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Evaluation of stability of Wushaoling multi-tunnel under earthquake loading

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ABSTRACT: Wushaoling tunnel is comprised of two parallel separate tunnels. During the construction in the Fault Zone No.7, which has complex geological conditions, excessive deformations occurred. In order to speed up the construction, another two advancing drifts were made to go through the collapsed regions and parallel to the two main tunnels. So there ever existed four tunnels within the fault zone. Moreover, It is shown from the regional seismic data that the Fault Zone No.7 is in an active seismic zone. In order to ensure the safety, it is necessary to evaluate the influence of the earthquake loading on the tunnel structures. The actual earthquake responses were investigated using the commercial software of FLAC for the cases of four tunnels and only two main tunnels. Based on the calculated results, the stress distribution of the surrounding rock, the contact pressure between the shotcrete and reinforced concrete lining, and the stresses induced in the lining under two different conditions were discussed. It is concluded that the presence of two drifts has a great influence on the safety of the two main tunnels, and suggested that the two drifts should be backfilled before the Wushaoling tunnel was put into use.

1 INTRODUCTION

In recent years, because of mass construction of underground engineering and frequent occurring of earthquake, the influence of earthquake on underground structures have been concerned by many geotechnical engineers (Kirzhner and Rosenhouse 2000, Hashash et al. 2001, Pakbaz and Yareevand 2005). Especially, with the exploiting of the West of China, tunnels for railways or highways were always adopted on the West mountainous region with seismic activities and complex geological conditions. These projects were not only closely related to the national economy and the people's livelihood but also were costly, so it is essential that the earthquake effect on the underground structure be checked (Xu et al. 2004). At present, pseudo-static method as a conventional method is widely adopted on seismic analysis. However, many simplifications and assumptions would be addressed and the influence of some factors such as various nonlinear, anisotropy and complex boundary conditions cannot be considered precisely. So it is difficult to obtain the real seismic responses of the engineering structure. With the development of the computer, numerical method, by the advantage of convenient calculating and high precision, has been widely used in seismic research studies (Zhang et al. 2004).

Wushaoling Tunnel, which has a length of 22.05 km and is comprised of two parallel tunnels, is located at northwest of China. This tunnel is the longest railway tunnel in China at present and has been completed. Wushaoling tunnel was constructed under very complicated conditions such as highly in-situ stresses, soft rock, and regional faults named F4, F5, F6 and F7 (Fig.1). Especially, along the tunnel route, the Fault Zone No.7, about 785 m wide, has the most complex geological conditions with the nature of a squeezing and weak stratum. Some geotechnical problems, such as excessive deformation by squeezing fault rocks, excessive overbreak, instability of the face, were encountered during tunnel construction. In order to speed up the tunnel construction in Fault Zone No.7, another two advancing drifts, which named left drift and right drift, were made to go through the collapsed regions and parallel to the two main tunnels. The centre-to-centre distances between every two adjacent tunnels were 40 m. The sketch of layout of the four tunnels in Fault Zone No.7 was shown in Fig.2.

