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Monitoring study of shaft lining concrete strain in freezing water-bearing soft rock during mine shaft construction period in West China

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Abstract

In the water-bearing soft rock strata of West China, a field measurement is carried out on the shaft lining in bedrock section. The shaft lining is built with freezing method. From the measurement, some changes of regularity in construction, thawing and post thawing period are obtained, including the temperature, freezing pressure and the vertical and hoop strain of the shaft lining. Measurement studies have shown that: during the plastic stage of shaft construction period, with the release of hydration heat, the thermal expansion occurs in the concrete and the strain gauge, leading to tensile strain. In the earlier stage, the elastic modulus and strength of concrete increases rapidly. When the shaft lining temperature reaches its maximum, the cooling and growth in the freezing pressure make the hoop strain increase sharply. However, the hoop strain is at lower tensile or compressive value. In the early stage and mature stage, the strain change is mainly affected by temperature. In the thawing and post thawing period, the concrete strain is also primarily influenced by temperature change. During the measurement, when the maximum compressive strain is less than ultimate value, the shaft lining is in a safe state. To ensure the security of the shaft lining, the concrete strength growth and sidewall temperature should be controlled in the similar shaft condition. In addition, the reinforcement ratio should not be too small for the shaft lining in frozen bedrock. And further, the fiber reinforced concrete, shrinkage-compensating concrete and low hydration heat concrete technology can also be adopted to reduce the cracks as much as possible and to avoid penetrating cracks. For the soft aquifers in West China, the further field measurement is still needed to obtain the stress and deformation regularities of the shaft lining, which can not only provide a basis for security assessment of the shaft, but also guide its design and optimization to improve the design theory.

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1. Introduction

With the depletion of shallow coal resources in East China and the western development strategy being implemented, a batch of large-diameter shafts and inclined shafts will be constructed in the new energy bases in West China such as Inner Mongolia, Shaanxi, Gansu and Ningxia provinces. In this region, the topsoil is shallow and the bedrock is mostly cretaceous and Jurassic strata, which has more aquifers and low rock strength. The rich pore (crack) water leads to easier argillation and therefore, the effect of grouting pore (crack) is poor. The geological conditions of many shafts are very complex. In the initial stage of development, due to the lack of knowledge about the strata formation, several flooding shaft accidents happened, leading to a huge loss. To ensure fast and safe shaft construction, the shaft in bedrock section has to be built with freezing method in the western water-rich soft rock strata [1,2].

Although a few relatively mature theories have been developed based on experiences of using freezing method to build shaft in Eastern China [3-6], the applicability of this method in the western water-rich soft rock strata is still question marked. This is because no mature theories, experience or observed data in this area are available. Due to the changes in the geology, environment and mechanical properties in West China, the traditional theories, methods and techniques of the shaft structure that fit the East China have been partly or mostly disabled. Therefore, it is essential to deeply study the basic theory of deep water-bearing rock mass and engineering in West China [7].The force measure and design theory of the shaft structure has just started in the western water-rich soft rock strata. The stress and deformation regularities of the shaft structure obtained from the field measurement can not only provide a basis for security assessment of the shaft, but also guide its design and optimization to improve the design theory. The security of the shaft is dependent on the relative value of its load and capacity, which directly reflects the strain or deformation of the shaft lining concrete. Therefore, the field measurement of the strain should be carried out during the period of freezing sinking. Comparing the measured strain with the allowed or ultimate strain can assess or predict the security of shaft lining and instruct construction scientifically. To ensure the construction safety of a mine in West China, the information-oriented construction techniques are used during the period of freezing sinking in the water-bearing soft rock strata, monitoring a lot of engineering information. Strain monitoring of the shaft lining concrete is one of the most important parts.

2. Project overview and monitoring programme

In a western mine, the inner diameter of the air shaft is 6.5m and the shaft goes through the sand layer, Cretaceous and Jurassic rock formations, whose thicknesses are 4.35m, 100.85m and 314.8m respectively. The rock is mostly soft sandstone and mudstone and all of the sandstone is aquifer. When the rock is in contact with water, disintegration and argillation easily occur. The shaft was built using freezing method and the freezing depth is 423m. Single-layer reinforced concrete shaft lining was used, and the single-layer reinforcing steel bars were set at the inner side of the shaft lining with protective layer thickness of 100mm.

