The load sharing behavior of geosynthetic-reinforced and pile-supported high-speed railway subgrade under fill and dynamic loads

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ABSTRACT

Over soft soil area the geosynthetic-reinforced and pile-supported subgrade was often used to reduce the post-construction settlement. But after operation it was found that the settlement sometimes was bigger than required. For settlement evaluation the stress concentration ratio between pile and soil is very important and the arching effect is often considered to solve this problem. There are some methods to analyze the sharing of fill load, but the dynamic train loads were often ignored. In this paper the finite element was used to simulate the stress concentration ratio during fill stage construction and dynamic load which were compared with the in-situ test. The results during fill stage also were compared with EBGEO and BS8006. They showed that the reliability of current methods is related to some factors including fill height, the stiffness ratio of pile and soil. There is a critical filling height whether the dynamic load decrease arching effect or not. According to FE results, the critical height is 3m. When the filling height is smaller than 3m, the stress concentration ratio should be re-evaluated by the reduction factor.

Key words: load sharing, soil arching effect, dynamic loads, fill stage, the finite element

1 INTRODUCTION

Geosynthetic-reinforced and pile-supported subgrade (GRPS) was used to construct high-speed railway and highway on soft soil due to their rapid construction, low costs, and small total and differential settlements. This effect is related with the efficiency of load transfer in the whole system especially between pile and soil which was termed the “soil arching effect”. Several methods have been proposed for calculating the vertical load distribution. Hewlett and Randolph (1988) conducted 3D model tests and presented a semi-spherical model to describe soil arching. Low et al. (1994) undertook 2D model tests to evaluate soil arching. BS8006 (2010) design method is based on a simplified analyses developed by Jones et al. (1990). The German standard (EBGEO, 2004) is based on a three-dimensional arching model proposed by Kempfert et al. (1997), which appears similar to the Hewlett & Randolph (1988) approach. Chen Yun-min et al. (2008) conducted experimental investigation on reinforced and unreinforced piled embankments to study the effects of soil arching.

However, soil arching effect maybe change due to dynamic train loads after railway operation. Most of current methods treat dynamic loads as static state. Large scale model tests were carried out by Heitz C. et al. (2006) in order to examine the stress-distribution in static and cyclic loading conditions. Through the tests a modified calculation procedure considering soil arching reduction by cyclic loading was given. The model tests and theoretical analysis were performed by Yu Chuang et al. (2009) to investigate the different behavior of piled embankment under embankment loads and traffic loads. They also found that the vertical dynamic stress in the embankment increased with increased repeated loading numbers which showed no soil arching effect.
Han Gaoxiao et al. (2011) have investigated the properties of soil arching under dynamic loads by performing numerical studies using the Discrete Element Method (DEM) and model experiments. The results showed that there were three types of soil arching broken according to the thickness of the covering soil and the amplitude of the dynamic loads. With an increase in thickness of the covering soil, the required time of failure of soil arching increased significantly.

In China most of GRPS were constructed in soft soil area and adjacent to the railway station, where the heights of subgrade are low. In order to investigate the soil arching features by train dynamic loads, in this paper the finite element was used to simulate the stress concentration ratio during fill stage construction and dynamic loads which were compared with the in-situ test results, EBGEO and BS8006.

2 NUMERICAL MODELING

In this study, the numerical modeling of GRPS was performed using Adina finite element program (FE method). The typical cross section in Fig. 1 is from Jing-Hu (Beijing-Shanghai) high-speed railway. The height and width of subgrade is 4.15m and 13.6m separately. Below the ground is 6m-thick clay layer and then a strong weathering amphibolite layer is underlain.

![Fig. 1. typical cross section of GRPS.](image)

The 0.5m-diameter pile is concrete and end-bearing pile and arranged in square pattern whose spacing is 1.8m. To simplify the analysis, the single pile and fill just under the track was chosen to be analyzed and considered as an equivalent circle with surrounding soil shown in Fig. 2(a). A finite element mesh was developed for the cylindrical column as shown in Fig. 2(b) considering symmetry condition. The stage construction was included in the analysis firstly, then a static and dynamic surcharge was put on the subgrade surface for modeling the traffic loads. In static simulation, soil and fill were taken as elastic-plastic constitutive model and Mohr-Coulomb yield criterion. The pile and geosynthetic were both considered linear elastic materials. Coulomb friction model was used to simulate interface behavior between pile and soil. The interface between gravel and geosynthetic was assumed fully bonded for simplicity. In dynamic analysis all of the materials were taken as linear elastic material. Both of the soil and fill were discretized with four-node quadrilateral isoparametric solid elements. The geosynthetic was modelled with bar elements, which can sustain only an axial force and have no resistance to bending. The pile was modelled with beam element. Due to the geometric symmetry, the horizontal displacement on the left-hand-side is zero. The right-hand-side and the bottom boundary are both considered as viscoelastic. All parameters used in the analysis are tabulated in Table 1. In the parametric study, some of parameters were varied, such as the magnitude of dynamic load, the elastic moduli of soil. For most cases, only one parameter was varied.

