Research on transitional pavement structures based on foundation settlement in goafs

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Abstract: Based on actual engineering geological conditions, foundation settlements and the effects of goaf’s positions on the settlements were measured to study the effects of underlying goaf on the road construction. Four transitional pavement structures with various base course were designed in goaf-affected areas. Under the soil consolidation settlement and traffic loading, the mechanical response of transitional pavement structures was simulated and analyzed. The critical safety zone of the goaf was obtained along the depth and the horizontal directions, respectively. The results indicate that the transitional pavement structure containing graded gravel base exhibited the minimum uneven settlement and pavement inclination under the condition of soil consolidation settlement. Under traffic loading, the minimum tensile stress existed at the bottom of graded gravel base compared with that of the other three transitional pavement structures. Therefore, the flexible pavement with graded gravel base course is proposed as the transition pavement the mined-out areas.

1. Introduction

The road construction plays a great role in promoting the development of the national economy and the increasingly intensive road network inevitably encounters with geological conditions of the mined-out area. The underlying goafs bring about more adverse effects on highway, e.g., severe uneven settlement, the cracking and even the partial collapse, etc. These pavement distresses affect the traffic operation and safety seriously, and result in the negative social impacts. Consequently, it is urgent to refine the road construction technology under the geological conditions of goafs.

Stability estimation provides the basis for the construction of roads, railways and other structures in the goaf-affected area. In recent years, domestic and international scholars have conducted a great number of researches[1-3] with respect to foundation stability. However, the previous results do not keep consistent due to complex and diverse geological conditions. It is essential to confirm the safety region for road building according to the depth and horizontal position of the goaf.

The goaf generally does not cause damage to the road within the stable settlement period, whereas seriously threatening the construction and operation of the road in the active settlement period. Thus, transitional pavements should be introduced preferentially to accommodate the existing large subgrade settlement, maintaining the normal traffic and reducing the risk and costs of the road construction. At present, fewer studies have been focused on the transitional pavement structure to adapt the large
ground deformation, and particularly on the transitional pavement structure subjected to the underlying goaf.

The graded gravel base is adopted in the transitional pavement structure which is rarely recorded in the international designs of pavement structure. In the United States, Australia and South Africa, the graded gravel layer is generally introduced to reduce the reflective cracks of the asphalt surface layer. The high quality graded gravel is adopted as the base course of the asphalt pavement alone in Australian design method, whereas the design specifications are not clear[4]. In the domestic studies, the graded gravel structure is generally involved in studies of the reflective cracks of the asphalt pavement. Ren et al. (2005) proposed the thickness of graded gravel layer could be determined by taking wheel cutting and the flexural tensile strain at the bottom of pavement as control indexes in the design method of the asphalt pavement structure with semi-rigid base of graded crushed stone[5]. Dong (2013) selected three parameters (i.e., the thickness of surface course, the thickness of graded gravel course, and modulus) to study the layer functions of the asphalt concrete pavement structure, and the structure contained flexible base course with graded gravel. Furthermore, the nonlinear mechanical response of the pavement structure was analyzed[6]. Yang et al. (2017) analyzed the transient strain behaviors of the semi-rigid asphalt pavement under different pavement structures, layers, axle loads and driving speeds, in order to provide reference for the durability design of pavement[7]. The previous studies indicate that the base course with graded gravel exhibited great potential of application in both the flexible pavement structure and the semi-rigid transition pavement structure.

The road segments of K26 + 460 ~ K30 + 230 go through three gob areas of Dongping Coal Mine, Daping Coal Mine and Hongda Coal Mine in reconstruction project of provincial highway No.323, extending from Xinmi town to Dengfeng town in Henan Province, China. There still existed mining operations under the road section of 1.79 km. The support wooden poles were detected in coal mine tunnel at the depth of 40 ~ 50 m by means of on-site drilling. In this paper, numerical models were established to simulate the settlements of road embankment above the goaf under the geological conditions of the project. After being validated by the on-site monitoring results, the models were further introduced to explore the effects of the positions of the goaf on foundation settlement. Besides, four transitional pavement structures with different base courses were designed to study mechanical responses to soil consolidation settlement and traffic loading, respectively. Finally, the transitional pavement structure with excellent mechanical properties and strong resistance against large deformation was proposed.

2. Calculation models

2.1. Numerical models
Considering the soil particle properties of the simulated field experiments and the adaptability of the model itself, this paper intends to use the extended Drucker-Prager model for ABAQUS finite element analysis. The road segment near K27 + 450 was taken as the research object. The exploration results of rock distribution were listed in Table 1.

| No. | Material                        | Depth(m) | Thickness(m) |
|-----|---------------------------------|----------|--------------|
| 1   | Loess                           | 0~8      | 8            |
| 2   | Strongly weathered mudstone     | 8~39     | 31           |
| 3   | Strongly weathered sandstone    | 39~46    | 7            |
| 4   | Coal                            | 46~51    | 5            |
| 5   | Moderately weathered mudstone   | 51~73    | 22           |
| 6   | Moderately Weathered sandstone  | 73~83    | 10           |
| 7   | Mudstone                        | 83~101   | 18           |
| 8   | Sandstone                       | 101~113  | 12           |
| 9   | Mudstone                        | 113~130  | 17           |
The geometry of the model was presented as follows. The foundation: length 10 m (along the road direction), width 100 m, depth 120 m. The subgrade: The road was located centrally on the foundation with the top width of 24.5 m, the height of 4 m, and the slope gradient of 1:1.5. The goaf: Considering the most unfavorable situation, the goaf was located directly below the roadbed and parallel to the road with the length of 10 m, the width of 40 m and the height of 3 m. The depth of the goaf below the ground was set as a variable. The geometric model after meshing is shown in Figure 1.

