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ORIGINAL PAPER

Puncture Behavior of HDPE Geomembranes with Defects: Laboratory Investigation

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Abstract

In this study, a series of puncture tests were conducted to investigate the puncture behavior of defective geomembranes with different types of defect, including crack, scratch and circular hole. The rupture patterns of geomembranes with different types of defect were summarized to further understand the rupture behavior of geomembranes. In addition, the influences of the thickness of geomembranes and the size of defects were evaluated. The results show, for defective geomembranes, the puncture resistance and puncture displacement are closely related to the length of the crack, the scratching depth and the diameter of circular hole, and some mathematical fitting models can well predict the relationship between the puncture resistance and defect size. The expansion of the defect to relatively large size can be observed during puncturing, which significantly reduces the puncture resistance of geomembranes. The present laboratory study provides a great reference value for the practical design of protective layer to avoid puncturing of geomembranes or for minimizing the adverse effects of existing defects of geomembranes.

Keywords Geosynthetics · Geomembranes · Puncture test · Defect type · Puncture resistance · Rupture patterns

Introduction

Geomembranes are made from relatively thin continuous polymeric sheets or asphalt impregnated of geotextiles, elastomer or polymer sprays. Due to its low permeability, a geomembrane mainly acts as synthetic membrane liner or barrier used to control fluid (or gas) migration in the environmental, hydraulic, geotechnical, and transportation-engineered projects [1, 2]. In addition, the stable chemical properties, great corrosion resistance and relatively mature application experience are remarkable advantages of geomembranes [3]. It is well recognized that geomembranes can effectively work with composite liners [4–6]. Along with many other considerations involved in the engineered design, the puncture of geomembranes is a major threat to their integrity which can reduce their effectiveness as barrier materials. The geomembrane puncture may occur during the placement of the overlying drainage material mixed with a complex composition of stones, sticks or other debris when the vertical loads are imposed [7]. Nosko and Touze-Folz [8] reported that 71.2% of the geomembrane damage is caused by stone puncture. Once puncture-induced defects occur in geomembranes, it is difficult to ensure the effectiveness of the impervious barrier of engineered facility, e.g., for a landfill, waste transport through geomembranes can occur through defects and the surrounding environment will be contaminated [9–11]. Thus, the investigation of puncture behavior of geomembranes is significant for practical engineered design, and physical experiments are typically used to evaluate the puncture behavior of geomembranes. Brachman and Sabir [12] assessed the possible puncture of a 1.5-mm-thick HDPE geomembrane under compacted clay liner with intentionally placed stone particles through physical experiments. The influences of applied pressure, stone size and stone burial depth on the geomembrane strains were examined, and several suggestions were provided to avoid the geomembrane puncture. Connor et al. [13] developed a design procedure for the puncture behavior of polyvinyl chloride (PVC) geomembranes using truncated cone test. The results indicated that the puncture resistance of PVC geomembranes increases with increasing thickness. In

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addition, the PVC geomembranes exist greater puncture resistance than the polyethylene geomembranes even with thinner thickness. Brachman et al. [14] conducted preliminary experiments to examine the puncture behavior of HDPE geomembranes with coarse, poorly graded granular materials above and below when subjected to vertical pressure. It was observed that many puncture holes were developed during the test, and the protective layer was ineffective at limiting tensile strains as the short-term tensile strains exceeded the upper bound of proposed allowable limits by a factor of nearly 5. Xue et al. [15] investigated the puncture behavior of the HDPE geomembranes under different corrosion conditions. The results showed that the tension and puncture failure of the HDPE geomembranes are progressive. As corrosion time increases, puncture strength decreases and corresponding deformation increases, and the increase of corrosion temperature induces the decrease of geomembrane tensile strength.

Typically, physical experiments are used to evaluate the puncture behavior of geomembranes. Some external factors, e.g., the temperature [16–18], types of contacts [19] and protective layer [20], have been considered in these experimental research. However, there is a paucity of data on how the possible existing defects, such as the damage induced by operation or the long-term stress crack [21–25], affect the puncture behavior of geomembranes. Once defects occur in geomembranes, the behavior of punctured geomembrane might greatly differ from that of intact geomembranes, which is worth investigating. Considering the CBR (California Bearing Ratio) puncture test, an international standard test to measure the force required to puncture geosynthetics, can provide reasonable evaluation of puncture resistance [26–28], this study conducted a series of CBR tests to investigate the puncture behavior of geomembranes with different types of defect including crack, scratch or circular hole. The influences of thickness of geomembranes and the size of different defects in geomembranes on the mechanical behavior were explored in the puncture test. The experimental data of puncture resistance versus defect size are fitted by different mathematical models. The typical deformation process was postulated to further understand the rupture behavior.

