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Study on Mechanical Characteristics of Tunnel Structure with Cavities Behind Linings in Arch

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Abstract: Cavities behind the linings are common quality defects in tunnel construction, among which the cavities behind linings in arch are the most serious ones. Cavities behind the linings cause no contact between surrounding rock and supporting system, and also influence tunnel structure stress status. In order to obtain the structural force laws of the tunnel linings influenced by the cavities behind linings in arch, model tests, which include cavities with different sizes behind linings in arch, are designed to simulate the deformation characteristics, stress characteristics and failure modes. The test results are as follows: cavities behind linings in arch change the tunnel structure deformation and stress status dramatically; two cracks beside the cavities have formed as the loads grow; the cracked linings can also bear certain surrounding rock pressure. The test results can provide reference for tunnel site inspection and maintenance work.

Keywords: tunnel engineering; void; deformation characteristic; stress characteristic；model test；failure mode

INTRODUCTION

The number, scale and mileage of China’s highway tunnels and railway tunnels have been ranked first in the world (HONG Kairong). However, in the process of tunnel construction, the quality defects of the cavities behind the lining in the operating tunnel is widespread (ZHANG Dingli, ZHANG Sulei, FANG Qian, etc.). The existence of cavities behind the lining deteriorates the interaction between surrounding rock and support, which is one of the main causes of tunnel lining disease (ZHANG Sulei, ZHANG Dingli, LIU Shengchun, et al.). Therefore, it is of great practical significance to study the mechanical characteristics of tunnels under cavities behind the lining. In recent years, a lot of researches on the mechanical characteristics of tunnels under cavities behind the lining have been carried out, such as MA Meguid et al. (M.A. Meguid，H.K. Dang), (M.A. Meguid，Sherif Kamel) analyzed the influence law of the eroded cavities in the stratum on the internal force of the lining structure based on the Elastic plastic finite element method. Wu Jiangbin (WU Jiang-bin) deduced the calculation formula of the three-time stress of surrounding rock and lining internal force which have cavities behind the lining based on the Plane complex variable function method；Liu Hai-Jing，Xia Caicu et al. (LIU Haijing, XIA Caichu, CAI Yongchang) built the calculation model of the tunnel behind the lining by the contact method；Zhang Chengping,，Zhu Chunsheng et al. (ZHANG Chengping, FENG Gang, ZHANG Xu, etc.), (ZHU Chun-sheng, YANG Xiao-hua, LAI Hong-peng, et al.) studied on the safety state of tunnel structure under the condition of cavities based on numerical calculation and model test; Dingzu De et al. (DING Zude, PENG Limin, HUANG Juan, et al.) built the dynamic model to study the influence of the cavities on the safety of railway tunnel based on the plastic-damage constitutive model of concrete. He Chuan, She Jian, Li Ming et al. (HE Chuan，SHE), (SHE Jian, HE Chuan, WANG Bo, et al.), (LI Ming, CHEN Hongkai, DUAN Huaizhi.), (LI Ming, CHEN Hongkai, XIONG Fengwei) studied the stress characteristics of lining structure with different cavities behind the lining by means of similar model test. And Xie Feng, Qu Ronghuai et al (XIE Feng, ZHOU Yuan.), (QU Huairong.) studied the influence law of the cavities behind the lining on the pressure of surrounding rock based on the numerical simulation. But there is still a lot of research work to be carried out. This paper based on the existing research results, combining with the data of non-destructive testing, statistical analysis the general shape laws of the cavities behind the lining and design model test of cavity distribution based on statistical acquisition. Finally study the law of the structure characteristics of surrounding rock influenced by the cavities behind the lining.

1 STATISTICAL ANALYSIS OF THE MORPHOLOGY LAWS OF THE CAVITIES BEHIND THE LINING

1.1 Statistical Analysis of the Morphology law of the Cavities behind the Lining

169 cavities behind the lining were detected in the detection of tunnel. At the locations of all cavities behind the lining, there are 73 cavities behind the lining at the vault, 77 at the two sides arch and 19 at the two sides wall. The statistical results about the mean μ, standard deviation σ and coefficient of variation δ of the length and height of cavities behind the lining shown in Table 1.

Table 1. Form statistical characteristic result table of cavities behind lining at different position.

Location / Statistical characteristics	Length of cavity（m）			Height of cavity（cm）		
	Vault	Arch	Side wall	Vault	Arch	Side wall
Mean μ	5.00	4.97	3.87	8.98	7.41	6.135
Standard deviation σ	3.12	2.95	1.85	3.08	2.98	2.86
Coefficient of variation δ	0.62	0.59	0.48	0.28	0.27	0.25
Max	14.10	12.30	11.20	21	19	13
Min	0.9	1.0	0.7	5	3	4

It can be seen from the above data:

（1）The distribution of the length and height of the cavities behind the lining presents the obvious normal distribution.

