

Direct shear tests on sand-contaminated ballast based on SmartRock sensing technology

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Abstract: A series of large-scale direct shear tests (DST) was conducted on sand-contaminated ballast (SCB) in order to address the paucity of research on subgrade fillers contaminated with sand. Wireless attitude sensors, known as SmartRock, were used to monitor the internal particle movement during the shear process of the SCB. The results show that the shear strength of the SCB decreases with an increase in the void contamination index (VCI), leading to changes in the shape of the shear stress-shear strain curve of the SCB. Additionally, the power function offers a more accurate fit for the peak shear strength envelope diagram of the SCB at various VCI levels. The volumetric strain exhibits a pattern of shear compression-dilation, and the power function better predicts the critical shear strain and peak volumetric strain in the shear compression-dilation process of the SCB specimens. The SmartRock sensor can capture the motion pattern of individual particles within the shear plane. The DST accurately reflects the behavior of the real ballast bed under train loading conditions. Moreover, the study shows that the motion pattern of particles within the ballast layer is multidimensional. The interaction forces between particles in the ballast bed, perpendicular to the train travel direction, can be described by unidirectional shear action.

1 Introduction

Railway ballast plays a vital role in the maintenance of railway infrastructure, providing stability and distributing the load of trains to the substructure^[1]. Especially in heavy rail track, the dynamic properties and stability of the ballast foundation are critical to the overall performance of the railway system^[2]. However, over time, fine particles inevitably settle in the voids within the ballast, gradually forming the phenomenon of ballast contamination. This significantly reduces the drainage capacity^[3] and increases the wear of the ballast^[4]. The presence of contaminated media can alter the contact state of the ballast, resulting in modifications to the mechanical properties of the ballast. In extreme instances, this can result in disruption to the normal functioning of the railway and the safe operation of the train^[4]. It is therefore essential to monitor the mechanical properties of the ballast under a range of conditions in order to ensure optimal performance. To address these issues, one potential solution is to utilize the direct shear tests (DST) on the sand-contaminated ballast (SCB). The DST method has been extensively employed to examine the mechanical properties of railway ballast. This method

provided valuable ideas for engineers to understand the influence of different sand types and contents on strength and durability of SCB. Researchers have conducted an analysis of the impact of contamination on the shear performance of ballast, employing direct shear tests in an indoor setting. The mechanical properties of clean ballast and contaminated ballast have been compared under both dry and wet conditions^[5]. The results demonstrate that the shear stability of the ballast is diminished following the accumulation of debris and contamination^[6]. Furthermore, direct shear tests were conducted on dirty ballast with geogrid, and it was observed that the shear resistance of the ballast was enhanced following the installation of the geogrid^[7-9]. Furthermore, the researchers conducted cyclic loading tests under triaxial conditions to elucidate the impact of repetitive loading on ballast degradation^[10]. The mechanical properties of contaminated ballast in old railway foundations in France were characterized through large-scale triaxial tests, which revealed the effect of long-term contamination on ballast performance^[11]. In response to these issues, a comprehensive investigation of the Neoballast cross-section was conducted, and the railway track design was optimized to enhance its performance^[12]. A model of the

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ballast interface that accounts for grading evolution due to particle breakage was also developed to more accurately represent the behavior of ballast under stress^[13]. However, a limitation of these approaches is that they focus primarily on the mechanical properties of ballast in a laboratory setting. This makes it difficult to quantify the interparticle contact forces that transfer pathways in real ballast and the particle motion that may result.

Recently, the SmartRock sensor has garnered significant interest as a potential instrument for monitoring the mechanical properties of sand-containing ballast. The SmartRock is capable of accurately capturing and recording the movement of granular materials under load^[14], and it is anticipated that it will become a DST tool for ballast containing sand^[15–16]. The sensor has been developed and tested for use in railway ballast, demonstrating its efficacy in capturing particle movement^[17]. The angular signals were employed to elucidate the intricate motion patterns of these particles. The response patterns of the particles were evaluated by monitoring their motion characteristics during compaction, including translation and rotation. This approach provided insights into the compaction mechanism of unbound aggregate base layers^[18]. Subsequent studies compared laboratory tests of the SmartRock sensor with simulation results, investigated the motion of ballast particles at different positions under the sleeper, and assessed the effect of geogrid on particle motion^[19–22]. With DST, this technology enables engineers to gain a deeper understanding of the influence of different sand contents on the strength and deformation characteristics of ballast. Furthermore, the use of SmartRock and pattern recognition techniques to identify the state of the ballast indicates that the technology can effectively monitor the health of the ballast^[23].

In order to quantify the degree of contamination of ballast aggregates. The fouling index (FI) is calculated as the sum of the percentages by weight of the materials passing the 4.75 mm and 0.075 mm sieves^[24]. The percentage void contamination (PVC) is defined as the ratio of the total volume of contaminant material to the initial ballast void volume^[25]. However, these methods may not provide an accurate assessment when the ballast is contaminated with different types of contamination material. The void contamination index (VCI) is based on the FI and PVC methods and measures the percentage of dry weight of sand compared to the ballast particles^[26]. In comparison with ballast contamination indices such as the FI or the PVC, the VCI simplifies the measurement of the volume of contamination and takes into account the effect of the gradation of the contamination.