Laboratory Tests

Test Apparatus

In this study, a constant-rate-of extension (CRE) electronic universal testing machine was used to conduct the short-term puncture tests of geomembranes. The geomembrane specimens were clamped by a specific clamping apparatus consisting of two concentric plates with an internal diameter of 150 mm to avoid slippage during the tests. The load range of the machine is 0 ~ 100 kN and the loading rate can be set from 0.1 to 500 mm/min. A steel plunger with a flat diameter of 50 mm was used to apply the vertical load against the center of the specimen according to ASTM D6241 [29]. A personal computer equipped with an autographic recorder was used to store and manipulate the experimental data to draw the plots of resistance versus displacement.

Test Materials and Schemes

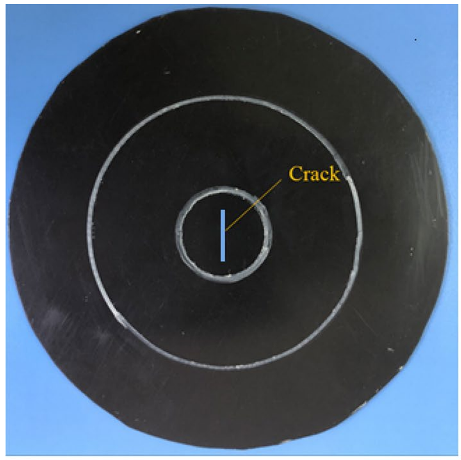
Smooth HDPE geomembranes with a nominal thickness of 2.0 mm were used in this study. The index properties of geomembranes used are given in Table 1. To investigate the puncture behavior of geomembranes with defects, three types of defect, including circular hole, crack and scratch, were produced in the center of each specimen as shown in Fig. 1. The specimens were prepared with a diameter of 250 mm so that the edge of specimens can extend beyond the edge of the clamp by 50 mm in all directions.

In this study, a series of puncture test were conducted to investigate the puncture behavior of 2.0-mm-thick geomembranes with different types of defect. Different defect sizes were also considered for geomembranes with a circular hole or crack. The length of the crack was set as 6 mm, 12 mm, 24 mm, and 48 mm, and the diameter of the circular hole was set as 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm, respectively. For a geomembrane with a scratch, the depth of the scratch was set as 0.5 mm, 1.0 mm, and 1.5 mm, which accounted for 25%, 50%, and 75% of the thickness of geomembranes (2 mm), respectively. Figure 2 shows the cross-sections of geomembrane specimens with a crack or scratch. Table 2 presents the test schemes. A loading rate of 20 mm/min was chosen for all specimens.

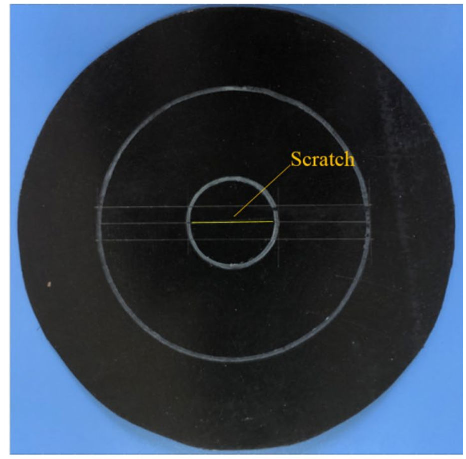
Table 1 The index properties of the geomembranes

Nominal thickness (mm)	Density (g/cm^3)	Tensile strength (kN/m)	Tear resistance (N)	Break elongation (%)	Puncture resistance (kN)	Puncture displacement (mm)
2.0	0.94	20.3	249.5	621	3.81	41.17

