Damage mechanism and stability analysis of rock mass in the high geo-stress tunnel subjected to excavation

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ABSTRACT

High geo-stresses and complicated geological conditions are two typical characteristics in the traffic tunnel of the tailrace surge chamber at the Shuangjiangkou hydropower station, Southwest China. Rock failures such as spalling and rockbursts induced by excavation were encountered repeatedly in this tunnel. To evaluate the stability of rock mass of the tunnel during excavation, the high-precision microseismic (MS) monitoring technology was introduced. Through analysing the tempo-spatial distribution characteristics of MS events, the main damage areas and their influencing factors were studied. The rock fracturing mechanisms of MS clusters were revealed based on the source parameters of MS events. A three-dimensional model was established to obtain the stress and deformation characteristics of rock mass. Results indicated that the MS events mainly occurred between July 10 and 26, 2017 and the energy release was higher during this period. The main damage areas of rock mass were located at the Stake K0 + 110m–K0 + 170m. Weak structures and multi-cavern effect aggravated rock mass damage subjected to excavation-unloading. Tensile failure was the main fracturing type of rock mass. Rock mass damage influenced by weak structures was especially prominent. The numerical simulation results are consistent with the MS monitoring results. The results could provide significant references for safety evaluation and construction design of similar tunnels.

1. Introduction

There are myriads large rivers in Southwest China that reserve abundant water resources. Rapid development of China’s economy increases demand for energy and
many large hydropower projects in Southwest China are being constructed. These projects usually include numerous tunnels, such as access tunnels, diversion tunnels and tailwater tunnels, etc. Due to great depth, multi-cavern effect and complicated geological conditions, many conventional or unconventional surrounding rock failure phenomena are often encountered (Gong et al. 2020), such as deformation, spalling and rockburst, which pose a threat to the safety of tunnel construction.

A lot of methods are applied to study the stability of rock mass in underground caverns, such as mechanical analysis, numerical simulation, engineering analogy, physical model and field monitoring. Among these, the field monitoring technology is more and more widely used in underground engineering (Andersson and Martin 2009; Kwon et al. 2009; Li et al. 2008; Maejima et al. 2003; Martin et al. 1997; Yan 2007; Yan et al. 2015). Field monitoring data can reveal the stress and deformation of the caverns and also provide references for other analysing methods including mechanical analysis, numerical simulation and physical model. The monitoring data such as surrounding rock deformation and bolt stress variation can be directly obtained by traditional monitoring technology. However, the monitoring results are after deformation or even instability of rock mass, which can be hardly applied for damage evolution analysis and disaster forecasting of underground caverns. As a three-dimensional monitoring technology for monitoring rock mass microfracturing that always occur prior to rock mass instabilities, the MS monitoring technology has been developed in recent three decades (Wang and Ge 2008). Through receiving and analysing the elastic waves emanated by rock fractures, abundant MS source parameters including time, space position, apparent stress, energy and moment magnitude, can be obtained (Xue et al. 2020). Therefore, the MS monitoring technology can be used to study rock damage mechanism and evaluate the stability of rock mass. The important technical support for the safety of engineering construction is provided by MS monitoring technology.

Previous researches have achieved abundant results and provide significant technical references for engineering construction using the MS monitoring technology. Hudyma and Potvin (2010) established an MS approach to manage hazards in underground hard rock mines. Ma et al. (2019) investigated the focal mechanisms of induced seismicity in underground mines with the optimized moment tensor inversion method. Leśniak and Isakow (2009) performed a hazard analysis based on the MS clusters of a coal mine and correlated the evaluated hazard function to the time of occurrence of high-energy tremors. Cai et al. (2020) and Dou et al. (2018) built a MS monitoring system to study the mechanism of rockbursts in the mining area and provided quantitative early warning of rock burst risk. Mborah and Ge (2018) proposed a new technique based on the discrete stationary wavelet transform (DSWT) and higher order statistics, which was proposed for processing noisy data from underground mines. Liu et al. (2016) established a MS monitoring system in Hongtoushan copper mine and evaluated the stability of a rock mass near a fault. Cai et al. (1998), (2001) proposed a tensile model to estimate fracture sizes from MS measurements and quantified the rock damage of the AECL Mine-by Experiment test tunnel. Feng et al. (2019, 2020) studied the characteristic microseismicity during rockburst in deep-buried tunnels of Jinping-II hydropower project. Ma et al. (2016) used
the MS monitoring technology in underground storage caverns and put forward a method by integrating numerical simulation and MS monitoring for evaluation of cavern stability. Li et al. (2019, 2020, 2020) introduced the MS monitoring technology to underground powerhouse caverns and analysed the effect of MS events on rock mass deformation.