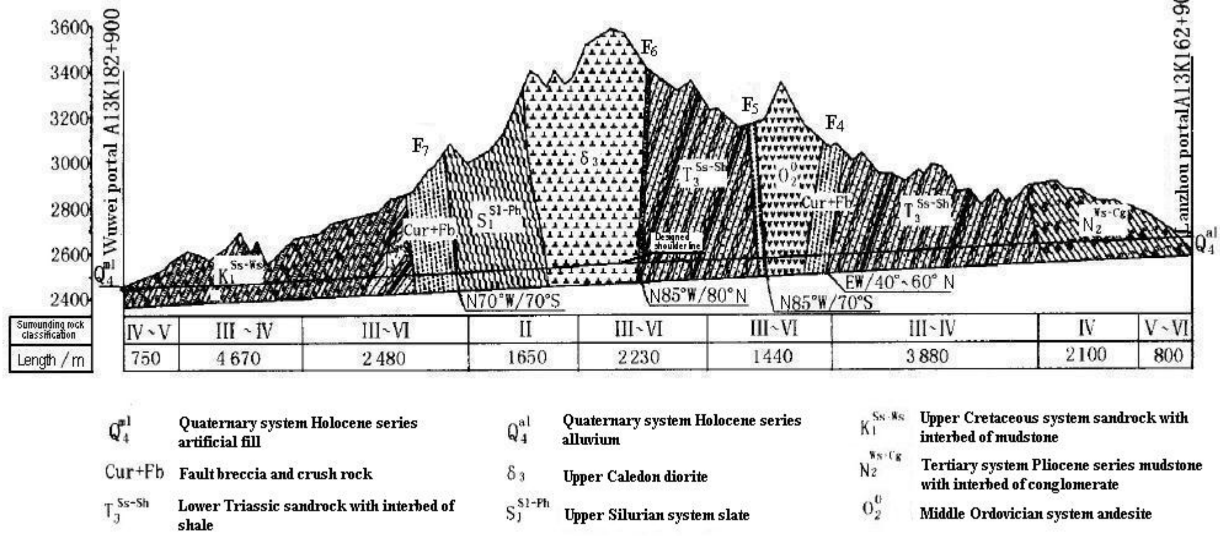


Fig.1 Geological profile of Wushaoling Tunnel (Liang and Li, 2004)

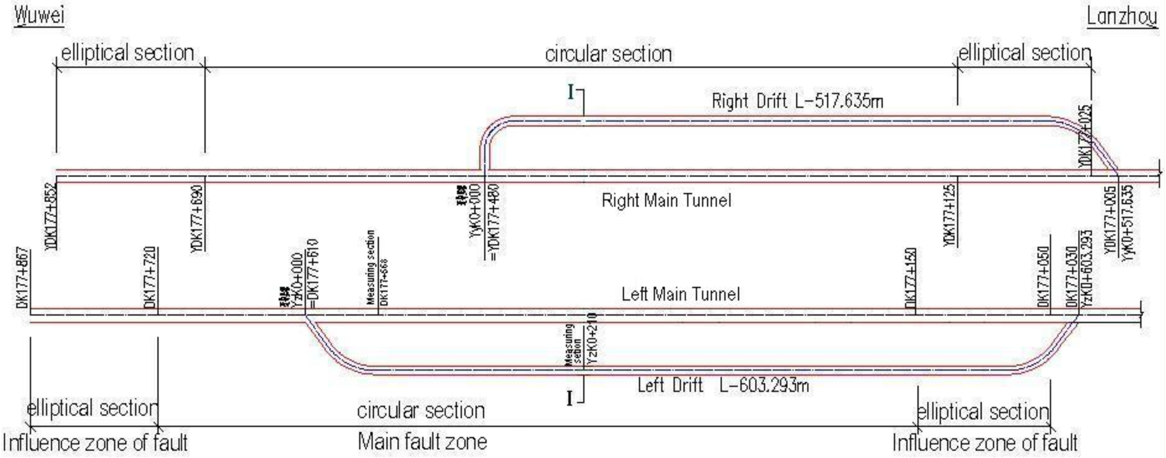
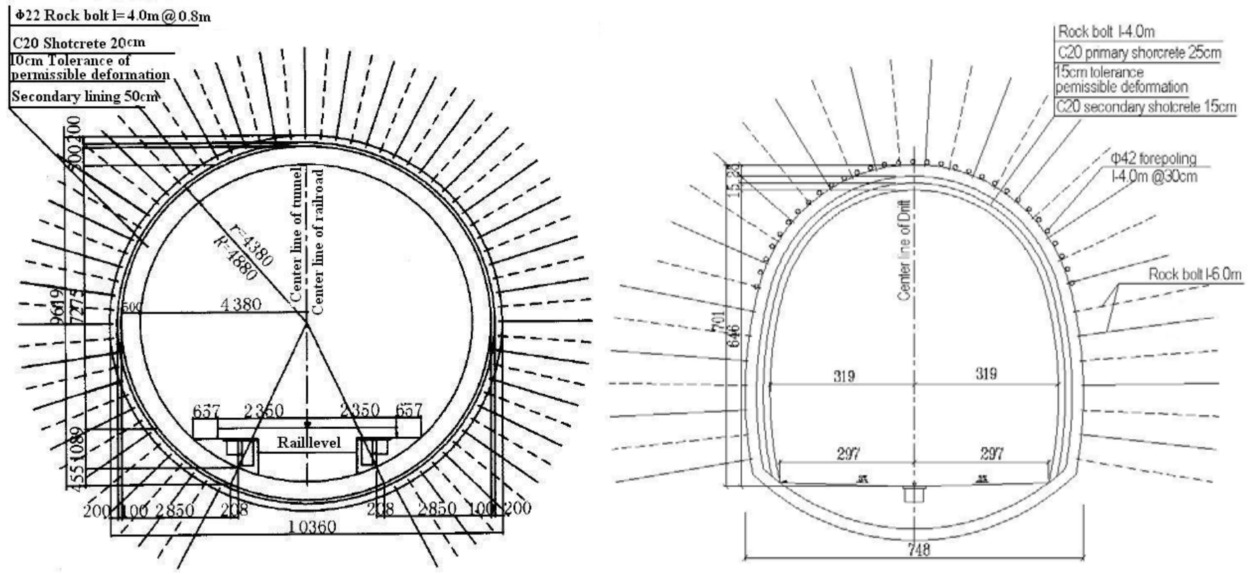