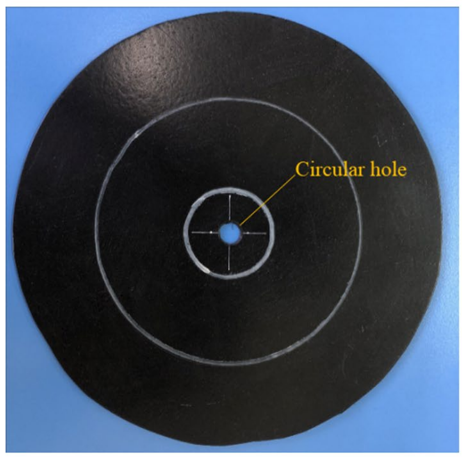
Fig. 1 Geomembrane specimens with different defects



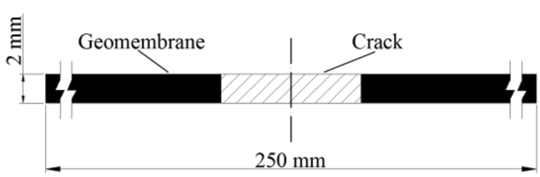
(a) Crack



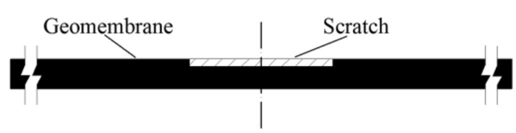
(b) Scratch



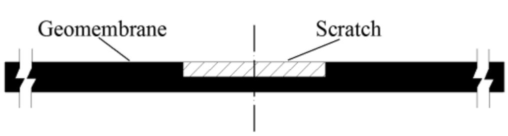
(c) Circular hole



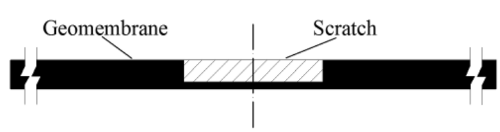
(a) Crack



(b) Scratch (H=0.5 mm)



(c) Scratch (H=1.0 mm)



(d) Scratch(H=1.5 mm)

Fig. 2 Cross-sections of geomembrane specimens with defects

Table 2 Test schemes

defect type	Thickness t_{GM} (mm)	Defect size L/D (mm)	Scratching depth H (mm)
Crack	2.0	L=6, 12, 24, 48	–
Scratch	2.0	L=48	0.5, 1.0, 1.5
Circular hole	2.0	D=5, 10, 15, 20	–

Test Results and Discussion

Geomembranes with Crack

Figure 3 presents the final rupture patterns of geomembrane specimens with different size cracks. The specimens with the cracks of 6 mm and 12 mm show similar failure characteristics compared with the intact specimen, and the crack of 12 mm expanded during the test. For cracks of 24 mm and 48 mm, both the expansion of crack and the breakthrough of plunger occur during the tests.

Table 3 presents puncture resistance and the corresponding displacement from the experimental curves of geomembrane specimens with different size cracks. The crack evidently changes the puncture behavior of the geomembrane. Both the puncture resistance and corresponding displacement decrease with increasing length of the crack. Further, for the case that the plunger passes through the specimen, e.g., for the specimen with a crack of 48 mm, the puncture resistance exists obvious drop compared with other specimens with a smaller length of the crack. Thus, it is essential to take effective measures to prevent geomembranes from cracking or to remediate the geomembranes in time if crack with large size occurs.

Figure 4 shows the plot of puncture resistance versus length of crack in geomembranes. As can be seen, the data points exhibit an evident decreasing trend that is well fitted with a quadratic curve, i.e.,

Table 3 Puncture resistance and puncture displacement of geomembrane with cracks

Length of the crack (mm)	0 (intact)	6	12	24	48
Puncture resistance (kN)	3.81	3.72	3.62	3.32	1.62
Puncture displacement (mm)	41.17	39.35	38.39	32.60	23.41