There are four fiber-optic sensor test layers in the single-layer reinforced concrete shaft lining, as shown in Table 1. Six measuring points were circumferentially distributed along the inner edge of the shaft ling in every test layer. The concrete strain gauges were put near the vertical and circumferential steel bars with a vertical gauge and a hoop gauge in every measuring point. In every test layer six pressure cells were uniformly fixed on the sidewall corresponded with the test points. The strain gauges and pressure cells were anticlockwise numbered A ~ F from the south. At the same time four thermometers were uniformed along the sidewall to measure the sidewall's temperature, numbered T1 ~ T4. After the shaft lining was poured, the signal transmission cables were laid along the shaft lining to the ground connected with the fiber optic sensors to carry out long-term and automatic monitoring.

Table1 The monitoring layers of a coal mine air shaft lining

Monitoring layer	Depth (m)	Concrete strength grade	Shaft lining thickness (mm)	Rock character	Rock thickness (m)	Rock water Yes or No	Range of uniaxial compressive strength (MPa)	Uniaxial compressive strength (MPa)
The 1st layer	-132	C40	500	Sandy mudstone	21.5	No	7.2~12.2	9.4
The 2nd layer	-214	C40	500	Post stone	18.8	Yes	7.9~14.4	11.5
The 3rd layer	-307	C40	700	Sandy mudstone	11.3	No	8.0~13.1	10.6
The 4th layer	-385	C50	700	Grit stone	16.5	Yes	8.1~16.9	12.5

3. Assured data analysis

3.1. The variation of concrete strain

The field measurement had been carried out in the four monitored layers of a ventilation shaft in West China. The typical curves for concrete vertical and hoop strain changing with time are shown in Figure 1, while the typical curves for temperature of shaft lining and sidewall changing with time are shown in Figure 2. In addition, Figure 3 shows the relationship between freezing pressure and time (the curves in other monitored layers are similar with the first layer). By analyzing the curves it can be found that the change process of concrete strain can be divided into three periods after the shaft lining is poured completely: the construction period (the shaft is built to the bottom), the thawing period and the post thawing period. In this paper tensile concrete strain ε is taken as positive. ε_z and ε_θ represent the vertical and concrete hoop strain respectively. P represents freezing pressure and pressed P is taken as positive. Letter "t" is the time after the shaft lining is poured completely in monitored layers, and the starting point is the pouring completion time. And T represents the temperature of the shaft lining and sidewall.

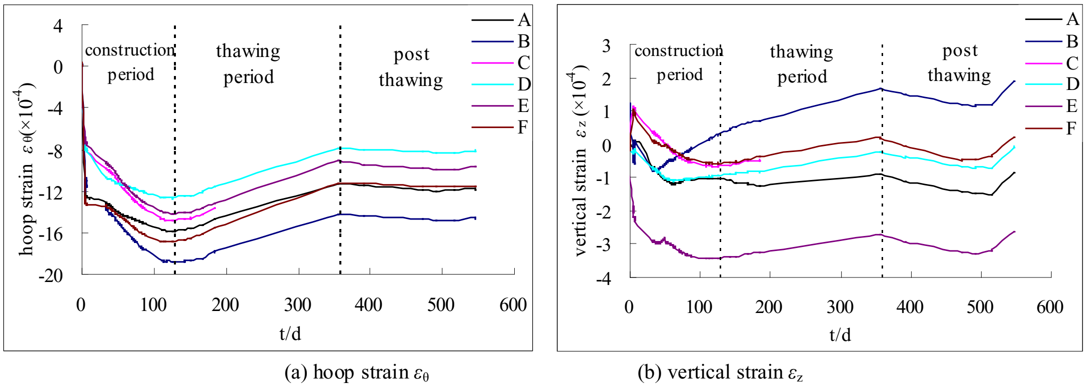

Fig.1 The 1th layer shaft lining strain (ε) vs. time (t) curves

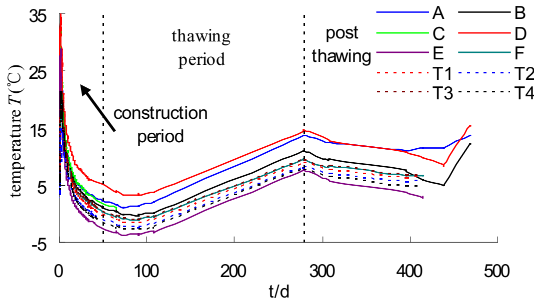

Fig.2 The 3rd layer shaft lining and sidewall temperature (T) vs. time (t) curves

