The Effects of Isolation Pile on the Ground Deformation due to a Deep Pit Excavation

Guiping Nie, 1,2,3 Ying Liu, 1,2,3 Peilin Lv, 1,2,3 Shaokun Ma, 1,2,3 Zheng Chen, 1,2,3 and Xusheng He 4

1 Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Guangxi University, Nanning, China
2 School of Civil Engineering and Architecture, Guangxi University, Nanning, Guangxi, China
3 Guangxi Key Laboratory of Disaster Prevention and Engineering Safety, Guangxi University, Nanning, China
4 Nanning Rail Transit Group Co, Ltd., Nanning 530029, China

Correspondence should be addressed to Ying Liu; lyily1112@126.com

Received 25 July 2022; Accepted 12 September 2022; Published 3 October 2022

Pit excavation could inevitably introduce ground movement and threaten the safety of nearby existing high buildings, metro tunnels, or roads. To reduce ground movement and protect those existing structures against large deformation, isolation pile is widely used in engineering practices. A series of physical model tests was carried out to investigate the effects of isolation piles on the ground deformation induced by excavating a pit. Digital image correlation (DIC) analysis was employed to study the ground deformation and slip surface under different pile lengths and locations relative to the retaining wall. The results indicate that the ground deformation and the shear band in the ground are less affected by the existence of a pile if the isolation pile’s end is above or slightly extends beyond the slip surface. In contrast, if the isolation pile extends beyond the slip surface sufficiently, even though the ground movement behind the pile is reduced, the settlement of the soil between the pile and retaining wall would be enlarged. Meanwhile, the horizontal deformation shows an arching shape along the depths and has a noticeable value in the middle section of subsoil. The ground deformation behind the isolation pile shows dependence on the pile’s horizontal displacement, regardless of the pile’s length and location. An empirical model is proposed to evaluate the efficiency of isolation piles on settlement protection. The comparison of the prediction and the results from tests and FEA shows a reasonable agreement.

1. Introduction

Due to the rapid expansion of urbanization and space limitation, many pits are inevitably constructed adjacent to existing high buildings, metro tunnels, or roads. The nearby excavation could cause soil unloading and introduce ground movement which threatens the safety of those existing structures [1–7]. To reduce ground movement and protect the existing structures against large deformation, isolation pile is widely used in engineering practices [1, 8]. Understanding the effects of isolation piles on the ground deformation induced by a deep pit excavation is critical for assessing the safety and serviceability of existing structures.

Much research has been performed to study ground or existing structure deformation caused by an excavation [2, 9–18] and tested the slip surface of cohesionless narrow backfill behind rigid retaining walls under translation movement mode. The authors claimed that a backfill width/height ratio of at least 0.5 is required to ensure sufficiently wide backfill in which the slip surface is not much affected by the model boundary. Zhang et al. [16] proposed a two-stage method to estimate the deformation of an existing tunnel due to the excavation of a new pit. In the method, the additional stress induced by the excavation was obtained using the Mindlin solution and then imposed on the existing tunnel resting on the Winkler foundation. Doležalová [9] claimed that due to soil unloading, pit excavation introduced ground deformation and resulted in beneath tunnel heaving. A similar finding was also reported by Zhang et al. [15] and Liang et al. [10]. The effects of isolation piles on the ground deformation...
deformation induced by pit excavation have been also reported in the existing literature. Chen et al. [1] performed a series of three-dimensional numerical simulations to investigate the effects of pit excavation on the nearby ground and existing tunnel deformations. Isolation piles were simplified as cutoff walls and simulated using plate elements. The authors reported that if the cut-off wall experienced large lateral displacement and inflection, it would fail to reduce the horizontal displacement of the exiting tunnel. Xu et al. [11] carried out a series of physical model tests to investigate the influence of the existence of isolation piles on existing tunnel deformation induced by pit excavation. The authors claimed that the performance of the isolation pile depends on the types of isolation piles. For the case of an isolation pile fully embedded into the ground, the horizontal displacement of the existing tunnel could be reduced remarkably, while for the case of an isolation pile partly embedded into the ground, the horizontal displacement would be increased compared with that without an isolation pile.