Different numerical modelling approaches, due to the convenience, efficiency, and repeatability, have been developed to study the deformation and failure mechanism of underground caverns. Wang et al. (2018) established a three-dimensional finite element model reflecting the engineering geological condition and initial design scheme. On the basis of field monitoring deformation data, the surrounding rock geotechnical and rheological parameters of the roadway are obtained by back analysis. Hao and Azzam (2005) analysed the effects of joints with different dip angles on plastic zones and displacements of underground caverns using the discrete element method (DEM). Das et al. (2018) assessed the effect of the fault on the stability of underground coal mines by numerical simulation with distinct element method. Cheng et al. (2019) studied the surface subsidence induced by high dip coal seam using the finite difference method. The deformation and failures of high geostress tunnels are usually influenced by a variety of factors including high geostress, excavation unloading, geological structures, etc. Rock mass damage evolution mechanism dominated by different factors is fundamental for stability analysis. The traffic tunnel of tailrace surge chamber of Shuangjiangkou Hydropower station was in high in-situ stress environment and the rock mass strength is between 60 Mpa and 80 Mpa, and the ratio of ground stress to rock mass strength is between 0.25 and 0.5. Rock burst phenomenon is very easy to occur. During the construction of similar tunnels at Shuangjiangkou Hydropower Station, the problems of block falling and rock burst frequently occurred. In addition, the conditions of further deterioration of surrounding rock mass quality, such as weak structural plane and construction support tunnel excavation, were involved in the traffic tunnel of tailwater pressure regulating chamber from Stake K0 + 0 – K0 + 250. Therefore, microseismic monitoring was carried out in this section of tunnel to provide technical support for on-site construction safety. In the past, many scholars studied the stability of tunnel surrounding rock by microseismic monitoring technology. And the influence of structural plane or group hole effect was considered singly. However, the influence of the them on the stability of surrounding rock is rarely compared (Feng et al. 2015, 2019; Xue et al. 2020). In the present study, an MS monitoring system was established in the traffic tunnel of the tailrace surge chamber at the Shuangjiangkou hydropower station, Southwest China. Based on the characteristics of MS tempo-spatial activities induced by excavation unloading, the main damage areas of rock mass were delineated. Combined with field construction and geological conditions, the main factors resulting in rock mass damage were revealed. The source parameter characteristics of different MS clusters were analysed to investigate the damage evolution mechanism. Finally, a three-dimensional model was established and the stress and deformation characteristics of rock mass were compared with MS monitoring results. It was expected to provide technical support for the construction safety of the deep-buried tunnel of Shuangjiangkou Hydropower station and other similar tunnels.
2. Engineering background

The Shuangjiangkou hydropower station is located in the upper source of Dadu River and 3 km away from the junction of Zumuzu River and Chuosijia River. It is the upstream controlled reservoir project of hydropower cascade development in Dadu River basin. The height of the earth core rockfill dam is 312.0 m, which is the highest among the same dam type in the world. The diversion power system is located in the mountain on the left bank and comprised of underground powerhouse, diversion tunnels, tailwater tunnels, traffic tunnels, spillway tunnels, etc (see Figure 1). The normal water level of the reservoir is 2500 m and the regulated storage capacity is 2.152 billion cubic meters. The installed capacity of the power station is 2000 MW and the annual generating capacity is 8.34 billion kWh (Sichuan Dadu River Shuangjiangkou Hydropower Development Co, Ltd 2016).