Table 1. Main parameters of soil and pile.

|    | E*  | C*  | φ*   | γ*  | µ*  | Ed* |
|----|-----|-----|------|-----|-----|-----|
| 1  | 60  | 0.1 | 18.7 | 18.6| 0.3 | 180 |
| 2  | 85  | 75  | 35   | 20.5| 0.3 | 225 |
| pile | 30000 | /   | /    | 24  | 0.15| 40000 |
| geosynthetic | 500 | /   | /    | 0.001| 0.15| 1500 |
| fill | 60  | 10  | 35   | 20  | 0.25| 180 |

Notes: E*: Static elastic modulus/MPa; C*: Cohesion/kPa; φ*: Friction angle°; γ*: Density/kN/m³; µ*: Poisson’s ratio; Ed*: dynamic modulus /MPa.

①clay
②2*: strong weathering amphibolite; E*: Static elastic modulus/MPa; C*: Cohesion/kPa; φ*: Friction angle°; γ*: Density/kN/m³; µ*: Poisson’s ratio; Ed*: dynamic modulus /MPa.
3 ANALYSIS OF RESULTS

3.1 Soil arching effect with stage construction

Fig.3 shows the vertical displacements at different soil depth. The Fig.3 (a) to Fig.3 (h) indicate different fill height. Line A, B, C are different position showed in Fig.2 (b). Line A indicates the soil above the center of pile head. Line B and C indicate the soil between two piles. If the fill height is smaller, such as 0.6m and 1.1m, the displacements in line A, B and C are not intersecting, which means that the soil arching does not exist or the arching is not formed completely. With fill height increasing, the displacements near the fill surface in line A, B and C are tending to be the same, which means the soil arching forming. According to the theory of a plane of equal settlement Terzaghi (1936), we found that the height of soil arching in this analysis was between 1.1m and 1.6m.

(a) fill height 0.6m.  
(b) fill height 1.1m.  
(c) fill height 1.6m.  
(d) fill height 2.1m.  
(e) fill height 2.6m.  
(f) fill height 3.1m.
In Fig. 3 the pile cap was not taken into account. Fig. 4 shows the displacements in line A, B and C when the fill height is 3m and there is a pile cap. According to the same theory, the height of soil arching is about 1.25m.

Fig. 4. vertical soil displacements with pile cap (h=3m).

Table 2. comparison of soil arching heights (m).

| Height/m | BS 8006 | EBGEO (2004) | FE method |
|----------|----------|--------------|------------|
| No pile cap | 1.82     | 1.27         | 1.6        |
| With pile cap | 1.12     | 1.27         | 1.25       |

In British and Germany Standards BS 8006 and EBGEO (2004) there are different formulas to calculate the height of soil arching. The comparison between these two standards and the FE results is tabulated in table 2. The FE result is almost the same as EBGEO (2004) with pile cap, but the value is more closer with BS 8006 without pile cap.

3.2 Stress concentration ratio with stage construction

In filling period the fill mass between piles tends to move downward and forms the soil arching effect. This leads to stress concentration ratio changing with fill height, which is showed in Fig.5. According to the changing properties, it can be divided into three phases. In phase I the stress concentration ratio increases very fast. In phase II it increases slower compared with phase I. In phase III it is almost stabilized and change a little bit. In phase I the fill height is bigger than 1m and smaller than 1.6m, or the ratio of h (the height of embankment ) to s (the center-to-center spacing of two piles) is smaller than 0.9. In phase II the fill height is bigger than 1.6m and smaller than 3.1m, or h/s is bigger than 0.9 and smaller than 1.7. The complete soil arching is formed. In phase III the fill height is bigger than 3.1m, or h/s is bigger than 1.7. The complete soil arching is stabilized.

Fig.5. the stress concentration ratio changing with fill height.

