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DOI
10.1007/978-3-030-77234-5_37

Publication date
2022

Document Version
Final published version

Published in
Advances in Transportation Geotechnics IV - Proceedings of the 4th International Conference on Transportation Geotechnics

Citation (APA)
Jing, G., Aela, P., Zhou, Q., & Jia, W. (2022). Steel Slag Aggregate Characteristics Evaluation as Railway Ballast. In E. Tutumluer, S. Nazarian, I. Al-Qadi, & I. I. A. Qamhia (Eds.), *Advances in Transportation Geotechnics IV - Proceedings of the 4th International Conference on Transportation Geotechnics* (pp. 449-460). (Lecture Notes in Civil Engineering; Vol. 165). Springer. https://doi.org/10.1007/978-3-030-77234-5_37

Steel Slag Aggregate Characteristics Evaluation as Railway Ballast

Guoqing Jing, Peyman Aela, Qiang Zhou, and Wenli Jia

Abstract The use of recycled materials is a new tendency in the field of railway engineering. Steel slag aggregates (SSA) are one of the recycled materials derived from the steel industry. The application of SSA in ballasted railway tracks requires mechanical examination. In the present paper, the shear behavior of the ballast layer constructed by SSA and basalt aggregates was considered to assess the use of SSA as a substitution for basalt. In this regard, a series of large-direct shear tests were performed on basalt and SSA under various normal stresses. Based on the results, basalt aggregates have higher shear resistance than SSA for all normal stress. However, steel slag has sufficient shear strength as well as particle abrasion resistance. Overall, it was proven that the SSA has suitable stability against shear forces that could be applied on railway ballast.

Keywords Shear resistance · Large-direct shear test · LA abrasion · SSA · Basalt

1 Introduction

In terms of the mitigation of environmental issues, the application of recycled materials in construction has grown considerably. The use of different types of recycled materials was reported by Prezzi [1], including tire rubber, fly and bottom ash, blast furnace slag, steel slag, cement kiln dust, glass, reclaimed asphalt pavement (RAP), and silica fume. Steel slag aggregates (SSAs) are one of the materials widely used in civil structures. Chemical properties of SSA were provided by Yildirim [2]. From a durability and economic perspective, the application of steel slag as fine aggregates in concrete and asphalt mixtures was a new approach investigated by many researchers [3–8]. On the other hand, due to the high density, better drainage properties, rough

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E. Tutumluer et al. (eds.), *Advances in Transportation Geotechnics IV*,
Lecture Notes in Civil Engineering 165,
https://doi.org/10.1007/978-3-030-77234-5_37

texture, and high resistance to changes in temperature, the SSA could also be used in railway superstructure applications [9].

Steel slag is a by-product of steel making formed during the separation of the molten steel from impurities in steel-making furnaces by one of the following methods:

- Basic Oxygen Furnace (BOF), where iron is transformed into steel, with the injection of oxygen to hot liquid metal, scrap, and fluxes.
- Electric Arc Furnace (EAF), where steel is produced by melting scrap steel, with melting the cold metal scrap.

In the process of BOF and EAF, 25%–35% and 100% old steel (scrap) is used for steel-making slag, respectively [10]. Although a massive amount of steel slag is utilized in the USA and European countries, only 22% of the produced slag is reused in the industry of China [11], and about 70 million tons of steel slag is released in China every year [12]. To produce SSA, firstly, the raw material (below 350 mm) enters the vibrating feeder (Fig. 1). Particles with a size of < 100 mm and > 100 mm are transferred to the cone crusher and jaw crusher, respectively. Afterward, material crushed in the jaw crusher move to the cone crusher for secondary crushing. Throughout this process, iron material is removed by the iron remover. Subsequently, the iron remover is screened by the vibrating screen, and the return cone crusher of more than 10 mm continues the aforementioned procedure, and particles with the size of lower than 10 mm are accumulated as the final product output [13].