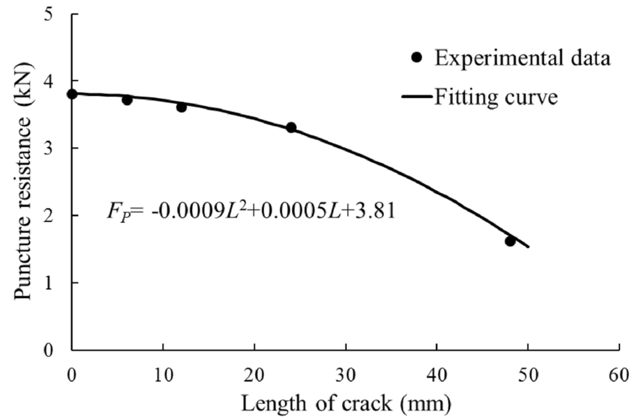


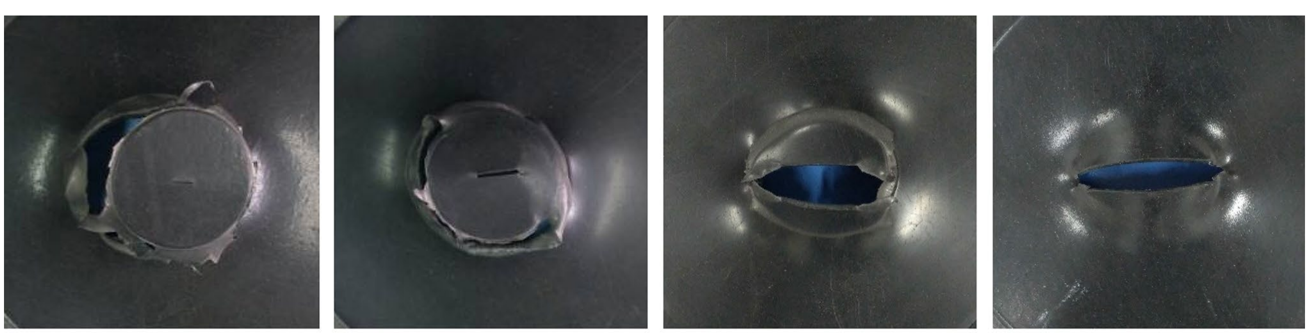
Fig. 4 Simulation of puncture resistance for geomembranes with different cracks

$$F_P = -0.0009L^2 + 0.0005L + 3.81, \quad (1)$$

where L is the length of crack in geomembranes.

Geomembranes with Scratch

Figure 5 shows the final rupture patterns of geomembrane specimens with different depth scratches. It indicates that the scratch with a depth of 0.5 mm has no obvious influence on the specimen (T = 2 mm) after the puncture. For



(a) L=6 mm **(b)** L=12 mm **(c)** L=24 mm **(d)** L =48 mm

Fig. 3 Rupture patterns of geomembrane specimens with different crack sizes

Fig. 5 Rupture patterns of geomembrane specimens with different scratch depths

Table 4 Puncture resistance and puncture displacement of geomembrane with scratches

Scratching depth (mm)	0 (intact)	0.5	1.0	1.5
Puncture resistance (kN)	3.81	3.43	3.31	1.89
Puncture displacement (mm)	41.17	39.77	38.40	26.75

the depth of 1 mm, however, the scratch develops during puncturing, but does not evolve to an entire crack, which can be found in Fig. 5b. For the depth of 1.5 mm, the scratch of the geomembrane develops into a crack and the plunger finally passes through the crack. In practical engineered project, the scratched may be ignored because they do not damage the geomembranes. However, the experimental data in this study indicate that a scratch that is deeper than 50% of the thickness of geomembranes may develop into a crack under high normal pressure resulting in the leakage of gas or liquid. Thus, the scratches in geomembranes should be emphasized and need to be patched with careful detection.

Table 4 shows the puncture test results for geomembranes with different scratch depths. As scratches with depths of 0.5 mm and 1.0 mm do not affect the final failure characteristics of the geomembrane specimens, there are little decreases of the puncture resistances and puncture displacements. For a scratch with a depth of 1.5 mm, however, the puncture resistance and puncture displacement evidently drop because an entire crack finally occurs. Compared with the crack, the scratch with relatively shallow depth has little influence on the puncture behavior of geomembranes. If the scratch is deep, it may develop to a crack, and the geomembranes are easily punctured by plunger through the defect. As shown in Fig. 6, the puncture resistance of geomembranes with