Even though the effects of isolation piles on the ground or existing structure deformation have been widely reported, those studies are limited to isolation pile spacing and diameters, while the location of the pile is also of importance to ground deformation. There exist few studies on the ground deformation field and failure characteristics of subsoil with isolation pile reinforcement. This paper reports the results of a series of physical model tests on a deep pit excavation. The ground settlement, horizontal displacement, and shear bands due to the excavation of a nearby deep pit are investigated under different pile lengths and locations relative to the retaining wall. The dependence of ground deformation behind isolation piles on the piles’ displacement is discussed. An empirical model is proposed to evaluate the efficiency of isolation piles on settlement protection. The proposed model is validated using finite element analysis (FEA).

2. Physical Model Tests

2.1. Tested Soil. Air-dried sand with a specific gravity of 2.71 was used in this study. The maximum and minimum void ratios are 0.83 and 0.35, respectively. The mean grain size \(d_{50}\) is about 0.5 mm, and the coefficient of uniformity \(C_u = d_{60}/d_{10}\) is about 5.5. The grain size distribution curve of the sand is shown in Figure 1. The internal friction angle \(\phi\) of the sand is determined to be about 44\(^\circ\) at a relative density of 0.46–0.52 by following GB/T 50124-1999 [19].

2.2. Experimental Apparatus. A retaining wall model system as shown in Figure 2 was developed to simulate a deep pit excavation. The system had a length of 0.89 m, a width of 0.4 m, and a height of about 1.1 m for backfill. The system consisted of a rigid steel frame, movable retaining wall, isolation pile, steel structures, motors, and linear variable displacement transducers (LVDTs). The front side of the box was made of toughened glass for measuring soil’s movement. According to Potyondy [20], the soil-steel wall and soil-glass wall interface friction angles were expected to be lower than the internal friction angle of sand; therefore, the model test condition could be assumed as plane strain [21]. The movable retaining wall was connected to two motors through steel struts. The deep pit excavation was achieved by moving the retaining wall using the motors simultaneously. To prevent soil from moving into the rectangular box, as shown in Figure 2(b), a small thickness of brush was used to fill the gap between the retaining wall and the steel box. Shahin et al. [21] employed polyurethane plates to simulate pile foundations as the tests were carried out under two-dimensional plane strain conditions. In this study, a wood plate with a thickness of 15 mm and a width of about 39.5 cm was used to simulate the isolation pile. The elastic modulus of the pile is about \(6 \times 10^6\) kN/m\(^2\) corresponding to that of \(6 \times 10^7\) kN/m\(^2\) in its prototype if a similarity ratio of about 10 is assumed and the accessibility to testing material for simulating the isotropic pile is considered. The value in the prototype has the same magnitude of the order of \(1.276 \times 10^7\) kN/m\(^2\) used by Shahin et al. [21] for pile foundation. This leads to a depth of about 10.5 m for the pit in the prototype, which falls into the depths in practice [22]. Similarly, to prevent soil from moving through the pile, a sponge was used to fill the gap between the pile and the rectangular box. The sponge is very soft, so the pile can move freely.

2.3. Test Program. Soil was poured into the rectangular box from 5 cm height using a large hopper. By keeping a very small pouring height during the process of preparation, uniform medium-dense sand with an average relative density of 0.46–0.55 was obtained. According to Bolton [23], soils show greater dilatancy at lower confining stress. This means that soil in the reduced scale model test under 1g condition would show more dilatancy than that in the field. To minimize such an effect and partially meet similarity conditions, relatively looser sand is expected in model tests as recommended by Zheng et al. [24]. Considering the difficulty to obtain every loose sand in model tests, a relative density of 46–0.55 was used, which is lower than those used in previous research [25].
The deep pit excavation was simulated by moving the retaining wall. This was achieved by moving two rigid structures at the same rate of 1 mm/min via the two motors. A digital camera was used to record the soil deformation during the test process. A total of seven tests were carried out to illustrate the effects of the pile’s length and the location relative to the retaining wall on the ground deformation. The arrangement of physical model tests is summarized in Table 1 and Figure 3(a). The soil surface settlement and the pile’s displacement were monitored using LVDTs with a stroke of 50 mm. Digital image correlation (DIC) analysis was carried out to determine the ground deformation. The analyzed area is presented in Figure 2(a). The details about DIC can be found in the work of the authors in [26].

### 3. Test Results and Discussion

This section presents and discusses ground deformation under different test conditions.