CaO and SiO_2 are the main components of SSA for different processes of production, such as BOF, EAF, and Ladle slag [14]. As shown in Table 1, SSAs have approximately the same mechanical behavior as mineral aggregates [12, 15]. The higher density of particles could be a positive characteristic to enrich track stability. As mentioned earlier by Guo et al. [12], the type of treatment, including layer pouring,

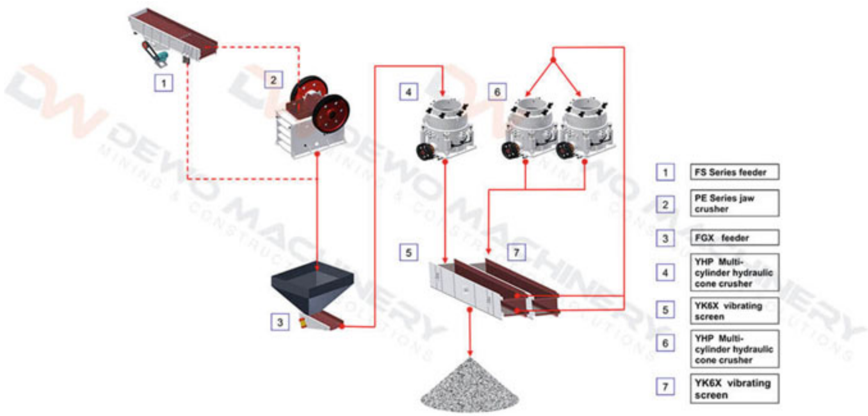

Fig. 1 Process of steel slag production [13]

Table 1 Mechanical properties of steel slags versus mineral aggregates [12]

Properties	Steel slag	Basalt	Granite	Greywacke
Particle density	3.1–3.7	2.8–3.1	2.6–2.8	2.7
Comprehensive strength	200	300	120	200
Impact value	17	17	–	20
Resistance to polishing (PSV)	54–57	50	45–55	56
Water absorption	0.2–1.0	< 1.0	0.3–1.2	< 0.5
Resistance to freezing	< 1.0	< 1.0	0.8–2.0	< 0.5

rotary cylinder, self-disintegrated by steam, and air-granulated, has a significant impact on the stability of steel slag production.

SSA is widely used in asphalt aggregate, cement, agriculture amendment, railroad, road base, and gabions [9, 16]. So far, SSAs have a high proportion of road construction by 67% [17]. In the current study, the application of steel slag was considered as a substitution of mineral aggregates in the ballast layer. The application of SSA in ballast tracks will contribute to sustainable development, decreasing the accumulation of waste material in the environment. However, less than 1% of SSA was used as ballast material in 1996–2001 [17]. From the environmental perspective, the radioactivity of slag does not influence the health condition of humans in case of using outdoor construction [18]. The hardness and rough surface of SSA are effective physical characteristics be likely to enrich ballast lateral resistance so that the angle of internal friction and hardness of SSA on the Mohs scale is in the range of 45–50 and 6–7, respectively [14]. However, the application of SSA as an unbound layer should fulfill the requirements of EN 13242-2013-05 [19]. On the other hand, in order to examine the stability of a layer constructed by SSA, volume expansion of the unbound granular material should be checked based on physical properties of a given slag according to the following formula:

$$F \leq k\frac{(\gamma_s - \gamma_0)}{\gamma_s^2} \times 100\% \tag{1}$$

where F is the hydratable oxide content of the slag; γ_s is the specific gravity of the slag; γ_0 is the bulk relative density of the slag, and k is a constant associated with the physical characteristics of the slag. If the hydratable oxide content (F) is lower than the right-hand term, aggregates will not extend in the case of using as granular material. It should be noted that the electrical resistance of SSA does not cause disturbance for the railway track circuit [20]. However, for the safety and reliability of railway operation, it is not recommended the furnace slag to be used in poor drainage or heavy rain conditions in case of track circuit problems.

The mechanical behavior of SSA should be assessed in order to apply to railway ballast tracks. Cyclic and monotonic triaxial tests on SSA with 1/3 of actual ballast size had higher strength and lower deformation than granite particles, as reported by

Delgado [21]. In other research, the lateral resistance of the ballast layer is another factor that should be considered in terms of track buckling. In this regard, different components influence the lateral resistance, such as sleepers, ballast, and fastening system [22]. The replacement of stone aggregates with SSA could be an economical and environmental solution. The field test result conducted by Esmaeili et al. [23] confirmed 27% growth in lateral resistance of track due to the replacement of limestone with SSA. In addition, the application of SSA could increase the rail support modulus by 64% in comparison with the limestone ballast track. There was a reduction in the contact stress between sleeper and slag ballast due to the high durability of SSA [24].