The traffic tunnel of the tailrace surge chamber is arranged on the right side of No. 2 pressure regulating chamber and is regarded as the excavation construction passage on the upper layer of main powerhouse, main transformer chamber and tailrace surge chamber (see Figure 2). The length of this tunnel is about 707 m. The entrance elevation is 2272.6 m and the floor elevation at the connection with the 2# surge chamber is 2282.6 m. The standard section is of the gate type with the main excavation size of 8.0 m × 7.6 m (see Figure 2(c)) and the vertical burial depth is about 200 m. The surrounding rock is mainly porphyritic black cloud feldspar granite. Plenty of long and large fractures are developed and divided into three groups. Their attitudes are respectively N70°~85°W/SW 55°~68°, N60°~85°W/SW 20°~30° and N70°~85°E/SE 12°~28°. The fractures above are mainly rough and undulating rigid structural planes. The main rock mass structure is block or subordinated block. The walls are damp and the water drips in some areas. After considering the high geostresses factors, the main rock type is class III. The geostress of the Stake K0 + 0~K0 + 200 m reaches up to 20 Mpa~30 Mpa. The rock uniaxial compression strength in this area is approximately 60 Mpa to 80 Mpa and the ratio of geostress to...
rock uniaxial compression strength is ranging from 0.25 to 0.5, which indicates that the geostress of this tunnel is high.

3. Construction of the MS monitoring system

3.1. Composition of the MS monitoring system

An MS event is a rock fracture involving the generation of a new crack or extension of an existing crack in localized rock mass (Xu et al. 2011). The MS source information such as location, energy, magnitude and apparent stress can be obtained through analysing the waveform signals emanated by rock fractures. The network topology

Figure 2. Traffic tunnel of the tailrace surge chamber. (a) Geological profile of the traffic tunnel of the tailrace surge chamber, (b) Local diagram of the diversion power system, (c) Outline drawing of the traffic tunnel of the tailrace surge chamber.
diagram of the MS monitoring system in the traffic tunnel of the tailrace surge chamber is shown as Figure 3. The hardware components mainly include 6-channel acceleration sensors, Paladin data acquisition instrument and Hyperion digital signal processing system. After the occurrence of MS events, the vibration signal is captured by the sensors. The original source information is collected by the Paladin data acquisition instrument and transmitted to the Hyperion digital signal processing system, which can be sent to Shuangjiangkou office through the wireless transmitter for data processing. The final data is transmitted to Chengdu for calculation and analysis.

3.2. Dynamic layout scheme of sensors

Six sensors were arranged in three sections behind the excavation face of the tunnel. For each section, two sensors would be installed in the sidewalls, and one is on the left and another is on the right. And the sensors have a height difference of 3 meters between the sensors in adjacent sections. The P-wave pickup time difference is too small and the accuracy decreases when the section of the adjacent sensor is less than 35 m. If the sensor is more than 150 m away from the excavation surface, the sensor can hardly receive the fracturing signal effectively. To achieve the best monitoring effect and avoid blasting induced destruction to monitoring lines, the distance between adjacent sensor section is set to 40 m and the distance between excavation face and the sensors closest to the excavation face is 30 m (see Figure 4). Once the
distance between excavation face and the sensors closest to the excavation face is 70 m, the farthest two sensors would be recycled and moved to the section close to the excavation face. Through this dynamic adjustment, rock fractures around excavation areas can be sufficiently captured. Twelve sensor installation holes should be drilled within the Stake K0 + 0~K0 + 220 m of the traffic tunnel of the tailrace surge chamber.

4. Characteristics of MS activities during tunnel excavation

4.1. Temporal distribution of microseismicity

The MS monitoring system of the traffic tunnel of the tailrace surge chamber in Shuangjiangkou hydropower station has been in normal operation since July 10, 2017. Until September 13, 2017, 336 MS events have been identified within the effective space (see Figure 5). Figure 5 illustrates the temporal distribution of MS events including MS rate and energy in each day. During July 10, 2017 to July 26, 2017, the MS events frequently occurred, and the number of events accounted for 48% of the total number of MS events during the all monitoring period. A rock fracture (MS event) represents a damage of rock mass and each fracture of surrounding rock is accompanied by energy release. Based on the principle of energy dissipation, larger energy means more serious rock damage. The cumulative energy release curve of MS events shows an obvious increment on July 15, 2017 and July 20–22, 2017. Moreover, the MS event rate reached the maximum in a single day on July 15, 2017. The above phenomenon reflects serious rock mass damage during July 10, 2017 to July 26, 2017. According to the feedback of field construction conditions, both the main tunnel and the branch tunnel were being excavated simultaneously at Stake K0 + 170 m~K0 + 110 m. In addition, there was also the soft interlayer exposed in this region. According to the actual situation on site, during the period of July 10–18, 2017, blasting excavation was carried out in Stake K0 + 170 m–K0 + 130 m, and weak interlayer was found in the side wall of the hole section. During the period of July 19–26, 2017, support hole excavation was carried out at Stake K0 + 160 m. Therefore, this period is divided into two processes (July 10–18, 2017 and July 19–26, 2017) for analysis.
Figure 5. Temporal distribution of MS events.