Fig.2 Sketch of the layout of four tunnels in Fault Zones No.7 of Wushaoling Tunnel

The left and right main tunnel were designed to be circular cross-sections within Fault Zone No.7, and the support system comprising typical support elements of shotcrete, rock anchors, steel arches and forepoling is shown in Fig.3(a). The horseshoe cross-sections were adopted for the left and right drifts, and Fig.3(b) shows the dimensions of the drift and its support system.

Furthermore, it is shown from the regional seismic data that the Fault Zone No.7 is in an active seismic zone (The First SDICR 2004). Based on Yang et al. (2006), it is found that the safety during the construction of the four tunnels can be ensured. In order to ensure the safety when the tunnel was put into use, it is also necessary to evaluate the influence of earthquake loading on the tunnel structures after the construction was completed. A certain amount of information on the blasting vibration influence between two parallel tunnels is given by field measurements and numerical studies (Yang 1998, Wu et al. 2004, Wang et al. 2004, Bi and Zhong 2004). However, the influences of earthquake loading on parallel multi-tunnel have seldom been reported. In this paper, a series of numerical analyses are performed using FLAC to evaluate the dynamical response of Wushaoling multi-tunnel under earthquake loading, and the treatment with the drifts is discussed.



(a) Section of support system in the tunnel (b) Section of support system in the drift

Fig.3 Sections of tunnels and the support system

2 NUMERICAL ANALYSIS

2.1 Modelling

In order to investigate the seismic responses of four tunnels in Fault Zone No.7, the typical Section I-I vertical to the route as shown in Fig.2 was selected. The depth of overburden is so high, up to 450 m, that the ground surface cannot be modelled. As a result, a local zone, which is 240 m wide and 160 m high, was chosen in the analysis. The outer boundaries were extended to a distance greater than five times the tunnel diameter to minimize boundary effects. Based on the actual design and construction proposal, the circular and horseshoe cross-sections were adopted for main tunnels and the drifts respectively. The bottom boundary was applied displacement limitation on the horizontal and vertical direction, the top boundary was fixed vertical direction, and the horizontal displacements were limited on the side boundaries. The vertical and horizontal in-situ stresses of 11.2 MPa, namely K_o=1 (K_o is the ratio of horizontal to vertical stresses), were adopted in this analysis (The First SDICR et al, 2005).

The actual layouts, construction sequences and supporting parameters of the four tunnels were adopted, and the commercially available code FLAC was used in the analysis. The surrounding rock was assumed to be an elasto-plastic material conforming to Mohr-Coulomb failure criteria. Quadrilateral elements, cable elements and beam elements were used to model the surrounding rock, the rock bolts and the shotcrete and reinforced concrete lining, respectively. The gap between the shotcrete and the secondary lining was modelled using no-thickness interface element. The mesh of the model was shown in Fig.4.

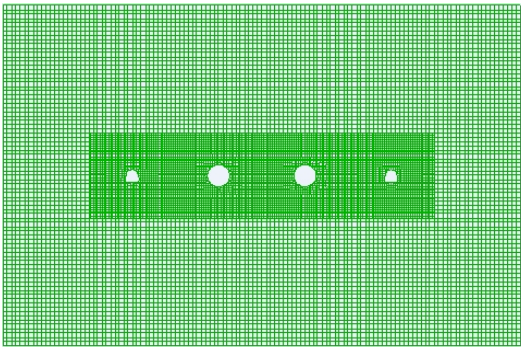


Fig.4 Mesh of model

2.2 Calculating Parameters

The material properties of surrounding rock and tunnel supports, which were obtained from laboratory or field tests and back analysis etc., were listed in Table 1.