The shear behavior of the ballast layer is an important parameter that influences track lateral resistance. So far, several studies have been conducted on the shear behavior of ballast particles using the large-direct shear test. Large-direct shear tests carried out on clean and contaminated ballast with and without reinforcement were presented in Table 2. Due to the various sizes of the shear box, ballast gradation, and type of material, the shear resistance of ballast aggregates is variable.

So far, there is no experiment to evaluate the shear behavior of steel furnace slag using the large-direct shear test. Although adding 10% rubber crumb to the mixture of steel slag-coal wash (SFS-CW) causes an increase in the damping of ballast layer and consequential reduction in the ballast breakage, there is a reduction in the shear resistance of the mixture [33]. Therefore, the application of the steel slag without rubber crumb was preferred in this study in order to improve the shear behavior of ballast track. In this regard, the comparison between steel slag and basalt aggregates

Table 2 Different authors performed shear box tests

References	Test type	Box size (cm^3)	Material	Maximum normal stress (kPa)	Shear resistance (kPa)	Friction angle (°)
Huang [25]	Simulation	30 × 30 × 20	Granite	200	283	46.6
Dissanayake [26]	Experiment	40 × 30 (cylindrical)	Biotite gneiss	92	150	58 - 65
Liu [27]	Experiment	30 × 30 × 20	Granite	200	400	55 - 64
Jing [28]	Experiment	30 × 36 × 24	Basalt	200	230	_
Danesh [29]	Experiment	31 × 31 × 21	Andesite	183	280	55–65
Toloukian [30]	Experiment	44 × 44 × 36	Dolomite limestone	200	280	53
Indraratna [31]	Simulation	30 × 30 × 20	_	75	120	–
Sweta [32]	Experiment	45 × 45 × 30	Granite	70	126	64.7–66.5

was examined in terms of shear resistance by means of large-direct shear tests. In addition, the hardness of SSA was measured by the Los Angeles abrasion test in order to determine the actual physical parameters of SSA in this research. The range of LAA value for SSA is 15–20, as already proposed by Morata et al. [34].

2 Material Properties

In order to survey the use of SSA as a substitution of common ballast aggregates, Electric Arc Furnace (EAF) and basalt aggregates were tested (Fig. 2a). According to China National Standard TBT 2140, both types of material were provided with the same particle size distribution, as shown in Fig. 2b. In order to evaluate the durability of SSA, Los Angles Abrasion (LAA) test was conducted based on TB/T 2328.1 and ASTM C535-96 (Table 3). The results indicate that basalt and steel slag abrasion