Figure 6. Spatial distribution and density contour of MS events during July 10–18, 2017. (a) Front view, (b) Top view, (c) Density contour in front view, (d) Density contour in top view.
4.2. Spatial distribution of microseismicity

Figure 6(a) and (b) illustrate the spatial distribution of MS events (spheres in Figure 6(a) and (b)) in the traffic tunnel of the tailrace surge chamber from July 10 to July 18, 2017. Different sphere colours represent different moment magnitudes, while different sphere sizes reflect different energy scales. There were 99 MS events occurring during this period, which were mainly distributed near the tunnel face along the direction of the footage in both sidewalls and the arch shoulder areas. There were more MS events in the sidewalls than the arch shoulder area, and the MS events were more concentrated in the left sidewall than the right sidewall (see Figure 6(c) and (d)). This was J2 fissure exposed in the side wall. And the J2 fissure might be more widely distributed on the left side of the tunnel. In addition, frequent blasting construction and blasting effect in this period were the reasons for this phenomenon. Most of the MS events accumulated along J2 fissure with relatively high energy (see Figure 6(b) and (d)). During this period, the blasting excavation was being conducted at Stake K0 + 170 m–K0 + 130 m, causing the internal stress adjustment of the surrounding rock around the excavation face. The weak interlayer further aggravated the fracturing of the surrounding rock. As a result, the MS events with high energy frequently occurred.

Figure 7(a) and (b) present the spatial distribution of MS events in the traffic tunnel of the tailrace surge chamber from July 19 to July 26, 2017. The 61 MS events...
were distributed in the left sidewall and arch shoulder area near the tunnel face along the direction of the footage. During this period, the main tunnel was excavated at Stake K0+130 m–K0+110 m, and the branch tunnel was excavated near the Stake K0+160 m. The branch tunnel is located on the left side of the main tunnel (see Figure 8). The excavation of two tunnels would form larger free face and result in more intense unloading around the excavation areas that is also called as the multi-cavern effect. The stress concentration was more likely to appear in the included angle region during stress adjustment and redistribution, led to a large number of rock mass fractures, which was adverse to the stability of tunnel rock mass. The spatial distribution of MS events was consistent with the actual situation. The number of MS events on the left side of the main cave was significantly more than that on the right side. Therefore, the surrounding rock damage was mainly located in the angle region between the left side wall of the main cave and the branch cave.

4.3. Characteristic parameters of MS clusters

4.3.1. Es/Ep

$E_s/E_p$, which means the ratio of S-wave energy to P-wave energy, is an important index to reflect the fracturing type of surrounding rock. In the field of microseismic monitoring, $E_s/E_p$ is often used as the main reference index to judge the type of rock micro-fracture represented by microseismic signals. Both ES and EP can be calculated by formula (1):

$$E = 4\pi \rho c r^3 \frac{J_c}{F_c^2}$$

(1)

In the formula, $\rho$ represents the density of rock (kg/m$^3$). The $r$ represents the distance between the sensor and the microseismic source position (m). The $c$ stands for...
wave velocity (m/s). The $F_c$ represents the empirical coefficient of seismic wave radiation type. The $J_c$ is the integral of the velocity of the particle.

Boatwright and Fletcher (Boatwright and Fletcher 1984) found that for shear type or fault-slip type seismic events, $E_s/E_p$ was usually larger than 10, while this value closer to 3 indicated a non-shear failure. Hudyma and Potvin (Hudyma and Potvin 2010) analysed the difference of $E_s/E_p$ in two MS clustering areas in a mine. The $E_s/E_p$ value for 70% of the MS events in one area was more than 10, which was related to shear failure of the exposed faults in this area. In another region, the $E_s/E_p$ value of more than 85% of MS events is less than 10, and the main failure type of rock is tensile failure caused by unloading fracture.