In FLAC, the dynamic input can be applied in one of the following ways: (a) an acceleration history; (b) a velocity history; (c) a stress (or pressure) history; or (d) a force history (Itasca 2005). In this study, the input seismic loading data was obtained from some actual measured data and recorded by the acceleration history. As a result, an acceleration history with a peak value of 3.7 m/s^2 was adopted as shown in Fig.5. For simplification, the maximum amplitude is simplified as a periodic sinusoidal wave as presented in Fig.6. The frequency and the duration are 5 Hz and 0.2 sec, respectively. Dynamic input was applied at the bottom of the model.

Table 1 Properties of materials

Material	Properties
Surrounding rock	E = 0.8GPa, γ = 24.79kN/m^3, ν = 0.33, φ = 25°, c = 0.06MPa
Rock bolts	E = 2.0e11Pa, Φ = 22mm
Shotcrete	E = 2.1e10Pa, ν = 0.2
Secondary lining	E = 3.0e10Pa, ν = 0.2
Interface	kn = ks = 3.102e7 kPa/m

Where: E = elastic modulus, γ = unit weight, ν = poison ratio, c = cohesion, φ = friction angle, Φ = diameter, k_n = normal stiffness, k_s = shear stiffness.

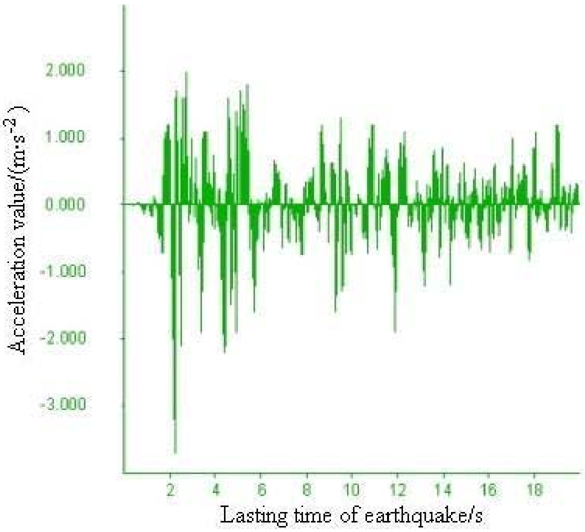


Fig.5 Acceleration history

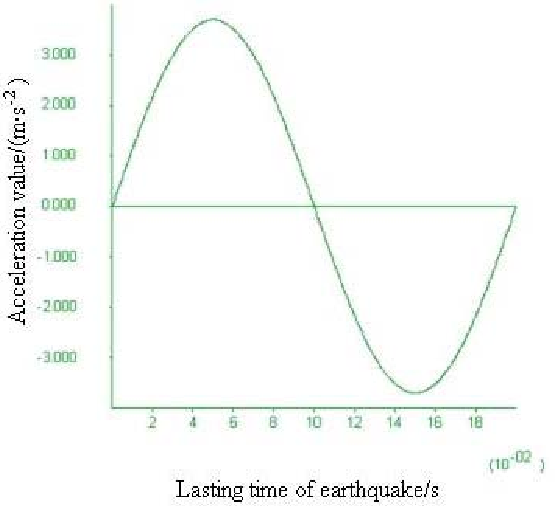


Fig.6 Simplified acceleration history

2.3 Calculating Steps

Two parts, static and dynamic calculation, were included in this numerical analysis. Firstly, the static calculation was performed. According to the actual layout of Wushaoling Tunnel in Fault Zone No.7, the construction sequences were simulated as separated steps. Based on the ratio of the contact pressures between shotcrete and reinforced concrete lining to the pressure of surrounding rock, the equivalent load relaxation was considered in the calculation. The values of pressure were obtained from field measurements. Each step was described as follows: (1) Applying in-situ stresses; (2) Excavating and installing the support in the left main tunnel; (3) Excavating and installing the support in the right main tunnel; (4) Excavating and installing the support in the left drift; (5) Excavating and installing the support in the right drift, and finally the construction of the four tunnels in Section I-I of Fault Zone No.7 finished.

