Study on Section Selection of Super Large Oil Storage Tunnel Based on Strength Reduction Method

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Abstract. To study the section selection of super large oil storage tunnel could help make full use of underground space and arrange tunnels reasonably. The stability of tunnel with three different section (horseshoe section, circular section, elliptic arch section) was studied using the strength reduction method by finite difference element software. The FoS evolution with depth was discussed and the limiting failure state of tunnel were observed with the depth. The results indicated that the stability of different section are basically the same, because of the surrounding rock conditions are good. Cost and space utilization can be the main factors in the section selection.

1. Introduction

With the rapid development of China's economy, the oil production has been far from meeting the domestic demand, the degree of dependence on foreign crude oil imports is also increasing. As a non-renewable energy source, petroleum has been listed in the strategic reserve plan by many countries in the world. The underground oil storage has been widely used to storage oil, such as United States, Japan, Germany and other developed countries [1][2][3].

At present, underground oil storage mainly consists of underground water-sealed oil storage cavern, and the underground water-sealed oil storage cavern has high requirements on surrounding rock quality, great environmental threat, high maintenance cost and poor applicability. The "storage tank tunnel" has been used to avoid the above problems [4][5][6][7]. The "storage tank tunnel" is a kind of tunnel with support and splice the tank in the tunnel space. The key to its successful application is to make full use of underground space and excavate as many tunnels as possible under the condition of ensuring the stability of surrounding rock.

This paper takes the construction of an underground oil depot on an island in ningbo as the engineering background. Compared and analyzed the stability of tunnel under different cross section forms, and analyzed the utilization rate of cross section by the strength reduction method. And to provide a theoretical basis for the design and construction of "storage tank tunnel".

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2. The Strength reduction method

The essence of strength reduction method is to reduce the strength of rock in equal proportion until the rock failure, under certain external load, the strength of rock is continuously reduced in equal proportion until the rock. And the reduction factor can be considered as the safety reserve of the rock, it is defined as the safety factor (FoS).

The strength reduction method is based on mohr-coulomb criterion. The cohesion (c) and internal friction Angle (\(\varphi\)) of the rock are reduced until the rock reaches its limit state [8], Such as:

\[
c_{cr} = c_0 / K
\]

\[
\varphi_{cr} = \arctan(\tan \varphi_0 / K)
\]

\(c_0\) and \(c_{cr}\) are respectively initial cohesion and limiting cohesion; \(\varphi_0\) and \(\varphi_{cr}\) are respectively initial internal friction angle and limiting internal friction angle, \(K\) is FoS.

At present, the criteria for tunnel ultimate failure state by strength reduction method mainly include [9]:

1. The displacement saltation of tunnel;
2. Penetration of plastic zone;
3. Numerical calculations do not converge.

The settlement curve of tunnel vault and plastic zone area under different reduction factor of a tunnel with 50m depth are respectively shown as figure 1 and figure 2.

Figure 1. The settlement curve of tunnel vault under different reduction factor

Figure 2. The settlement curve of rock mass plastic zone area

By comparing figure 1 and figure 2, it can be seen that the plastic zone saltation occurred before the displacement saltation. That is, The surrounding rock still has bearing capacity when the surrounding rock around the tunnel changes from elasticity to plasticity. And the tunnel became unstable when the surrounding rock enters the plastic state in a large area, causing the deformation of the tunnel salation.
As mentioned above, the criteria for tunnel ultimate failure state is based on the displacement saltation of tunnel, supplemented by the penetration of the plastic zone.

3. Surrounding rock stability and section form optimization of Super Large Oil Storage Tunnel

3.1. Simulation model
The project geology is mainly tuff and granite porphyry, Surrounding rock grade III. The mechanical parameters of surrounding rock are selected according to the < Railway tunnel design specification > (TB10003-2016) shown in table 1.

| Surrounding rock grade | Density / (g cm$^{-3}$) | $c$ / Mpa | $\varphi$ / (°) | E / Gpa | $v$ |
|------------------------|-------------------------|-----------|----------------|---------|-----|
| III                    | 2.4                     | 1.1       | 44.5           | 13.0    | 0.27 |

Under the condition that the tunnel section is 423m$^2$, Three basic tunnel section shapes are designed: horseshoe section, circular section and Elliptic arch section, shown as figure 3.