Figure 9 shows the frequency distribution of ES/EP values of MS events from July 10, 2017 to July 18, 2017. The number of MS events with an ES/EP value less than 10 reached 82% of the total number in this period, which indicated that the MS events in this region were mainly tensile fractures. Combined with the geological conditions in this region, stress concentration on the soft structural surface due to excavation unloading led to tensile fractures along both sides of the structural surface and continuous extension of cracks on the structural surface.

Figure 10 shows the frequency distribution of $E_s/E_p$ of MS events from July 19 to July 26, 2017. The number of MS events with an $E_s/E_p$ value less than 10 accounted for 73% of the total number in this period, indicating that rock mass damage in this region was also mainly induced by tensile fractures. Through analysing field construction situation near this region, the blasting excavation of the main and branch tunnels intensifies the unloading disturbance of rock mass, resulting in a large number of tensile cracks.

4.3.2. Magnitude-frequency relationship

Gutenberg and Richter (Gutenberg and Richter 1944) used the linear fitting method to fit the magnitude and frequency of earthquakes, and put forward the famous G-R law, expressed as:

$$\log N = a - bm_M$$

where $m_M$ is the seismic magnitude; $N$ represents the number of seismic events with the magnitude larger than or equal to $m_M$; $a$ and $b$ are two constants that can be
Figure 10. Percentage distribution diagram of $E_s/E_p$ (2017.7.19–2017.7.26).

Figure 11. Magnitude-frequency relationship curve of MS events (2017.7.10–2017.7.18).

Figure 12. Magnitude-frequency relationship curve of MS events (2017.7.19–2017.7.26).
obtained by linear fitting for a given set of data. The $b$ has its special physical meaning and can reveal the proportion of seismic events with large and small magnitudes. In general, a small $b$ value represents a large proportion of events with high magnitude, whereas a large $b$ value represents a dominant proportion of events with low magnitude.

The magnitudes of engineering MS events also meet the G-R law. The magnitude and frequency of MS events are fitted linearly with $D_M = 0.1$ during July 10–18 and 19–26. The G-R relation curve is shown in Figures 11 and 12. The $b$ values of two periods were 0.58 and 1.13 respectively. The former $b$ value was relatively small, which meant that high magnitude MS events in this region dominated by the weak structural plane accounted for a large proportion. The latter $b$ value was larger and indicated that low-magnitude events were dominant and the fracturing scale of MS events caused by excavation unloading strength was relatively small.

5. Numerical simulation using FLAC 3D

5.1. Numerical model

A three-dimensional model was established through synthetically considering the excavation sizes of the main caverns and geological conditions around the underground powerhouse caverns (see Figure 13). The scope of the model is $120 \, \text{m} \times 100 \, \text{m} \times 150 \, \text{m}$, and this model was divided into 748899 elements (see Figure 13(a)). The main weak structure (long and large fracture J2 in Figure 2) exposed in this tunnel was taken into account in the model, and the mesh of the main research section is intensively denser (see Figure 13(b)). The excavated part during July 10 to 26, 2017 is shown as Figure 13(c). The mechanical parameters of rock mass and structures were obtained through field and laboratory tests, as shown in Tables 1 and 2. The geostress of vertical direction was almost equivalent to the gravity. Displacement constraints were applied to the sides and underside. The Mohr-Coulomb elastic-plastic constitutive model was applied for mechanical calculation of this model.
5.2. Simulation results

According to the MS tempo-spatial characteristics, the simulation results during two construction phrases (July 10–18, 2017 and July 19–26, 2017) were mainly analysed. Figure 14 shows the displacement contour without the influence of J2 fracture during July 10 to 18, 2017 and the maximum value is about 9 mm. When the J2 fracture is considered, the maximum displacement of this area, located near the weak structure, is up to 12 mm (see Figure 15). It can be seen that the displacement affected by the weak structural plane is much larger and the weak structural plane aggravated the surrounding rock disturbance during July 10 to 18, 2017. In addition, the displacement on the left side of the tunnel is larger than that on the right and the displacement along the soft structural plane is large. Figure 16 illustrates the maximum stress of the typical section after excavation during July 10 to 18, 2017. There is obvious tensile stress occurring around the weak structural plane (see Figure 16), which can also account for the MS accumulation and tensile failures around this area.