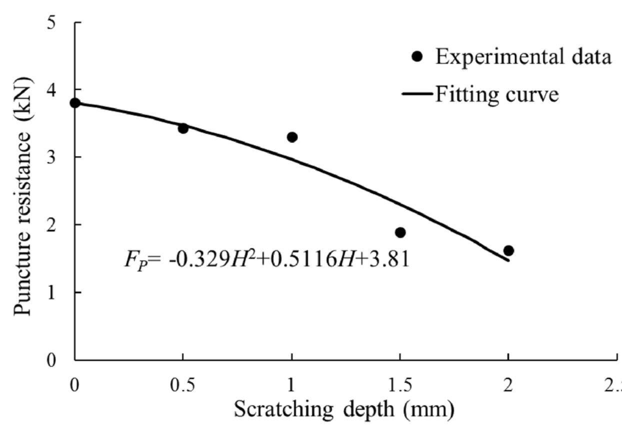


Fig. 6 Simulation of puncture resistance for geomembranes with scratch

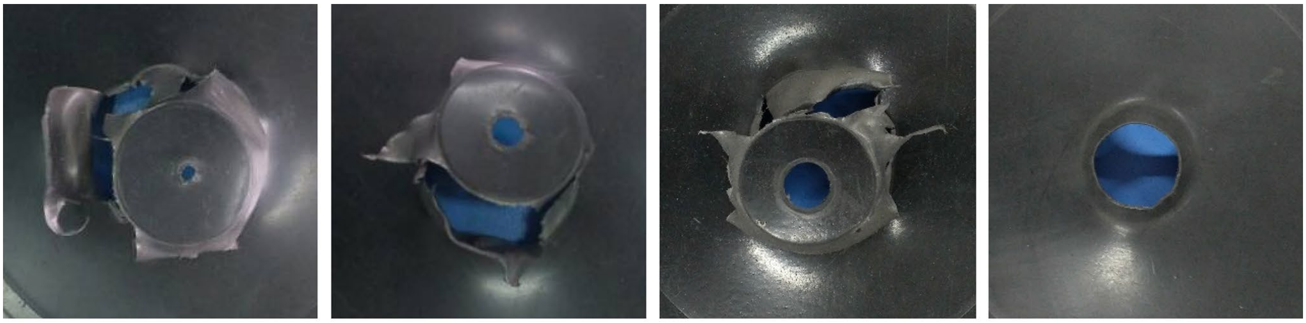
scratch with different depths can also be determined using a quadratic function:

$$F_P = -0.329H^2 + 0.5116H + 3.81, \quad (2)$$

where H is the scratching depth.

Geomembranes with Circular Hole

Figure 7 presents the final rupture patterns of geomembrane specimens with different sizes of circular hole. For diameters of 5 mm and 10 mm, the size of the defect is relatively small compared with the diameter (50 mm) of the plunger. Thus, the defect has little influence on the puncture characteristics of the specimen, and the rupture still occurs at the edge of the plunger (Fig. 7a, b). For the diameter of 15 mm, apparent expansion of the circular



(a) D=5 mm **(b)** D=10 mm; **(c)** D=15 mm **(d)** D=20 mm

Fig. 7 Rupture patterns of geomembrane specimens with different diameter circular hole

Table 5 Puncture resistance and puncture displacement of geomembrane with circular holes

Diameter of circular holes (mm)	0 (Intact)	5	10	15	20
Puncture resistance (kN)	3.81	3.62	3.64	3.50	2.23
Puncture displacement (mm)	41.17	33.62	35.16	34.99	22.36

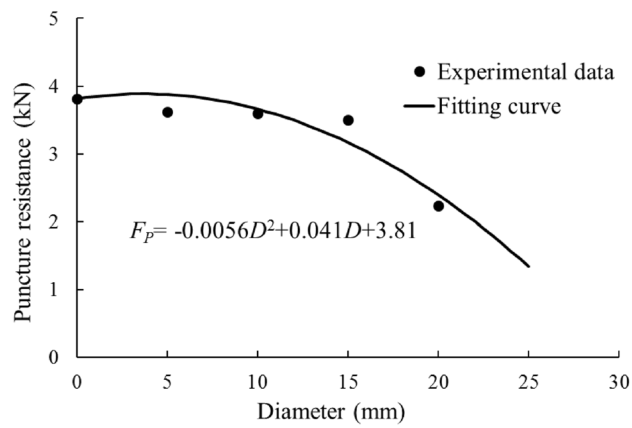


Fig. 8 Simulation of puncture resistance for geomembranes with circular hole

hole can be observed, but the puncture of the specimen is still similar to the intact one (Fig. 7c). For the diameter of 20 mm, the rupture pattern shown in Fig. 7 d is absolutely different with other three circle holes with a smaller diameter. The circular hole evidently expands to a greater one, and the plunger passes through the defect at the end of puncture.