#### 3.1. Greenfield

Figure 4 illustrates ground settlement in sample M0 without an isolation pile. As can be seen, the ground settlement decreases with the distance to the wall. For example, the settlement decreases from 10.5 mm to about 2.9 mm if the distance to the wall increases from 5 cm to 56 cm under the movement of 5 mm. Figure 5 shows the relationship of maximum settlement normalized by the

---

**Table 1: The arrangement of physical model tests.**

<table>
<thead>
<tr>
<th>ID</th>
<th>L (cm)</th>
<th>D' (cm)</th>
<th>Extending beyond the slip surface?</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>M1</td>
<td>40</td>
<td>18</td>
<td>No</td>
</tr>
<tr>
<td>M2</td>
<td>73</td>
<td>18</td>
<td>Yes</td>
</tr>
<tr>
<td>M3</td>
<td>87</td>
<td>18</td>
<td>Yes</td>
</tr>
<tr>
<td>M4</td>
<td>99</td>
<td>28</td>
<td>Yes</td>
</tr>
<tr>
<td>M5</td>
<td>73</td>
<td>33</td>
<td>Yes</td>
</tr>
<tr>
<td>M6</td>
<td>99</td>
<td>33</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Note: The location is relative to the retaining wall.

---

The maximum settlement at the soil surface is in the range of 11.25–13.13 mm, which is comparable with that of 10.5 mm measured using LVDTs as shown in Figure 4. In addition, the settlement obtained using DIC analysis decreases as the distance to the retaining wall increases, which is constant with the
deformation field measured using LVDTs. Such phenomena suggest that DIC analysis can be employed to reproduce the deformation field in this study. Due to lateral unloading, soil moves towards the moveable boundary, showing a negative horizontal displacement value as indicated in Figure 6(b). Significant horizontal displacement is observed at the ground surface, which is consistent with the finding reported by Wang et al. [30]. Figure 6(c) shows the shear strain in the sample. The slip surface initiates at the toe of the moveable retaining wall and develops to the ground surface.

3.2. Isolation Pile above or Slightly Extending beyond the Slip Surface. Figure 7(a) shows the ground settlement in sample M1 with an isolation pile. The pile with a length of 40cm is at a distance of 18cm from the retaining wall. The pile’s end is above the potential slip surface which was determined in sample M0. As can be seen, the ground settlement is comparable with that in sample M0. This means that the ground settlement is not much affected by the existence of the pile. Figure 7(b) shows the soil surface settlement in sample M2 where the pile’s end slightly extends beyond the potential slip surface. As can be seen, the ground surface settlement in this sample is comparable with that in sample M1, which suggests that the pile fails to effectively reduce the settlement of soil behind the pile.

Figure 8 shows the relationship of the ground settlement at about 44cm (location P5 in Figure 3) away from the retaining wall against the movement of the wall. The settlement is normalized by the depth of the retaining wall. As can be seen, for M1 and M2, the settlement at the location is comparable with that in M0. This also suggests that for both cases (M1 and M2), isolation piles fail to reduce the settlement of ground effectively.

Figures 9 and 10 show the displacement field for M1 and M2, respectively. The soil displacement above the slip surface is not much affected by the existence of an isolation pile. This confirms that the isolation piles fail to reduce the settlement of ground effectively. Since the pile slightly extends beyond the slip surface in M2, the soil around the pile’s end cannot efficiently resist the movement of the pile and shows significant deformation as shown in Figure 10, suggesting a local failure. Such a phenomenon means that pouring depth is important to the ground settlement behind the isolation pile and the failure characteristics of subsoil.

3.3. Isolation Pile Extending beyond the Slip Surface Sufficiently. Figure 11(a) shows the ground settlement in sample M3 where the pile is present with a greater length of 87cm. Compared with that in greenfield and samples M1 and M2, the ground settlement behind the isolation pile is notably reduced in sample M3. For example, at the location of about 44cm (P5) away from the retaining wall, the settlement is about 0.17%H, while it is about 0.3%H in sample
M1 under the retaining wall’s movement of 0.5%H (see Figure 8).

The reduction of ground deformation behind the pile can be better observed in Figure 12 which shows the DIC analysis result for sample M3. As shown in Figure 12(a), the vertical settlement shows a reduction around the isolation pile, and much smaller deformation is observed behind the pile. A similar reduction in the ground surface settlement can also be found in the samples M4, M5, and M6 as shown in Figure 13. Since the soil below the slip surface shows very small deformation, it provides additional resistance to the pile to move if the pile’s end is deeper than the potential slip surface.