（2）The mean and coefficient of the length and height of the cavities behind the lining follow the general law of the vault > hance > side wall. It can be seen that the situation of the cavities behind the lining is more serious at vault and the size of the cavities behind the lining at vault changes in a larger range, while the arch is the second, the side wall is the minimum.

（3）According to the statistical results of the cavities characteristics, the cavity behind the lining is most serious in the arch area with poor surrounding rock.

The similarity model test method was used to study the law of structure characteristics of surrounding rock influenced by arch ring cavities under V grade surrounding rock condition.

2 TEST SCHEME DESIGN

2.1 Test Equipment

This test used plain strain model test bench developed by Beijing Jiaotong University. The overall size of the model test bench is 3000cm×30cm×1620cm (length×width×height), the loading system is composed of a hydraulic jack, a pressure sensor, a reaction frame and the force transmission plate. Loading loads through hydraulic jacks and pressure sensors for graded loads.

2.2 Data acquisition system

The main parameters of the test are the lining internal force and the lining displacement. Among them, lining internal force measurement with the sensor for the micro-strain gauge, the acquisition system is JC-4A static strain gauge developed by the China Academy of Building Research

Monitoring the displacement of surrounding rock is the non-contact video measurement system consisting of a high-speed camera, data acquisition software, etc., which adopts the speckle image recognition technology to accurately measure the displacement information of image’s any point.

2.3 Confirmation of similarity relation

The prototype of the test for the design is the standard section of V-level surrounding rock of passenger transport line, the width of prototype tunnel is 1400cm and the lining is a C25 reinforced concrete structure with a thickness of 40cm. According to the similarity theory and the actual situation of the test bench, the geometric similarity ratio between the test model and the tunnel prototype is synthetically determined by geometric parameters and physical parameters. The prototype lining material is simulated by the equivalent bending stiffness EI.

2.4 Test material

(1)Surrounding rock material

Wang Shuping used barite and quartz sand as aggregates, Vaseline as binder, the ratio of barite, quartz sand, Vaseline is $9:3.75:1$. The physical and mechanical parameters of the grade V material and the corresponding material of the surrounding rock model are shown in Table 2.

Table 2. Physical mechanical parameters of surrounding rock materials.

material	Density γ（kN/m³）	Elastic modulus E（Gpa）	Poisson's ratio *μ*	Internal friction angle φ（°）	Cohesive force c（KPa）
prototype	20	4.5	0.3	30	700
Model	20.2	0.065	0.31	29.2	11.2
Similarity ratio	1	70	1	1	70

(2) Lining material

The material model for reinforced concrete lining with a diameter of 2mm wire and the water gypsum ratio for special gypsum is 1:1.Through the method of equivalent flexural rigidity of prototype and model simulation, whose mechanics index is the final set of gypsum test value, the elastic modulus is about 1.0GPa and the compressive strength is about 0.70MPa.

2.5 Test design scheme

（1）Cavity distribution

Four groups of experiments were designed, which were cavity-free, vault 15° range cavity, vault 30° range cavity and vault 40° range cavity (Figure 1). The loading laws of the surrounding rock structure in the presence of the cavity behind the lining are studied by means of progressive loading.

(a) cavity-free **(b) vault 15°range cavity** **(c) vault 30°range cavity** **(d) vault 40°range cavity**

Figure 1. Photos of test scheme.

（2）Measuring points arrangement

According to the purpose of the model test, the displacement of lining and surrounding rock, lining internal force should be mainly measured. Whereby the layout of strain gauges as shown in Figure 2.

Figure 2. Diagram of layout of strain gauges.

3 TEST RESULTS AND ANALYSIS

3.1 Analysis of displacement characteristics of lining vault

Under the load of various stages and each working conditions, the variation curve of the displacement of the lining vault with the loading process is shown in Figure 3.