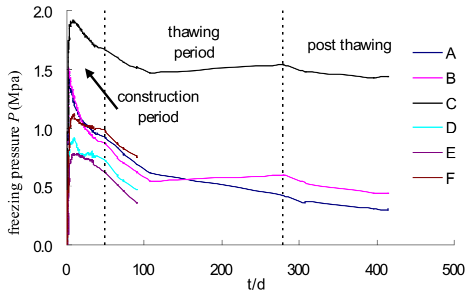

Fig.3 The 3rd layer freezing pressure (P) vs. time (t) curves

3.1.1. The variation of concrete strain in the construction period

According to cement hydration process, the variation of concrete strain can be divided into four stages in the construction period: plastic stage, earlier stage, early stage and mature stage [8].

In the plastic stage, it will usually cost about 6h~12h from pouring completion to the final setting completion. When the concrete is in a plastic state, it will intensely hydrate with its physical and chemical properties very unstable and its volume changed seriously. The shaft lining generally does not produce high stress or structural crack problems. Because the rock freezing pressure in the test layers does not exceed 2MPa, the hoop stress of the wall rock should not exceed 4MPa based on the elastic thick-walled cylinder theory. In addition, as the measured rock strength in the monitored layers is 7.2MPa~16.9MPa, the wall rock does not have radial non-attenuation-type creep displacement, which means that the sidewall does not move within when the shaft lining is under building and the shaft lining strain is mainly affected by the cement hydration process during the period between the building lining and the next digging. In 0 ~ 4h, the cement hydration reaction has just started, so the vertical strain ε_z and hoop strain ε_θ both change very little. The overlying fresh concrete flows viscously downward relative to the template and sidewall, so that vertical stress ε_z increases at the measuring points which relatively change slightly larger than the hoop strain ε_θ, varying over a range of -100×10^{-6}~ 40×10^{-6}. In 4h ~ 12h, although the vertical strain ε_z changes with measuring points, they all transform into tensile strain basically linearly. The reason is that the concrete mobility greatly diminished from the initial setting to the final setting after the shaft lining is built completely. The concrete and strain gauges expand thermally to produce tensile strain with the release of hydration heat. Ahmed Loukili [9] found that the coefficient of thermal expansion of concrete can be up to 90×10^{-6}/℃ at 1h after cast while 10×10^{-6}/℃ basically stably at 12h. However, it's worth noting that the concrete has a weak constraint on the strain gauges in the early hardening period, which leads to the incompletely synchronized deformation. The measured "strain" actually should be the "strain of strain gauge", including both synchronous strain and the desynchronized strain which is only in the strain gauges. And the strain is mainly temperature strain, so it is difficult to judge if pulling damage or tension cracks occur in the shaft lining based on it. However, with time and the hardening of concrete, the concrete has an increasing constraint on the strain gauges and the measured strain gradually begins to truly reflect the concrete strain.

In the earlier stage, generally referring to the period from completion time of the final setting (about 12h) to 3d, the cement hydration process past more than half and the elastic modulus and strength of concrete increases rapidly. The temperature of shaft lining and sidewall as well as the freezing pressure change greatly. The highest temperature in the inner shaft lining appears in 1.3d, but the time for freezing pressure P slightly lags behind T. Vertical strain gauges transform from compression state to the tension state at a low state of tension or compression, while hoop strain ε_θ sharply decreases and stays at the compression state with the changing rate decreasing gradually. Reason analysis: in this stage the concrete strength and stiffness increase rapidly. Concrete and strain gauges have coordinated deformation. With the release of cement hydration heat, the shaft lining temperature rapidly increases to maximum, followed by a slow decrease. The material feature "Expanding with heat and contracting with cold" makes the vertical and hoop strain trend to tensile strain, but this deformation is limited because of the constraints of templates and sidewall before stripping. At the same time freezing pressure also increases rapidly. Before the shaft lining temperature reaches its maximum, freezing pressure P has the fastest growth rate, which makes the hoop strain rapidly reduced and measured values change sharply. With the freezing pressure being stable, the change rate of measured values decreases gradually. Affected by the "Poisson effect ", the measured values of vertical strain gauges increase and vertical strain gradually shifts to the tension state, showing lower value of the tension or compression. During the period from the rock pieces under the cutting edge templates loosing to empty, most of the cutting edge templates disconnect with concrete and the new shaft lining and straight templates trend to relative sinking, making vertical strain gauge pulled. After the shaft lining is built completely, the inner template will be stripped in 1d ~ 2d later and moved to the next location to continue construction. Therefore, the shaft lining will lose the lateral support force of a high, releasing the inner constraint. For the 3rd and 4th layer, compared with the hoop stain prior to stripping, the hoop compressive stain after stripping increases with a respective change of -48 $\times 10^{-6}$ and -30 $\times 10^{-6}$. But in this process, vertical strain remained stable with a very slight change of -1 $\times 10^{-6}$ ~ -14 $\times 10^{-6}$. This stage is completed within 3d when the concrete strain rapidly changes. All these factors lead to crack easily.