As shown in Figures 11 and 13, even though the settlement behind the isolation pile is less than that in greenfield (M0), the settlement in front of the pile could be much greater. For example, at the location of 15 cm (13.6% H) to the retaining wall, the ground settlement is less than 9 mm (0.8%H) in the greenfield under the wall’s movement of about 0.5%H, while the value is about 16 mm (1.5%) in sample M3. This may be because if the isolation pile is greater than the potential slip surface, the soil between the wall and pile has a smaller ratio of backfill width to the wall’s depth. According to Wang et al. [30], applying smaller width of backfill results in a greater settlement at the soil surface. Another possible reason would be that the soil-wall interface friction is smaller than soil internal friction. This leads to the soil around the isolation pile moving more freely at the surface of the pile. Even though concrete is widely used for isolation piles in engineering practice where the soil-wall interface friction would be greater than that in this study [20], there exists the possibility that greater settlement is encountered in front of the isolation pile, depending on the soil-wall interface friction and soil properties. Such

Figure 6: The ground displacement in sample M0; (a) the vertical settlement, (b) the horizontal displacement, and (c) the shear strain.

Figure 7: LVDTs measured settlement of the soil surface in samples (a) M1 and (b) M2.
phenomena may indicate that the isolation pile should be carefully considered in the case if both the settlements of soil behind and in front of the pile are of concern in engineering practices.

As shown in Figure 12(b), in sample M3, the horizontal displacement does not monotonically change with the increasing depth but is significant in subsoil, suggesting an arching shape along depths. This is also observed in the samples M4, M5, and M6 as shown in Figures 14(a)–14(c), respectively. This may be because the existence of an isolation pile leads to the soil between the retaining wall and the pile behaving like limited-width soil, where the horizontal displacement in the subground would show an arching shape along the depths as reported by Wang et al. [30]. Such a phenomenon may suggest that a great deal of attention should be paid to lateral deformation and longitudinal moment of the existing tunnels in subsoil if they are within the influenced zone caused by a nearby deep pit excavation where isolation piles are used. The arching shape as shown in Figures 12(b) and 14 may indicate that lateral earth pressure on the retaining wall would show a large value at the middle section of the wall but a very small value at the box corner; i.e., there exists an arching effect behind the retaining wall in an active mode as confirmed by Khosravi et al. [31] and Yang et al. [13].

Figure 12(c) shows the shear strain of sample M3. Unlike those in the samples M0, M1, and M2 as shown in Figures 6(c), 9(c), and 10(c), respectively, where the shear bands are intact and develop to the ground surface along the potential slip surface, the shear band in sample M3 starts at the toe of the moveable retaining wall, intersects with the isolation pile, and then develops along with the pile. Similar
Figure 10: The ground displacement in sample M2; (a) the vertical settlement, (b) the horizontal displacement, and (c) the shear strain.

Figure 11: LVDTs measured displacement of the soil surface in the samples (a) M3, (b) M4, (c) M5, and (d) M6.
Shear bands are also found in the samples M4, M5 and M6 as shown in Figures 15(a)–15(c), respectively. The slip surface is much similar to that of cohesionless narrow backfill behind rigid retaining walls as reported by Yang et al. [13] and Yang and Tang [12]. Since limited deformation is encountered behind the isolation pile, the shear band is not observed.