### Table 1. Mechanical parameters of rock mass.

| Rock mass classification | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | Cohesion (MPa) | Friction angle (°) | Tension strength (MPa) |
|--------------------------|----------------|--------------------|---------------------|----------------|-------------------|-----------------------|
| IIIₐ                     | 2550           | 23.2               | 13.5                | 1.5            | 45                | 6.5                   |

### Table 2. Mechanical parameters of weak structures.

| Structure name | Normal stiffness (MPa/m) | Tangential stiffness (MPa/m) | Friction angle (°) |
|----------------|--------------------------|-----------------------------|--------------------|
| J₂             | 1.53                     | 0.46                        | 20                 |

![Figure 14](image-url) Displacement of typical section during the construction period between July 10 and 18, 2017.

![Table 1](image-url) Mechanical parameters of rock mass.

![Table 2](image-url) Mechanical parameters of weak structures.
Figure 17 shows the displacement and maximum stress of typical sections in the tunnel after excavation during July 19 to 26, 2017. Compared with the period during July 10 to 18, 2017 (Figure 15), the displacement near the weak structural plane has an increment with the value less than 1 mm (Figure 17(a)). The excavation unloading of the main and branch tunnels still made some difference on rock mass damage near the weak structural plane. Influenced by excavation unloading of the main and

Figure 15. Displacement of typical section affected by J2 fracture during the construction period between July 10 and 18, 2017.

Figure 16. Maximum stress of typical section affected by J2 fracture during the construction period between July 10 and 18, 2017.
branch tunnels, the rock mass displacement of the included angle area is much larger than that on the left side of the branch tunnel, but it is just a little larger than on the right side of the main tunnel (see Figure 17(b)). It can be reflected that the multi-cavern effect on the rock mass is not too severe. The tensile stress concentration still occurred in rock mass near the fracture J2 (see Figure 17(c)). Figure 17(d) illustrates the maximum stress of the typical section after excavation during July 19 to 26, 2017. Tensile stress occurs in a large range of the included angle region, which also matches up well with the damage type revealed by $E_s/E_p$ of MS events. It can be seen from above that the simulation results are generally in good agreement with those of MS monitoring.

Figure 17. Displacement and stress of the tunnel after excavation between July 19 and 26, 2017. (a) Displacement of typical section affected by $J_2$ fracture, (b) Displacement of typical section affected by multi-cavern effect, (c) Maximum stress of typical section affected by $J_2$ fracture, (d) Maximum stress of typical section affected by multi-cavern effect.
6. Conclusions

The MS monitoring technology was introduced to the traffic tunnel of the tailrace surge chamber at the Shuangjiangkou hydropower station for monitoring, analysis and evaluation of rock mass stability. Through analysing the characteristic microseismicity and numerical simulation results, main conclusions are as follows:

1. During the monitoring period, the MS events occurred frequently between July 10, 2017 and July 26, 2017, accounting for 48% of the total number, and were mainly distributed in Stake K0 + 110 m–K0 + 170 m. The damage area of surrounding rock is delineated by the degree of microseismic events and energy release in the study period.

2. In the excavation unloading process of the traffic tunnel of the tailrace surge chamber, the aggregation and focal parameter characteristics of MS events differ dominated by different factors. Influenced by the weak structural plane, the MS events mainly accumulated in the middle of the lateral wall and the arch shoulder area, with more concentrated distribution in the left sidewall. The MS events accumulated along the weak structural plane and the phenomenon of high energy release occurs during this period. Dominated by multi-cavern effect, the MS events mainly accumulated on the left sidewall of the main tunnel.

3. The $E_s/E_p$ characteristics of MS events revealed that the clustering MS events were mainly tensile fractures. The $b$ value of MS events dominated by soft structural plane was small, while the $b$ value of MS events caused by multi-cavern effect was large. The number and proportion of high magnitude MS events near the weak structural plane are large.

4. The simulated displacement near the weak structural plane is larger than intact rock mass and tensile stress occurs in this region. The included angle rock mass affected by the multi-cavern effect also has a larger displacement value and there is obvious tensile stress in the rock mass. The simulation results are generally consistent with the MS monitoring results.

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Disclosure statement

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**Data availability statement**

The data used to support the findings of this study are available from the corresponding author upon request.

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