freezing Wall Temperature Field in a Coal Mine Shaft. Chinese Journal of Underground Space and Engineering,12 (02) pp.420-425.

[13] ZHANG Jiwei, LIU Zhiqiang, SHAN Renliang, et al. (2019) Review and prospect of abnormal condition of shaft frozen wall monitoring technique in complex formation condition. Coal Science and Technology, 47(1) pp. 103-109.