3.4. Movement of Isolation Piles. Figure 16(a) shows the horizontal displacement of the isolation pile under different conditions. As the retaining wall moves, the isolation pile moves towards the retaining wall in all the samples, and such a horizontal displacement increases as the retaining wall’s movement increases. For example, in sample M2, the horizontal displacement of the pile shows an increase from about 0.1%H (H is the depth of the retaining wall) to about 0.5%H when the retaining wall’s movement increases from 0.1%H to 0.5%H. The horizontal displacements are greater in the samples M1, M2, and M3 than those in the samples M4, M5, and M6. This is because the piles in the samples are much closer to the retaining wall, which leads to a greater volume of soil sliding behind the pile. In addition, for the samples M4, M5, and M6 with isolation piles extending beyond the slip surface sufficiently, the horizontal displacement increases at a greater rate when the wall’s movement is small but at a lower rate if the wall’s movement is greater than a certain value. For sample M6, since the pile...
is far away from the retaining wall and it extends into the slip surface deeply, limited lateral displacement is observed. Figure 16(b) illustrates the vertical settlement of the isolation pile in the samples. The pile’s settlement reflects the settlement of surrounding soil at the pile’s end if the pile is assumed to be rigid. The settlement can be grouped into two clusters depending on whether the pile extends into the slip surface sufficiently or not. For samples, M1 and M2 in which the pile is above or just extends into the slip surface, the pile’s settlement increases with the development of the retaining wall’s movement. As the pile in sample M2 has a greater embedded depth and deeper subsoil shows smaller vertical deformation as shown in Figures 9(a) and 10(a), the pile’s settlement in sample M2 is smaller than that in sample M1.

In contrast, for the samples, M3, M4, M5, and M6 where the pile extends into the slip surface sufficiently, the pile experiences very limited settlement, suggesting that subsoil around the pile’s end experiences little settlement, which is consistent with DIC analysis results as shown in Figures 12(a) and 13.

3.5. Relationship of Ground Settlement with the Pile’s Settlement. It is observed that even though the pile in sample M3 experiences little settlement, the soil behind it shows noticeable deformation as shown in Figure 12. It can also be seen in Figure 17(a) which shows the relationship of ground settlement at about 44 cm (P5) away from the
As can be seen, in samples M1 and M2, the ground settlement increases with the development of the pile’s settlement. However, the ground settles noticeably in the samples M3, M4, M5, and M6 even without the pile’s settlement. Figure 17(b) shows the relationship of ground settlement at the location against the pile’s horizontal displacement. In all the samples, the ground settlement increases with increasing the pile’s horizontal displacement, independent of the pile’s location and length. This may be the reason that the existence of an isolation pile would not reduce the horizontal displacement of the lateral existing tunnel if the pile experienced large lateral displacement and inflection as reported by Chen et al. [1]. Such phenomena suggest that the pile’s horizontal displacement, rather than the pile’s settlement, could be potentially used as an indication for the assessment of ground deformation behind the pile.

4. Prediction of Settlement behind Isolation Piles

This section proposes an empirical model to predict the efficiency of isolation piles to reduce ground deformation.

4.1. Empirical Model

In sample M5, the pile has the same length as that in sample M2 but is located at a farther distance of about 33 cm from the retaining wall. The ground
settlement is reduced in sample M5 but not much affected in sample M2. It can be better seen in Figure 13(b) which shows the vertical displacement field of sample M5. Much smaller deformation is observed behind the pile in sample M5, while the displacement field is not much affected by the existence of the isolation pile in sample M2 as mentioned earlier. Such a phenomenon suggests that the location of the pile has significant effects on ground deformation. Similar effects of the pile’s location can also be found in samples M4 and M6 with the same isolation pile’s length but different locations. For example, as shown in Figures 11(b) and 11(d), noticeable settlement is observed in sample M4 with the isolation pile closer to the retaining wall, while little settlement is found in sample M6. This is because the farther the isolation pile to the wall, the smaller the sliding zone, and the greater the antisliding zone below the potential slip surface, therefore the greater the resistance to sliding. This means that when achieving an economical and effective design, the isolation pile is recommended to be placed far away from the new excavation if possible.

For samples M5 and M6 where the isolation piles are at the same location but with different lengths, as shown in Figures 11(c) and 11(d), the ground settlement behind the pile is insignificant in sample M6 but remarkable in sample M5, suggesting that the longer the isolation pile, the smaller the deformation behind it.

To consider the effect of the pile’s length and location on ground settlement, an influencing index (f) is defined as

\[ f = D' \times \frac{L}{(D \times H)} \]  

(1)

where \( D' \) is the distance of the pile to the retaining wall; \( L \) is the length of the pile; \( D \) is the width of the slip at the ground surface; \( H \) is the depth of the retaining wall (see Figure 3). \( D \) is affected by the depth of the pit and the soil parameter and can be expressed as

\[ D = \frac{H}{\tan(\pi/4 + \phi/2)} \]  

(2)

so, (1) can be rewritten as

\[ f = \frac{D' \times L \times \tan(\pi/4 + \phi/2)}{H^2} \]  

(3)