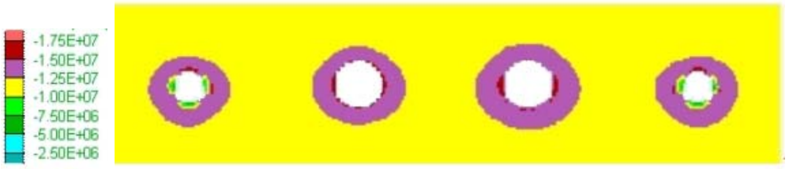
At following, based on the static calculation, the dynamic calculation was performed in which two different cases were considered. The first is to discuss the seismic response of tunnels in Fault Zone No.7 when there were four tunnels in Section I-I. And the other condition is to consider the seismic response of only two main tunnels in Section I-I when the two drifts were backfilled before the Wushaoling tunnel has been put into use.

3 ANALYSIS OF RESULTS

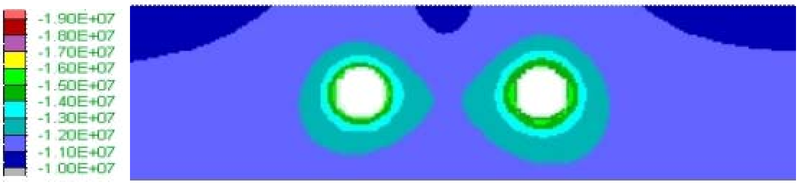
Stresses and deformations of surrounding rocks and internal forces of support system at different construction stages were investigated. After the static calculation, the calculated maximum horizontal convergence in the section YzK0+210 of left drift was 181.33 mm, which is fairly consisted with the field measured data 219.75 mm (Yang et al. 2006). This result has shown that the data obtained from field measurement is in good agreement with the result obtained from numerical analysis. Due to the page limit, this paper only presents the stress distribution of the surrounding rock, the contact pressure between the shotcrete and reinforced concrete lining, and the stresses induced in the lining of the tunnels after the dynamic calculation under two different conditions.

3.1 Distribution of Maximum Principal Stress

Fig.7 presents the distributions of maximum principal stress in surrounding rock caused by the seismic loading under two different conditions. It is shown that, when four tunnels existed, the maximum principal stresses around the main tunnels were larger than that around the drifts, and there was stress concentration on the both-side of the main tunnels. When there are two main tunnels due to the backfill of drifts, however, the distributions of the maximum principal stress around the main tunnels were rather uniform, and its peak is smaller than that when four tunnels existed, which no doubt still avail to the safety of the tunnel structures.



(a) All of four tunnels exist



(b) Two main tunnels exist

Fig.7 Distributions of maximum principle stress caused by seismic loading (unit: Pa)

3.2 Contact Pressure between Shotcrete and Reinforced Concrete Lining

Fig.8 presents the contact pressures between the shotcrete and reinforced concrete lining of the left main tunnel under two different cases after the dynamic calculation. It is shown that, when there were four tunnels in Fault Zone No.7, the contact pressure at the left basement is the maximum, and the average contact pressure was 0.18 MPa. However, in the case of two tunnels, the contact pressure at any positions of the left main tunnel was smaller than that in the case of four tunnels, the value developed at the vault is the maximum, and its average value around the left main tunnel was only 0.132 MPa.

3.3 Safety Degree of Reinforced Concrete Lining

There was no doubt that earthquake would induce extra stress increases in the lining of the existing tunnels, and might damage the reinforced concrete lining. Because the left main tunnel was made to go through the section I-I first, so it was representative to evaluate the safety of the lining of this tunnel.