The changing tendency of the stress concentration ratio by FE method is confirmed by the in situ tests, which have been done in the DK849+575 section of Jing-Hu high speed railway by China Academy of Railway Science. The results of in situ tests indicated that the stress concentration ratio increased very fast if the fill height is not big, such as smaller than 3.5, but when the height is bigger than 3.5m, the ratio is stabilized to 5.6 (6.5 in Fig. 5) and almost no change. Actually the sensors were positioned in the 0.4m above the pile head in the in-situ test. This is one of the reasons why the FE result is a little bit bigger.

The FE results were also compared with the results from BS8006 and EBGEO (2004). All of the results
show the same tendency that the ratio increases fast firstly and is stabilized with the fill height increasing except BS8006. We also find that the stabilized value without pile cap is 19.5 according to EBGEO (2004), which is bigger than FE and in-situ test results. It means that the stress concentration ratios are not rational to be evaluated by EBGEO (2004) and BS8006, especially BS8006 if the fill height is big. For EBGEO (2004) there are two reasons to explain the difference. One is that the soil above pile and arch is considered to be in limit state, but in actual stage construction it is almost not possible. Another one is that the soil cohesion is ignored. For BS8006, the load above the arch head is assumed to be totally undertaken by piles, which dues to the ratio increasing with fill height and is not stabilized.

3.3 Arch effect changing with dynamic loads

After train operation the subgrade soil is performed long-term dynamic loads, which are related with vehicle, speed, track structure and et al. To simplify the analysis a sinusoidal load was put on subgrade surface in FE model. According to in-situ tests, the dynamic stresses in subgrade surface is about 10 to 20kPa, the frequency is about 10Hz. So in FE model the average value was chosen to be 15kPa, the minimum and maximum values were 5 and 15kPa separately, which indicated in figure 6.

![Fig. 6. dynamic loads.](image)

The stress concentration ratios were evaluated according to different load situations, in which only static load (situation I), static plus dynamic load (situation II) and only dynamic load (situation III) were considered. According to changing features with fill height, it can be divided into two phases (Fig. 7). In phase I the ratio is smaller in load situation II and III, compared with situation I. It means that the dynamic load will decrease arching effect. Lower of fill height, smaller of ratio. But in phase II the ratio is almost the same. It means the dynamic load has no influence on arching effect when the fill height is big enough. According to FE results, the critical height is 3m.

![Fig. 7. the stress concentration ratio changing with dynamic load.](image)

The reduction factor of soil arching effect caused by dynamic loads indicated in Fig. 8 according to Heitz C. et al. (2006). When h/s is bigger than 1.44, the reduction factor is 1.0 and dynamic load can be not taken into account, vice versa.

![Fig. 8. the reduction factor changing with h/s .](image)

3.4 Arch effect changing with relatively stiffness between soil and pile

![Fig. 9. the relative deformation changing with relatively stiffness between soil and pile.](image)
If soil is weaker, the relative deformation between pile and soil is bigger. Then the pile will take more loads. It means that the stress concentration ratio is bigger if the stiffness ratio of pile and soil is bigger. The relative deformation change with relative stiffness is indicated in Fig. 9.

We also found that the stress concentration ratio was more accurate from BS8006 and EBGEO (2004) if the relative stiffness of pile and soil is bigger. The reason is that the arching effect is more obvious at this situation.

Fig. 10 is the reduction factor of arching effect acted by dynamic loads when the dynamic stiffness of clay and strong weathering amphibolite layer is 83MPa and 120MPa respectively. Compared with Fig. 8, we can find the influence on arching effect by dynamic loads is bigger with the weaker of soil and the reduction factor is bigger.

4 CONCLUSIONS

(1) This stress concentration ratio changing with fill height can be divided into three phases: In phase I the ratio increases very fast. In phase II it increases slower compared with phase I. In phase III it is almost stabilized and change a little bit.

(2) There is a critical filling height whether the dynamic loads decrease arching effect or not. According to FE results, the critical height is about 3m. When the filling height is smaller than 3m, the stress concentration ratio should be re-evaluated by the reduction factor.

(3) If the stiffness ratio of pile and soil is bigger, the stress concentration ratios by BS8006 and EBGEO (2004) are more accurate, and the arching effect decrease bigger by dynamic loads.

ACKNOWLEDGEMENT

The study was supported by Natural Science Foundation of China (Project No. 41472247) and is greatly appreciated.

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