The settlement reduction coefficient \( \beta \) is introduced to evaluate the efficiency of isolation piles on settlement protection. It is defined as the ratio of the settlement (\( \omega \)) of concern behind the isolation pile to that (\( \omega_0 \)) in the greenfield.

\[ \beta = \frac{\omega}{\omega_0} \]  

(4)

Figure 18(a) shows the relationship of the reduction coefficient \( \beta \) with the influencing index (f) in the model test. The settlements at P4 and P5, which are 37 cm and 44 cm away from the retaining wall, respectively, are of concern. As shown in Figure 2, there are three points (P4–P6) behind the piles. However, very limited settlement is found at P6. Therefore, only P4 and P5 are presented in Figure 18. As can be seen, the settlement coefficient \( \beta \) almost linearly decreases as the influencing index (f) increases and can be expressed as

\[ \beta = \alpha f + 1 \]  

(5)

where \( \alpha \) is the fitting coefficient, which is \(-1.45\) for the test condition.

4.2. Application of the Proposed Model. As the physical model tests were performed at a reduced scale under 1g condition, this may limit the application of the proposed model. To consider this, by using Plaxis 2D, FEA was conducted at an engineering scale to validate the proposed model. The dimension of the model was ten times that in the physical model tests, which leads to the depth of the pit being about 10.5 m. FEA was performed under a plane-strain condition, and the boundary condition was similar to that in the model tests. Dry sand was simulated using a hardening soil model with small-strain stiffness (HSS). The model parameters were calibrated using triaxial test results and are summarized in Table 2. The isolation piles were simulated using plate elements. A linear constitutive model was used to simulate the pile with an EA of 10^{10} kN/m.

Figure 5 compares the simulated result with that observed in the M0 test. As can be seen, the simulated result is comparable with the test result. This suggests that FEA is credible. Figure 18(b) shows the simulated results which are comparable with the prediction and the physical model test results. This means that the proposed model can be used to predict the efficiency of the isolation pile in settlement protection.

5. Summary and Conclusions

A series of 1g physical model tests was performed to investigate the effects of isolation piles on ground deformation due to a deep pit excavation. The deformation field, failure characteristics of subsoil, and the displacement of the isolation pile were presented and discussed under different pile lengths and positions relative to the retaining wall. From the limited number of tests, it was found that

(1) The ground settlement behind the isolation pile highly depends on whether the pile extends beyond the slip surface sufficiently or not. If the pile does not extend beyond the slip surface sufficiently, the ground settlement behind the isolation pile is less affected by the existence of the isolation pile. The horizontal displacement in the ground monotonously decreases with the depth increasing and would be similar to that in the greenfield. In contrast, if the pile extends beyond the slip surface sufficiently, the ground settlement behind the pile is decreased greatly. For example, under the wall’s movement of about 0.5%H, the ground settlement at the location of 13.6%H to the retaining wall is less than 0.8%H in the greenfield, while the value is about 1.5%H in sample M3 with a pile extending beyond the slip surface sufficiently. The horizontal displacement mainly develops in the soil between the retaining
wall and pile and shows an arching shape along depths, suggesting that a significant value would be encountered in subsoil.

(2) Even though increasing the buried depth of the isolation pile would reduce the settlement of soil behind the pile, the settlement of the soil between the pile and retaining wall would be enlarged. This may be because the existence of an isolation pile decreases the ratio of backfill width to the depth of the retaining wall and/or the soil-wall interface friction is smaller than soil internal friction.

(3) The ground settlement behind the isolation pile shows dependence on the pile’s horizontal displacement and is not much affected by the settlement of the pile, regardless of whether the pile extends beyond the slip surface or not.

(4) An empirical model is proposed to evaluate the efficiency of isolation piles in settlement protection. The comparison of the prediction and the results obtained from model tests and FEA shows a reasonable agreement.

**Data Availability**

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This work was supported by the National Natural Science Foundation of China (No. 51968005), the Natural Science Foundation of Guangxi Province of China (No. 2019GXNSFBA185038), the Interdisciplinary Scientific Research Foundation of GuangXi University (No. 2022CB0006), and the Innovation Project of Guanx Graduate Education (YCSW2022073). The first author would like to thank Dr. Zhiyong Liu from the University of New South Wales for his invaluable guidance on the tests, paper writing, and editing.

**References**