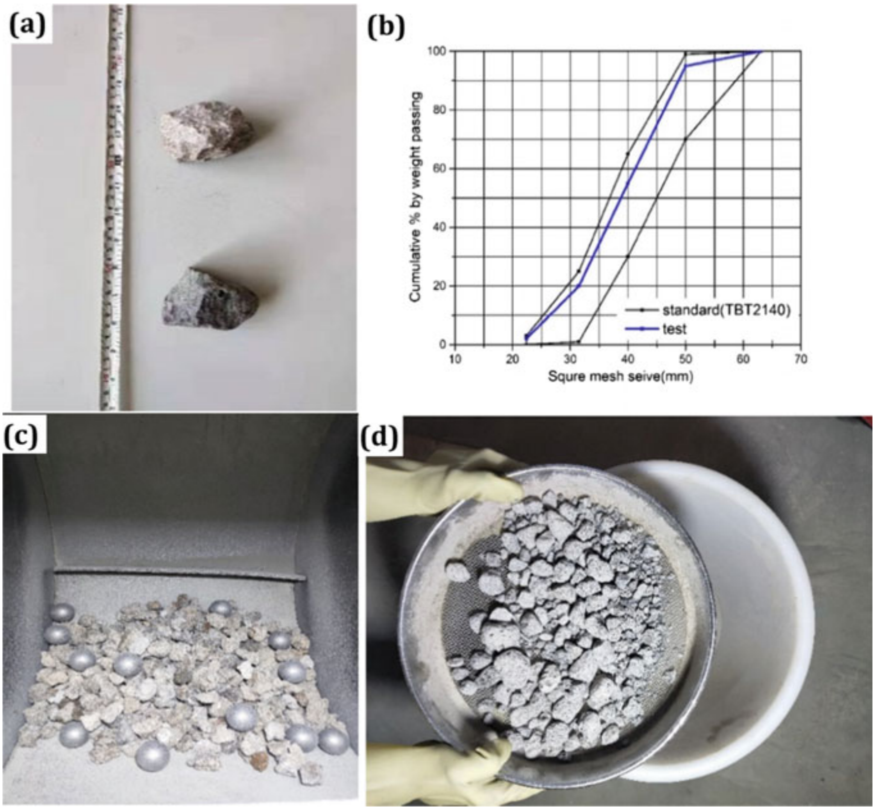

Fig. 2 **a** Sample of basalt and SSA, **b** particle size distribution, **c** particle abrasion after LAA test, **d** sieving particles

Table 3 Results of LAA tests on basalt and SSA

	China National Standard (20–40)		ASTM (31.5–50)	
	Basalt	SSA	Basalt	SSA
LAA (%)	6.0	29	4.93	24.4

resistance is in good agreement with the results of previous studies [14, 35] and meets the requirement of the American Railway Engineering and Maintenance of Way Association (AREMA) [36]. The lower LAA value of basalt could be attributed to the high strength of basalt material in comparison with SSA.

3 Test Procedure

Direct shear strength tests were performed on the reconstituted basalt and steel slag aggregates. Figure 3a shows the large shear box equipment comprised of two boxes

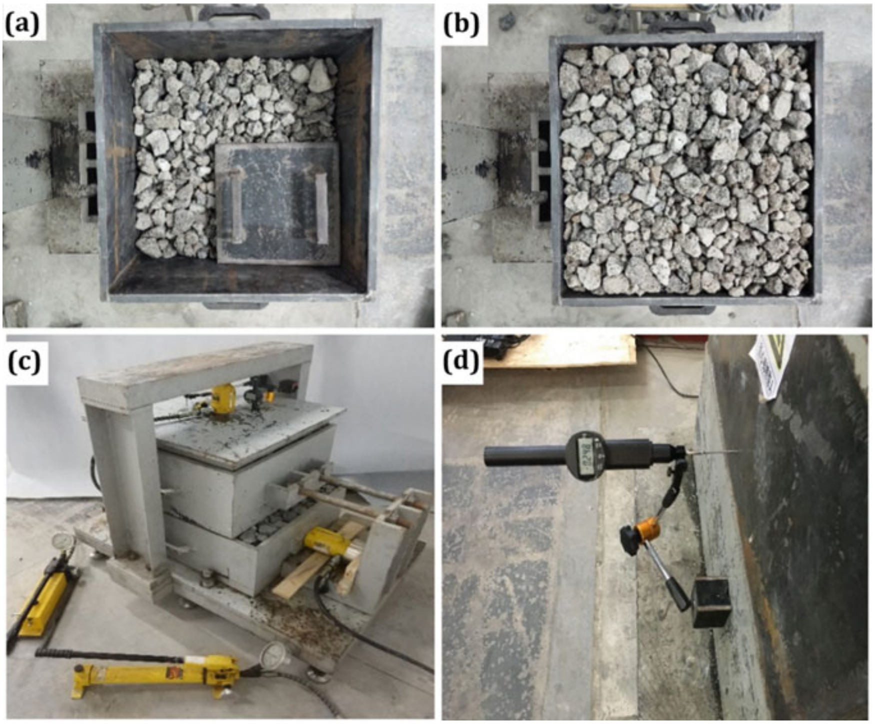

Fig. 3 **a** Compaction of samples, **b** full compacted sample, **c** instrumentation of shear test, **d** displacement gauge

with 600 mm, 600 mm, and 250 mm in length, width, and height, respectively. Ballast samples were prepared in five layers with a thickness of 10 cm along with the height of the shear box up to the top of the upper box. The bulk density of steel slag and basalt samples was 1570 kg/m^3 and 1420 kg/m^3, respectively, which were prepared by dropping the material into the box. Figure 3b shows the placement and compaction of samples in the lower box. The direct shear test was conducted for three normal pressures of 50, 100, and 200 kPa, and horizontal loading was applied by a hydraulic jack with a capacity of 100 kN to the bottom box. Simultaneously, the shear and vertical force were recorded using two digital indicators with a measurement course of 100 mm and 30 mm, respectively. Recording continued until the displacement of the bottom box reached 60 mm. This procedure was repeated three times to get the average value for each loading condition. It is noteworthy that the rate of applied force was 1 mm/min.