![Geometry model after meshing](image)

### 2.2. Constitutive relations and material parameters
In this paper, the elastic layer system was used to simulate the pavement structure, the C P model was used to simulate the constitutive relation of loess, and the Mohr-Coulomb model was used to simulate the constitutive relationship between subgrade soil and rock mass. The mechanical properties of the local rock formations obtained after the on-site drilling sampling are shown in Table 2.

| Material                        | Bulk modulus (MPa) | Poisson ratio | Cohesion force (MPa) | Friction angle (°) | Density (kg/m³) |
|---------------------------------|--------------------|---------------|----------------------|--------------------|-----------------|
| Sandstone above the goaf        | 11700              | 0.1           | 0.1                  | 22                 | 2620            |
| Weathered sandstone             | 6000               | 0.2           | 0.5                  | 22                 | 2620            |
| Mudstone above the goaf         | 250                | 0.2           | 0.05                 | 28                 | 2450            |
| Weathered mudstone              | 850                | 0.3           | 1                    | 28                 | 2450            |
| Loess                           | 2                  | 0.1           | 0.02                 | 18                 | 1780            |
| Coal seam surrounding the goaf  | 500                | 0.3           | 0.2                  | 30                 | 1860            |
| Mining coal seam                | 70                 | 0.3           | 0.02                 | 30                 | 1860            |
| Subgrade soil                   | 60                 | 0.3           | 0.08                 | 23                 | 1900            |

### 2.3. Boundary conditions
The pavement and the surface were free boundary. The transverse and longitudinal displacements were restricted by the two lateral boundaries of subgrade in the width and length direction, respectively. The horizontal and vertical displacements were restricted by the bottom boundary of subgrade. The void pressure on the surface of the foundation was zero in the calculation of loess consolidation settlement.

### 3. Analysis of subgrade settlement

#### 3.1. Simulation verification
According to the actual engineering drilling and in-situ monitoring, the depth of the goaf was taken as
50 m and calculating period was determined as 18 months. The cumulative settlement of subgrade was calculated for 18 months under the actions of broken rock distortion and soft soil consolidation in the mined-out area. The variation curves of subgrade settlement over time are shown in Figure 2. The results show that the cumulative settlements of subgrade center and shoulder are 353 mm and 332 mm respectively. The corresponding monitoring data are 336 mm and 306 mm respectively. The relative deviation is less than 10%. As can be seen from Figure 2, the variation curves of calculating settlement and monitoring settlement are in good agreement, thus verifying the reliability of the calculation models.

3.2. Critical safety zone of the goaf
The critical safety zone of the goaf indicates: inside this zone, the goaf affect the deformation of ground surface seriously; outside the zone, the influences of the goaf is negligible[8].

Considering the most unfavorable conditions, the goaf was located just below the center of embankment. The mining depth was set as 20 m, 40 m, 60 m, 80 m and 100 m, respectively. The cumulative settlements of the embankment midpoint are plotted, as shown in Figure 3. The maximum settlement is 485 mm with the mining depth of 20 m. With the mining depth increasing, the growth rate of final ground settlement decreases continuously. When the depth of the goaf reach to 80 m or more, the ground settlement tends to be stable. Therefore, from the view of vertical direction, the critical safety depth of the goaf is determined as 80 m.
As an example of the engineering in the paper, the mining depth was taken as 50 m and the horizontal distance between the centers of the goaf and the embankment was set as 0 m, 10 m, 20 m, 30 m, 40 m, 50 m and 60 m, respectively. The cumulative settlements of the subgrade midpoint are calculated and displayed in Figure 4. For a given mining depth, the subgrade shows the largest settlement when the goaf is located right below the subgrade. With the goaf apart from the subgrade increasingly in the horizontal direction, the final settlement of subgrade center decreases continuously. The results show that the settlement stops dropping basically when the horizontal distance is beyond 50 m. Therefore, it may be concluded that 50 m represented the lateral distance of the critical safety zone of the goaf in this case.

4. Transitional pavement structure over the goaf

When the road extends through the influential area of the goaf, it is advisable to adopt the design method combining near-term and far-term in the road structure because of the increasing deformation of ground. In the initial stage, the transitional pavement is a preferred alternative to adapt to the large deformation for ensuring the traffic. When the ground settlement becomes stable, the road can be rebuilt according to the conventional design. Thus, it will be cost-effective generally.