In order to investigate the effect of earthquake on tunnel lining, the safety coefficient of reinforced concrete lining was introduced to evaluate quantitatively the safety degree of tunnel structure. The reinforced concrete lining was simplified as a compressed member of large eccentricity with rectangle section ($x \le 0.55ho$), whose strength could be calculated as follows (The Second SDICR 2005):

(a) All of four tunnels exist (b) Two main tunnels exist

Fig.8 Contact pressure between shotcrete and reinforced concrete lining of left main tunnel (unit: MPa)

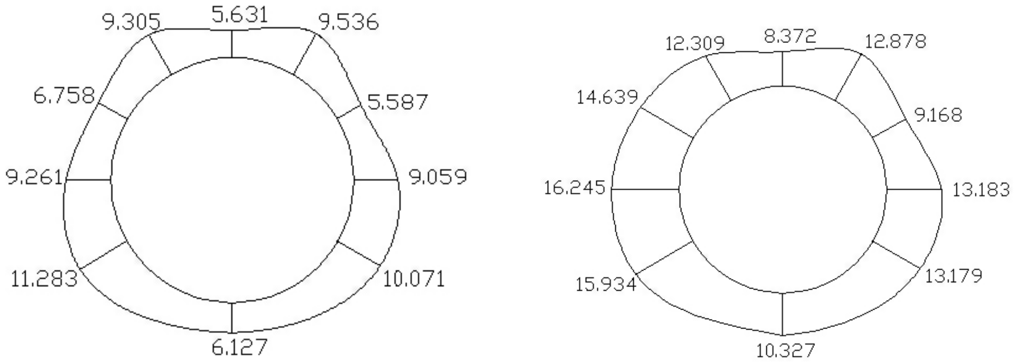
$$KNe \le R_w bx(h_o - x/2) + R_g A_g^{'}(h_o - a') \tag{1}$$

And the strength of small eccentricity compressed reinforced concrete member with rectangle section ($x > 0.55h_o$) was defined by the following equation:

$$KNe \le 0.5R_a bh_o^2 + R_g A_g^{'}(h_o - a') \tag{2}$$

where K is the safety coefficient of reinforced concrete lining; N is the axial force (MN); b is the section width (m); h is the section height (m); h_o is the section effective height (m), and $h_o=h-a$; e,e′ is the distance between barycenter of steel bar A_g, A_g' and action point of axial force (m); a,a′ is the distance from barycenter of steel bar A_g and A_g' to the nearest section edge(m); R_w is the flexural compressive strength of concrete; R_a is compressive strength of concrete; R_g is tensile or compressive calculating strength of steel bar; and A_g, A_g' are tension or compression areas of steel bar (m^2).

Using the calculated axial forces and moments, the safety coefficient K of reinforced concrete lining could be determined from equations (1) or (2). If the calculated minimum safety coefficient K of reinforced concrete lining is greater than 2.4, the reinforced concrete lining could be considered as safety.



(a) All of four tunnels exist (b) Two main tunnels exist

Fig.9 Safety coefficient of reinforced concrete lining of left main tunnel

The effects of earthquake on tunnel lining are also examined in the case of four tunnels and only two main tunnels. Fig.9 presents the value of the safety coefficient at the different positions of left main tunnel under two cases. It is evident that the safety coefficients in case of two tunnels were improved 30.9%-116.6% than those in case of four tunnels. And when there were only two main tunnels, the safety coefficients of the left main tunnel at right side, closed to the right main tunnel, is larger than those at the left side far from the right main tunnel. It is suggested that, once the earthquake occur, the presence of two drifts have a great influence on the safety of the two main tunnels. Therefore, for the safety of the Wushaoling tunnel, it is suggested that the two drifts should be backfilled before the Wushaoling tunnel was used.

4 CONCLUSIONS

Wushaoling multi-tunnel was constructed in very complicated conditions. Especially, along the tunnel route, the Fault Zone No.7 has the most complex geological conditions. And it is shown from the regional seismic data that the Fault Zone No.7 is in an active seismic zone. Based on the static calculation, the dynamic responses of Wushaoling multi-tunnel caused by the earthquake loading are discussed. It is shown that, once the earthquake occur, the maximum principal stress around the main tunnels and the contact pressure between shotcrete and reinforce concrete lining of the left main tunnel in the case of four tunnels were larger than those in the case of only two main tunnels. On the contrary, the safety coefficients of the reinforced concrete lining at different positions of the left main tunnel in the case of four tunnels were lower than those in the case of only two main tunnels. Therefore, it is concluded that the presence of two drifts would have a great influence on the safety of the two main tunnels. Considering the safety of the Wushaoling tunnel structures, it is suggested that the two drifts should be backfilled before the Wushaoling tunnel was put into use.

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