4 Test Results

4.1 Shear Strength of Fresh Ballast

The shear stress–displacement curve of basalt and SSA samples is presented in Fig. 4, which are approximately in the range of results reported by former studies [29, 37]. As shown in Fig. 4a, basalt samples had the highest shear strength at all normal stresses that can be attributed to the fact that basalt aggregates have a higher strength to bear applied stresses. In addition, with the increase of the normal stress, variation of strength between basalt and SSA became higher, so that the peak shear stress was 301.9 and 217.6 at 200 kPa normal stress, respectively (Fig. 4b). Since the recorded shear stress of SSA is in the range of ballast shear resistance reported by Estaire [37], SSA could be used as the substitution of rock material in ballasted railway tracks. As shown in Fig. 4c, the values of friction angle slightly decreased with the increase of normal stress for all samples. Due to the high vertical stress (200 kPa), the peak friction angle reduced about 19% in the case of using SSA as a substitution of basalt particles. As already reported by Estaire [37], parabolic curves could be precisely fitted on the variation of shear resistance and friction angle.

In order to make a comparison between the angle of repose and friction angle, samples of basalt and steel slag aggregates were selected and measured by a digital angle level device, as shown in Fig. 5. Although basalt aggregates have a higher friction angle than SSAs, the angle of repose of basalt is about 1° lower than SSA. As already mentioned by Al-Hashemi [38], the angle of repose could not be considered as the friction angle due to the different circumstances, such as moisture content, maximum dry density, and particle size. In the current test, the minor difference between the angle of repose of two samples could be attributed to the similar physical characteristic (e.g., static sliding friction coefficient) of SSA and basalt, whereas due

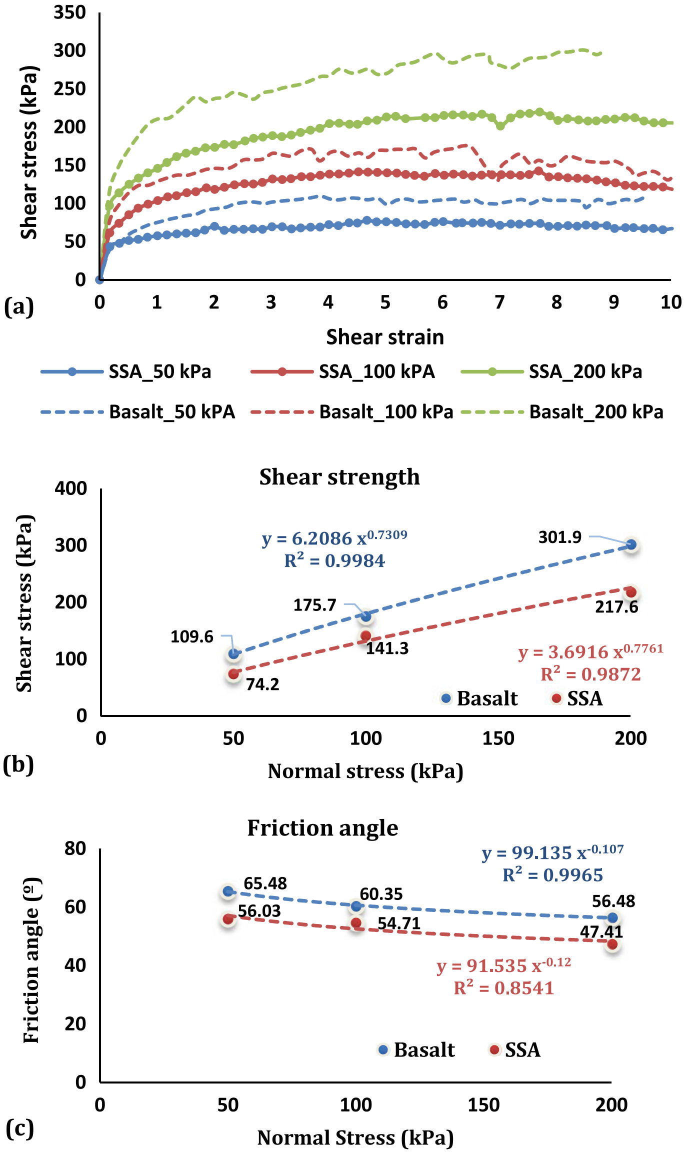

Fig. 4 **a** Shear stress–strain curves, **b** shear resistance of samples, **c** friction angle of samples

to the higher shear resistance of particles, the higher friction angle was obtained for basalt aggregates.