The early stage generally refers to the 3d to 90d after the shaft lining is built completely. In this stage, the hydration process gradually develops and concrete strength and stiffness improve continuously until being mature. The period after 90d is the mature stage, when there is still very weak hydration and concrete strength and stiffness develop very slowly, basically reaching steady state [9,10]. In the monitored layers the longest test time is up to 546d (1st layer). The measured data show the shaft lining strain reaches a relatively stable state after 7d. In the construction stage, with the temperature of shaft lining and the sidewall gradually dropping, the majority of the vertical and hoop strain decrease. The strain in this stage is mainly affected by temperature.

3.1.2. The variation of concrete strain in the thawing period

When the shaft is excavated to the bottom, the wall rock began to thaw naturally in the frozen rock region near the outer side of shaft lining. From the curves shown in Figure 1 for sensor strain in 1st layer changing with time, it can be seen that the concrete vertical and hoop strain have increased since thawing began at 130d after setting the first layer sensor. And at 360d, thawing is nearly complete. At the thawing start time the concrete age has reached 130d, staying in the mature stage, where the temperature of the frozen wall and the shaft lining gradually increases and affected by the "expanding with heat and contracting with cold", vertical and hoop strain also rises. However, as shown in Figures 2 and 3, the sensors in 3rd layer are set at the location -307m, deeper than the first layer. When freezing stops, the concrete age in 3rd layer is about 50d, when the concrete is at the early stage and still has weak hydration reaction. After stopping freezing, the sidewall temperature is affected by the thick frozen wall in the initial thawing period and continues to decrease. The freezing pressure shown in Figure 3 reduces with the decreasing temperature of the shaft lining and sidewall as well. The temperature begins to rise slowly until 80d ~ 90d after 3rd layer sensor are set, when the freezing pressure also no longer reduces and begins to increase slowly or remains unchanged. The temperature of the shaft lining and sidewall can reach 7 ~ 14℃ when thawing is basically complete. The strain change in this period is mainly affected by temperature.

3.1.3. The variation of concrete strain in the post thawing period

After the frozen wall thaw completely, the concrete strain changes with temperature in positive correlation. When temperature increases, strain increases. When temperature decreases, strain decreases as well. At this moment, because there is no other external loads, the vertical and hoop strain is affected by temperature.

3.2. Extreme value analysis on the concrete strain

3.2.1. The extreme value of concrete strain

The measured concrete strain of shaft lining and freezing pressure for 1st~4th layers is shown in Table 2. The maximum compressive strain of circular concrete is -1045×10^{-6}~-1886×10^{-6} and in the first layer average maximum value can reach -1559×10^{-6}. In contrast to the variation of vertical strain in Figure 1, the maximum hoop strain usually appears in the early thawing period when the shaft lining temperature is minimum. With the frozen wall thawing, the hoop compression strain increases gradually, and maximum value in the 1st layer increases from -1886×10^{-6} to -1427×10^{-6}. The concrete strain is the total strain obtained when the shaft lining concrete is poured completely, and it includes self-shrinkage strain in concrete hydration process, shaft lining structure strain caused by external load (mainly freezing pressure) and concrete shrinkage strain caused by temperature decrease. At present there are big different opinions for the ultimate concrete compression strain value, which will vary with different concrete formulations and force conditions. According to GB50010-2002 "code for design of concrete structures" [11], the allowed maximum compression strain is -3300×10^{-6} for the eccentric compression members. In this field measurement the concrete strength grades are C40 and C50 and the maximum hoop compression strain is about 57% of the maximum value in the specification. Therefore, the shaft lining will not be circumferentially crushed during the construction period and post thawing period.