Based on the ground deformation characteristics within the active settlement period of goaf and the current soil settlement theories[9-11], four kinds of transitional pavement structures (denoted by TP) were designed with the same surface course and subbase but the different base course. The detailed structure compositions and material parameters of the four pavements are presented in Table 3. In the Table 3, TP-1 and TP-2 are semi-rigid pavement structures, while TP-3 and TP-4 are flexible pavement structures. Based on the original numerical calculation program, the pavement structure was calculated by ABAQUS’s built-in elastic constitutive model. Firstly, the deformation capacities of the four transitional pavements against the uneven settlement were analyzed under the conditions of rock crushing and soil consolidation. Then, the stresses at the bottom of base course of the different pavement structures were compared under the standard traffic load. Finally, the desirable transitional pavement structure was clearly proposed.

| Pavement structure | Road level | Material | Thickness(cm) | Elastic modulus(MPa) | density(kg/m³) | Poisson ratio |
|--------------------|------------|----------|---------------|----------------------|--------------|--------------|
| TP1                | Surface course | asphalt concrete | 12          | 1400                | 1900          | 0.3          |
|                    | higher base course | graded gravel | 16          | 500                | 1850          | 0.3          |
|                    | lower base course | cement stabilized macadam | 16       | 1600                | 2230          | 0.3          |
|                    | Subbase course | lime-ash soil | 16          | 600                | 1700          | 0.3          |
| TP2                | Surface course | asphalt concrete | 12          | 1400                | 1900          | 0.3          |
|                    | Base course | cement stabilized macadam | 32       | 1600                | 2230          | 0.3          |
|                    | Subbase course | lime-ash soil | 16          | 400                | 1700          | 0.3          |
| TP3                | Surface course | asphalt concrete | 12          | 1400                | 1900          | 0.3          |
higher base course | large-size asphalt stabilized macadam | 10 | 1500 | 2250 | 0.3
lower base course | graded gravel | 22 | 300 | 1850 | 0.3
Subbase course | lime-ash soil | 16 | 600 | 1700 | 0.3

| Types | Center point settlement (mm) | Edge point settlement (mm) | Differential settlement (mm) | Inclination (mm/m) |
|-------|-----------------------------|---------------------------|-----------------------------|-------------------|
| TP-1  | 356                         | 295                       | 61                          | 5.1               |
| TP-2  | 335                         | 271                       | 64                          | 5.3               |
| TP-3  | 383                         | 335                       | 48                          | 4.0               |
| TP-4  | 394                         | 349                       | 45                          | 3.8               |

4.1. The analysis of settlement under rock crushing and soil consolidation
The depth of the goaf was fixed as 50 m. Under rock crushing and soil consolidation, the final settlements of central point and edge point of subgrade cross-section are calculated and listed in Table 4.

4.2. Mechanical response of transitional pavements under the action of standard traffic load
According to the design specification of highway asphalt pavement in China[12], the equivalent single axle load is designated to single axle and double wheel with the axle load of 100 KN (denoted by BZZ-100). The pattern of double wheels and double compressive circles is adopted for the design of the pavement structure. The distance between the two circle centers is three times larger than the grounding radius and the tyre pressure is 0.7 MPa. Assumed that material of pavement structure is homogeneous and isotropic in each layer and meets the Hooke's law, the mechanical response of transitional pavement structures are measured with BZZ-100 standard load applied to the original numerical models. The tensile stress beneath base course are displayed in Figure 5.
As shown in Figure 5, the tensile stress beneath the semi-rigid base course is 8.47 times larger than that of the graded gravel base. The calculated results also indicate that the maximum tensile stresses in the subbase varied slightly among the four pavement structures lying between 100 kPa and 106 kPa. Under the equivalent single axle load, the deflection values of the road surface are shown in Figure 6. The deflection values of different pavements are approximate, ranging from 8.4 mm to 8.8 mm, and meet the specification requirements.

Under the traffic load, the difference of tensile stresses beneath base course of the four pavement structures varied greatly. Based on the above analysis, it may be concluded that the flexible base pavement TP-4 shows superiority in bearing capacity and resisting large deformation compared with other pavement structures. Furthermore, the graded gravel base course is relatively cost-effective. Therefore, the transitional pavement structure containing the graded gravel base course is introduced to the pavements with heavy traffic volumes in the mined-out areas.

5. Conclusions
(1) The geotechnical creep model was employed to analyze the pavement settlements in the goaf zone and measure the affecting area of goaf. The calculation results were in good agreement with the monitoring data, which verified the reliability of the numerical model. The critical safety zone of the goaf was determined according to the vertical and horizontal positions of goafs, respectively.

(2) In the affecting area of the goaf, the settlements and mechanical responses of four transitional pavement structures were simulated and analyzed under the consolidation of soft soil and traffic loading, respectively. The analysis results indicate that the flexible pavement with the graded gravel base course showed superiority in bearing capacity and resisting large deformations. The differential settlement of the flexible pavement decreased by about 30% compared with that of the semi-rigid pavement. Under the traffic loading, the tensile stress beneath base course of flexible pavement represented only 12% of that of the semi-rigid pavement approximately. Therefore, the graded gravel base course is introduced to the pavements with heavy traffic volumes in the mined-out areas.

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