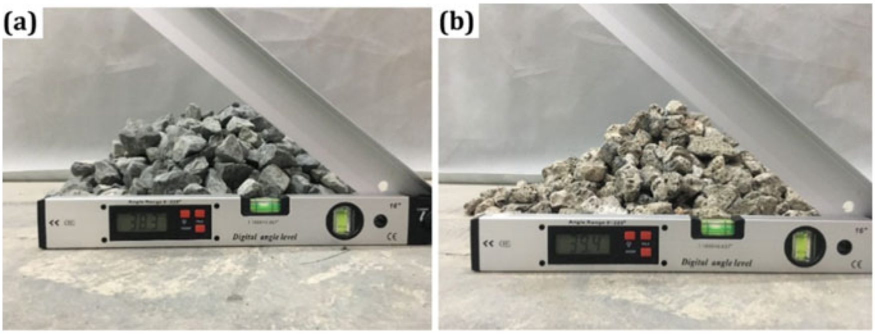

Fig. 5 Repose angle of **a** basalt and **b** SSA

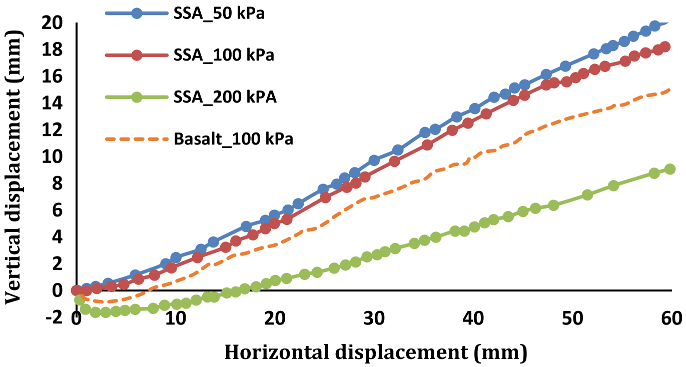

Fig. 6 Horizontal–vertical displacement during the shear test

4.2 *Vertical–Horizontal Displacement Curves*

Figure 6 shows the relation between the horizontal and vertical displacement. In all tests, the horizontal displacement caused growth in the vertical displacement. On the other hand, the dilation of the ballast increases with the reduction in the normal pressure. However, at 200 kPa normal stress, the contraction occurred in SSA sample up to the displacement of 17 mm. To compare the dilation of basalt and SSA, at 100 kPa normal stress, the dilatancy is higher for SSA specimens, in which the measured vertical displacement was about 20 mm, while in the specimen contained basalt aggregates, the vertical displacement was about 15 mm. It is noteworthy that the dilation of basalt samples was smaller than that reported by Estaire [37], which can be attributed to the application of the large size of the shear box (1 m × 1 m × 1.2 m).

5 Conclusion

The current study evaluates the mechanical behavior of steel slag aggregates derived from the steel industry as ballast aggregates. In this regard, a series of LA abrasion tests and large-direct shear tests were conducted on basalt and steel slag aggregates. The following results were achieved from this study:

- The physical properties of SSA fulfill the requirements of the Los Angeles abrasion test in order to be utilized as railway ballast materials.
- The shear resistance of basalt railway aggregates is higher than that of SSAs. The peak shear stress was 301.9 and 217.6, respectively, at 200 kPa normal stress.
- The increase of normal stress led to an increase and decrease in the values of shear strength and friction angle, respectively.
- The angle of repose could not be representative of the internal friction angle. Although the difference between the repose angle of basalt and SSA was insignificant, the internal friction angle of SSA was 19% lower than that of basalt aggregates.
- The dilatancy of SSAs was about 33% higher than basalt railway aggregates, and some reinforcement measures could be taken, such as geogrids, etc.

Acknowledgements Financial support of this study was provided by the Natural Science Foundation of China (Grant No. 51578051). This support is gratefully acknowledged.

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