Table2 Statistical table of concrete strain

Monitoring layer	Extreme of freezing pressure (KPa)		Extreme of hoop strain ($\times10^{-6}$)		Extreme of vertical tensile strain ($\times10^{-6}$)	
	Maximum	Mean	Maximum	Mean	Maximum	Mean
The 1st layer	1776	1299	-1886	-1559	121	58
The 2nd layer	1933	1201	-1584	-1070	335	95
The 3rd layer	1923	1299	-1518	-1190	253	146
The 4th layer	1037	787	-1045	-852	249	185

Measured by Somsak [12], the axial ultimate tensile strain of early-age ordinary concrete is 120×10^{-6} ~ 135×10^{-6}. Yang Yang [13] measured ultimate tensile strain of 1 day-age high performance concrete to be close to 200×10^{-6} and the strain changes little after 1day-age. As shown in table 2, except 1st layer, the maximum vertical tensile strain in the other three layers vary from 248×10^{-6} to 335×10^{-6}, which all surpassed the concrete strain value listed above. It is believed that the inner edge of shaft lining may have horizontal cracks, which is consistent with the phenomenon that horizontal cracks appear in the inner edge after stripping. The steel bars in the concrete play a positive role in preventing cracks from expanding to the outer edge. And further, the fiber reinforced concrete, shrinkage-compensating concrete and low hydration heat concrete technology can be adopted to reduce the cracks as much as possible.

3.2.2. The relationship between extreme value of concrete strain versus temperature and freezing pressure

In the construction period, with the temperature of frozen wall decreasing, the ultimate hoop compressive concrete strain gets to its maximum when the temperature reaches its minimum. In the thawing period of frozen wall, the shaft lining temperature gradually rises with the maximum hoop compression strain increasing, but the value differs slightly in each measured point. In post thawing period, the concrete strain maintains a positive relationship with the temperature. Therefore, the temperature is a major factor affecting the concrete strain.

The measured maximum value of freezing pressure is 1037KPa ~ 1933KPa and the mean value is 1299KPa. However, it is important to point out that freezing pressure has significant discreteness which can be affected by the harsh construction conditions, the embedding technology, the over-under-excavated problems of shaft lining, the dispersed measured values and the improperly set pressure cells. These problems can make the measured freezing pressure uneven, and it will not be able to fully reflect the true changes of freezing pressure. Due to the discreteness there is no corresponding relationship between freezing pressure and depth or lithology. From the regularity of freezing pressure and concrete strain changing with time, it can be seen that, during the early pouring process in construction period, the freezing pressure increases rapidly and the growth speed is quickest before the temperature gets to its maximum. The increase in the freezing pressure makes the hoop strain quickly decrease and the measured hoop strain values rapidly change. With the freezing pressure being stable gradually, the variation rate of measured value is decreasing. In the thawing period, the freezing pressure slightly increases or does not change when the measured hoop and vertical strain increases (mainly affected by temperature). In the post thawing period, the lateral pressure of shaft lining is permanent unchanged ground pressure. The concrete strain change is mainly associated with temperature, performing "Expand with heat and contract with cold".