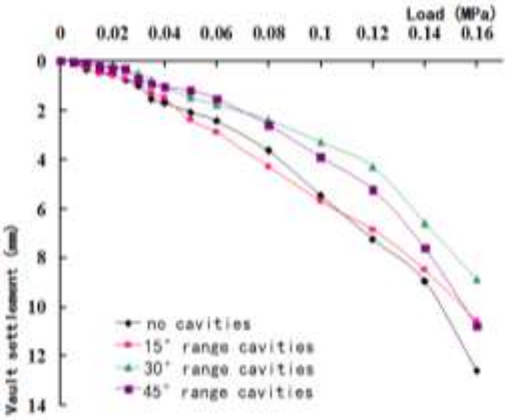
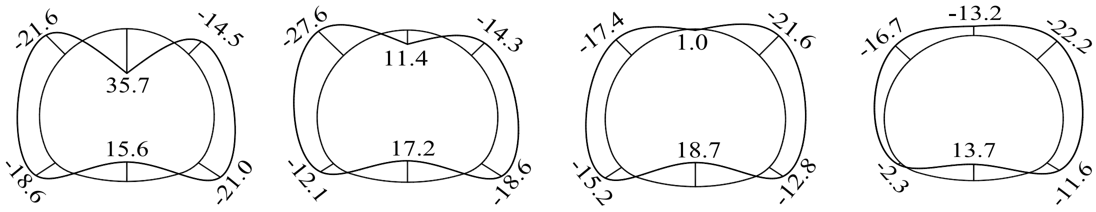


Figure 3. Change regulation curve of vault displacement of lining.

As can be seen from Figure 3, when the vault position exists cavities, the displacement of the lining vault under the same load is smaller than that of none cavities. Under the various range of the cavities behind the lining, when the load is generally in the range of 0.030~0.040MPa, the initial cracking occurs. At this time, the settlement of the vault is about 0.8~1.2mm and the bigger the cavities behind the lining, the smaller the settlement of the vault. When the load reaches about 0.08~0.15MPa, the settlement of the vault is about 4.0~6.0mm. At this time, the deformation of the lining is more rapid, and the cracks of the lining increase continuously with the increase of the load, until the gradual failure of the block, such as the phenomenon of instability failure.

3.2 Lining internal force analysis

Under the no cavities and 15°, 30° and 45° range cavities of arch, the bending moment of lining when the lining produces the initial cracking is shown in Figure 4.



(a) no cavities （0.042MPa） **(b) arch 15°range （0.040MPa）** **(c) arch 30°range （0.034MPa）** **(d) arch 40°range （0.030MPa）**

Figure 4. Bending moment diagram of reinforced gypsum lining under different types of cavities. Unit: N·m

According to the field monitoring of lining internal force, the influence of internal force on the position near the arch is obvious when the vault exists cavities behind the lining. Comparison of the internal force diagram of the various conditions shown in figure 4 can be seen, when it exists cavities behind the lining, the load corresponding to the lining cracks is small than it has no cavities except cavities at the 15° range of the vault, and for the same position of the cavities, the greater the cavities size, the smaller the cracking load.

3.3 Analysis of Lining Failure Mode

For tunnel lining without cavities, when the loads increase to about 0.034Mpa, inside open type longitudinal cracks would appear at the position of arch at first. And when the loads increase to 0.06Mpa, outside open type longitudinal cracks would appear at the position of two sides spandrel. As shown in Figure 5 (a).

(a) no cavities **(b) 15° range cavities**

Figure 5. Cracking of lining.

When the cavities behind the lining are in the arch 15°, 30° and 45°range, the failure mod of the lining structure under the rating load is almost the same, two inside open type longitudinal cracks would appear around at the contact position at first, and the bigger the position of the arch cavities, the crack position of the lining is closer to the position where the junctional zone of two sides edges of the cavities behind the lining with the lining. The crack position keeps from the position where two sides edges of the cavities behind the lining meet the lining at a distance when exists 15° cavities behind the lining (show in figure 5 (b)), the crack position is nearly the same for 30° and 40° range cavities. With the load increasing, the outside open type longitudinal cracks would appear at the position of two sides spandrel and the arch foot.

4 CONCLUSION

（1）When cavities appear at the arch, the settlement of the lining arch is smaller than which without cavities under the same load. However, with the expansion of the scope of the cavities, the settlement of the arch of the lining is obviously lower than which without cavities in the initial stage of loading.

（2）With the expansion of the scope of the cavities, the bearing capacity of lining structure has the trend of decreasing integrally. However, the deformation law, stress characteristics and failure mode of the lining structure are basically the same.

（3）The lining cracking mode is basically the same when there are different range cavities in arch, and the cavities near the lining are more likely to crack, indicating that the bearing capacity of the lining structure reduces obviously in the position of the cavities.

（4）It can be seen from the results of the experiment, the lining structure has not completely lost the bearing capacity after the initial cracking, and the tunnel lining structure after cracking has strong bearing capacity before the failure, and still can bear big pressure of the surrounding rock.

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