Table 5 lists the puncture resistance and the corresponding displacement of each geomembrane specimen with different diameter circular holes. The puncture resistance and puncture displacement decrease when circular holes occur in geomembranes and exhibit little difference for circular holes with diameters of 5 mm, 10 mm, and 15 mm. The circular hole of 20 mm severely weakens the anti-puncture ability of the geomembrane, and the test curve shows a significant decrease compared with other specimens. If the size of the hole in geomembranes is relatively smaller than the size of puncturing object in contact with geomembranes, the puncture behavior will not be obviously affected. However, once the size of a hole is approximately 40% of the stone size, the hole may expand and the puncturing object will pass through geomembranes. Thus, the occurrence of the hole, especially a relatively large one, should be avoided during the installation and operation. Figure 8 shows that a fitting curve with a decreasing trend is in good agreement with the experimental data of the puncture resistance for geomembrane specimen with circular hole.

Conclusions

In this study, a series of puncture tests were conducted to evaluate the puncture behavior of defective geomembranes with different types of defect (crack, scratch and circular hole). The influence of size of defects on the puncture behavior were the main foci, and the empirical relationships between puncture resistance and defect size are established using different quadratic curves for different defect types of geomembranes. Based on the results and discussion presented herein, some practical conclusions can be drawn.

1. The puncture resistance and puncture displacement indicate decreasing trend with increasing length of the crack in geomembranes. For the geomembrane specimens with a short crack (e.g., L = 6 mm or 12 mm), similar punc-

ture behavior occurs compared with the intact geomembrane. If the crack is long ($L = 24$ mm or 48 mm), it will expand under the applied puncture force, and the plunger finally passes through the defect with a drop of puncture resistance and puncture displacement.

2. For the geomembrane with scratches, different depths of the scratch have different influence on the puncture results. For the depth of 0.5 mm (25% of the thickness of the geomembrane), there is little difference for rupture pattern of the specimen after the test, and only a little decrease of the puncture resistance and puncture displacement occurs. For the depth of 1.0 mm (50% of the thickness of the geomembrane), the puncture resistance and puncture displacement are less than those of the specimen with a 0.5-mm-deep scratch, and the development of the scratch to a crack can be observed during the test. For the depth of 1.5 mm (75% of the thickness of the geomembrane), the scratch develops to an entire crack, and the plunger finally passes through the defect. Thus, there is a sharp decrease of the puncture resistance and puncture displacement for the geomembrane with a relatively deep scratch, and it is necessary to patch the scratch to avoid the development of defect under high pressure.
3. The size of the circular hole has different influence on the puncture behavior of geomembranes. For the circular hole with small diameter, e.g., 5 mm, the puncture resistance, the puncture displacement and rupture pattern are basically the same as those intact geomembranes. For the diameters of 10 mm and 15 mm, the expansion of the circular hole can be observed during the tests. In addition, as the hole with a diameter of 20 mm is easy to expand under the puncture force, the plunger directly passes through the circular hole with local large deformation of the geomembrane. There is an evident drop of the puncture resistance and puncture displacement for the specimen with a circular hole with the relatively large diameter (e.g., $D = 20$ mm).

In summary, the defects (crack, scratch or circular hole) reduce puncture resistance of geomembranes. Particularly, the puncture resistance significantly decreases for a relatively large defect in the geomembranes. Thus, some protective measures (e.g., overlying a layer of geotextile or fine sand) may be also adopted to avoid the occurrence of further damage or to minimize the adverse effects of the existing defects.

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Author Contributions Conceptualization, writing—review and editing, supervision, project administration, funding acquisition: CWJ; methodology, formal analysis, writing—original draft preparation, writing—review and editing: ZCH, WH, GLY, and WMM.

Data Availability In this paper, all data and models used during the study appear in the submitted article.

Declarations

Conflict of Interest The authors declare no conflict of interest.

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