4. Discussion on the shaft lining structure design in western water-bearing soft rock strata

4.1.1. The control of shaft lining concrete strength and frozen wall temperature

In West China, for the shaft building construction in the deep alluvium, the early strength of concrete is controlled, which makes a good effect. Along with shaft depth increasing, the shaft lining thickness and concrete grade are correspondingly increasing. Therefore, in the deep shaft construction, the hydration heat problem for mass concrete must be noted. The shaft lining easily produces the temperature cracks. Therefore, for the shaft lining construction in the water-bearing soft rock strata of West China, the improving concrete strength, the risk of temperature cracks and the adverse effects to the frozen wall should all be considered to ensure the reasonable concrete proportion, so as to control its total hydration heat and releasing rate. In order to guarantee the security of shaft lining structure, experiments should be firstly conducted to determine the reasonable concrete proportion. The crush accidents should not occur because of the insufficient early strength. The early concrete strength should be controlled and the concrete strength in 1d ,3d and 7d should achieve 30%, 70% and 90% of the configuration strength respectively to guarantee the early capacity of shaft lining. Secondly, the construction management and process control should also be strengthened to ensure the construction quality. Thirdly, it is also important to control the sidewall temperature in frozen wall to ensure shaft lining in a positive temperature curing conditions, so as to avoid the shaft lining in a negative temperature too early and/or its temperature differing between inside and outside which can make temperature stress too high to influence the strength growth. Fourthly, the steel bars in the concrete play a positive role in preventing cracks from expanding to the outer edge. Prudently, the reinforcement ratio should not be too small for the shaft lining in frozen bedrock. And further, the fiber reinforced concrete, shrinkage-compensating concrete and low hydration heat concrete technology can be adopted to reduce the cracks as much as possible to avoid penetrating cracks.

4.1.2. The deep research on designed load of shaft lining and the field measurement

From analysis on the concrete strain change process it can be seen that the concrete strain change closely relates to the load growth history of the shaft lining. The measured concrete strain is the total strain, including self-shrinkage strain in concrete hydration process, shaft lining structure strain caused by external load and concrete shrinkage strain caused by temperature decrease. Therefore, the researches on shaft lining stress and strength growth regularity are needed under the pressure curing conditions in early period, so as to have a better quantitative analysis on the measured data, which will play a crucial role in evaluating the overall security of shaft lining.

Due to the changes in the geology, environment and mechanical properties in West China, the traditional theories, methods and techniques of the shaft structure have been partly or mostly disabled. Using freezing method to build shaft wall in the western water-rich soft rock strata does not have mature theories and experience. The research on the basic theory has just begun. The field measurement is needed to obtain the stress and deformation regularities of the shaft lining, which can not only provide a basis for security assessment of the shaft, but also guide its design and optimization to improve the design theory. It is difficult and costly to measure the frozen pressure in rock and therefore, there are not many measured data in the water-bearing soft rock strata of West China. The acquisitions of the measured freezing pressure have significance in determining the external load of shaft lining. Therefore, it is still needed to conduct field measurement extensively with various means. The continuous field measurement will help to reasonably determine load value of shaft lining in the water-bearing soft rock strata of West China. By comparing the measured data with the data in paper [3~6], it can be found that the maximum hoop compression strain in this paper is approximately 85% of the shaft lining stain in the deep alluvium and the freeze pressure is about 50%, whose change regularity is also different. So it is not suitable to directly use the design method in the deep alluvium. Based on the above analysis, the structure design methods of the frozen shaft still need to be improved or optimized for the western water-bearing soft rock stratum. In general, deep studies on this issue need to be conducted as well.

5. Conclusions

In the plastic stage of the construction period, after the shaft lining is built, the concrete transforms from initial setting to the final setting with its mobility greatly diminishing. With the release of hydration heat, the concrete and strain gauges expand to produce tensile strain. In the earlier stage, the elastic modulus and strength of concrete increase rapidly. When the shaft lining temperature reaches its peak, the cooling and growth in the freezing pressure make the hoop strain increase sharply. In the early and mature stage, the strain change is mainly affected by temperature. In the thawing and post thawing period, the concrete strain is also primarily affected by temperature changes.

For the freezing shaft lining structure in the western water-bearing rock, the concrete strength growth and sidewall temperature should be controlled to ensure the shaft lining secure. In addition, the construction management and process control should also be strengthened to ensure the construction quality.

The steel bars in the concrete play a positive role in preventing cracks from expanding to the outer edge. Prudently, the reinforcement ratio should not be too small for the shaft lining in frozen bedrock. And further, the fiber reinforced concrete, shrinkage-compensating concrete and low hydration heat concrete technology can be adopted to reduce the cracks as much as possible to avoid penetrating cracks.

The variation of concrete strain has a close relationship with load growth history of shaft lining. For the soft aquifers in west china, the further field measurement is still anticipated to obtain the stress and deformation regularities of the shaft lining, which can not only provide a basis for security assessment of the shaft, but also guide its design and optimization to improve the design theory.

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