One of the Numerical model is shown in figure 4. It is 1m in longitudinal length, 130m in width, and 130m in height. The model contains 21548 elements and 42516 nodes. In terms of boundary conditions, No vertical displacements were allowed along the base of the model, and no lateral displacements were allowed along the vertical surface of the model, and the top surface of the model was allowed to be deformed freely. Full section excavation without support. The depth of the tunnel is 50 m, 60m, 70m, 80m, 90m, 100m, 110m, 120m, 130m, 140m, 150m respectively. Solid element is applied to simulate surrounding rock, complying with Mohr–Coulomb failure criterion that follows the elastic perfectly plastic stress–strain relationship[6][10]. The FoS and liming failure state has been calculated by the strength reduce method.
3.2. Stability analysis of tunnel surrounding rock based on FoS

![Graph showing the curve of FoS of different section shapes with burial depth](image)

The curve of FoS of different section shapes with burial depth is shown in figure 5. The FoS of circular section is greater than that of Elliptic arch section, and the horseshoe section has the lowest FOS. The FoS is greater than 3, and the tunnel is stable.

The FoS of tunnel decreases with the increase of buried depth, within the buried depth of 50-100. But the slope of the curve is getting smaller. Within the buried depth of 130m~200m, the decreasing trend of the FoS is gradually slow, that is, when the buried depth of the tunnel reaches a certain depth, the influence of the buried depth on the FoS of the tunnel is gradually reduced.

3.3. Analysis of limit failure mode of surrounding rock

The strength reduction method can not only quantitatively evaluate the stability of surrounding rock, but also obtain the limiting failure state of surrounding rock at the same time. A lot of tunnel construction practice shows that the surrounding rock produces shear yield and the plastic flow occurs after the tunnel excavation. Therefore, the limiting failure state of surrounding rock can be determined by equivalent plastic strain. The equivalent plastic strain of different tunnel section (limiting failure state) are shown in figure 6–8.

![Images showing the equivalent plastic strain of different burial depths](image)

Figure 6. The equivalent plastic strain of horseshoe section with different burial depths
The main results of elliptic section, horseshoe section and circular section are shear slip failure on both sides of side wall. When the buried depth is shallow, the shear slip failure has developed to the surface, with the increase of buried depth, shear slip failure gradually concentrated around the tunnel and no longer developed towards the surface, presenting an obvious buried failure pattern. Due to the high side wall of horseshoe section, the shear slip failure of the side wall is more obvious than that of the other two types.

Taking Elliptic arch section as an example, the failure state under 150m buried depth with reduction coefficient is shown in figure 9. As the strength of surrounding rock gradually decreases, the failure of surrounding rock gradually changes from the failure of arch and invert to the side wall.

3.4. Section Selection of Super Large Oil Storage Tunnel
Statistical table of parameters in different sections are shown in table 2.
Table 2. Statistical table of parameters in different sections.

| Section      | Vault crown settlement /mm | Ratio to circular section | Sidewall convergence /mm | Ratio to circular section | Plastic zone area /m² | Ratio to circular section | FoS                  | Ratio to circular section |
|--------------|-----------------------------|---------------------------|--------------------------|---------------------------|-----------------------|---------------------------|----------------------|--------------------------|
| horseshoe    | 7.5                         | 1.36                      | 0.95                     | 1.9                       | 1200                  | 1.41                      | 3.41                 | 0.986                    |
| Elliptic arch| 5.5                         | 0.73                      | 1.2                      | 2.4                       | 650                   | 0.76                      | 3.43                 | 0.991                    |
| circular     | 6.1                         | -                         | 0.5                      | -                         | 850                   | -                         | 3.46                 | -                       |

4. Conclusion
(1) In terms of tunnel stability, the best circular, horseshoe, horseshoe worst, but the stability of different section are basically the same, because of the surrounding rock conditions are good.
(2) The invert shall be backfilled to ensure the passage of vehicles after the completion of tunnel construction. And in terms of section utilization ratio, horseshoe is the best, followed by Elliptic arch and circular.
(3) In terms of construction cost and efficiency, the circular section is mostly constructed by shield with hard surrounding rock and high cost. The mining method is the most suitable for the hard rock.

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