In this study, large-scale direct shear tests were conducted using sand-contaminated ballast and the VCI method was employed to accurately quantify the degree of ballast contamination^[27–28]. The primary objective was to

examine the shear strength of the ballast bed filler and the movement of particles on the shear surface subsequent to the introduction of sand into the contaminated subgrade. Furthermore, the study endeavors to elucidate the interrelationship between shear stress-strain and volume compressional (dilatational) shear strain of SCB under disparate normal stresses and VCI levels, as well as the impact of VCI on the shear mechanical properties of ballast. The study captures the macroscopic evolution of the physical and mechanical degradation of aggregates under contaminated conditions. Additionally, it characterizes the movement behavior of SCB at the mesoscopic level using SmartRock sensors.

$$VCI = \left(\frac{1 - e_f}{e_b} \right) \frac{G_{s,b}}{G_{s,f}} \frac{M_f}{M_b} \times 100\% \quad (1)$$

where e_f is the porosity of sand, e_b is the porosity of clean ballast, $G_{s,b}$ is the dry density of ballast, $G_{s,f}$ is the dry density of sand, M_f is the added sand quality after drying, and M_b is the dry mass of ballast.

2 Test instruments and test methods

2.1 Test instruments

Figure 1 depicts a large-scale DST system (DW1280) comprising an upper shear box with dimensions of 600 mm (L) × 400 mm (W) × 400 mm (H) and a lower shear box with dimensions of 800 mm (L) × 400 mm (W) × 300 mm (H). The instrument is capable of conducting a large-scale DST on a range of materials, including coarse-grained soil, ballast, and soil and geosynthetic materials (geogrid, geotextile, geomembrane, etc.). The direct shear apparatus has a shear rate range of 0.1 to 20 mm/min. The maximum horizontal force is 100 kN, the maximum normal stress is 300 kPa, the maximum displacement limit is 120 mm, and the accuracy is 0.001 mm. The direct shear apparatus is equipped with two vertical displacement sensors, with a range of 100 mm and an accuracy of 0.001 mm. The vertical displacement sensor monitors the rise and fall of the pressure top plate throughout the entire shearing process. As the dimensions of the upper and lower shearing boxes remain constant throughout the shearing process, the displacement of the top plate can be monitored to determine whether the sample is in a shearing compression or shearing expansion state.

2.2 Filling and controlling sample density

In accordance with the *Railway ballast-part2: test methods* (TB/T 2140–2018)^[29], the standard gradation of the primary ballast material for new railway construction is illustrated in Fig. 2. Furthermore, Figure 2 illustrates the actual gradation of the ballast employed in this study.

The filling procedure is as follows:

(1) Clean the pulley in the car with a high pressure air pump to remove residual sand and prevent excessive friction.

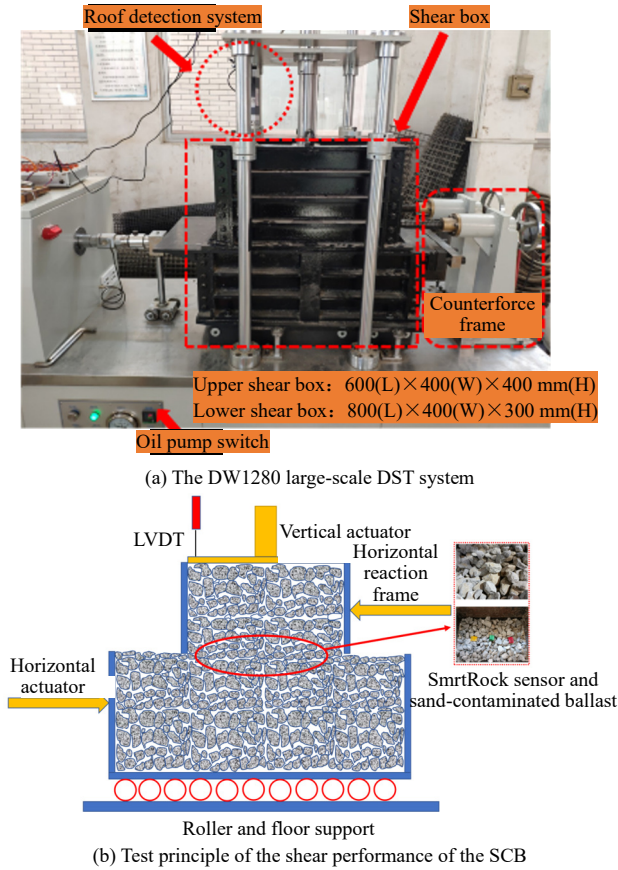


Fig. 1 Test instruments

(2) Connect and secure the lower shear box and trolley with fixing bolts.

(3) Weigh the ballast sample and sand to a specified mass.

(4) Fill the samples in layers into the lower shear box and compact them thoroughly, while controlling the relative compactness.

(5) Install the upper shear box, aligning the edges of the lower box.

(6) Install four stop bolts between the top and bottom boxes to maintain a 5 mm gap and eliminate friction.

The ballast samples intended for testing were prepared, and the ballast aggregate and sand were subjected to a sieving process to achieve a specified gradation. This was accomplished using a square-hole sieve and a sand sieve, respectively. The gradation curves of the tested ballast samples and the contaminated material (sand) were recorded as a percentage of the sieved mass (Fig. 2). The ballast and sand were mixed on a flat surface using a shovel. Thereafter, the mixture was placed in the lower and upper shear boxes and compacted into three layers (see Fig. 3(a)).

2.3 Shear and test stop conditions

Prior to the commencement of the shearing test, the fixed bolts connecting the upper and lower shear boxes are removed in order to facilitate the achievement of

relative displacement between them under the application of a uniform force. Once the set horizontal load has been applied, the shear test will commence at a displacement rate of 2 mm/min. During the test, the following variables are recorded: normal stress, horizontal displacement, horizontal force (converted to shear stress), and relative dilatancy displacement. According to *Standard for geotechnical testing method*

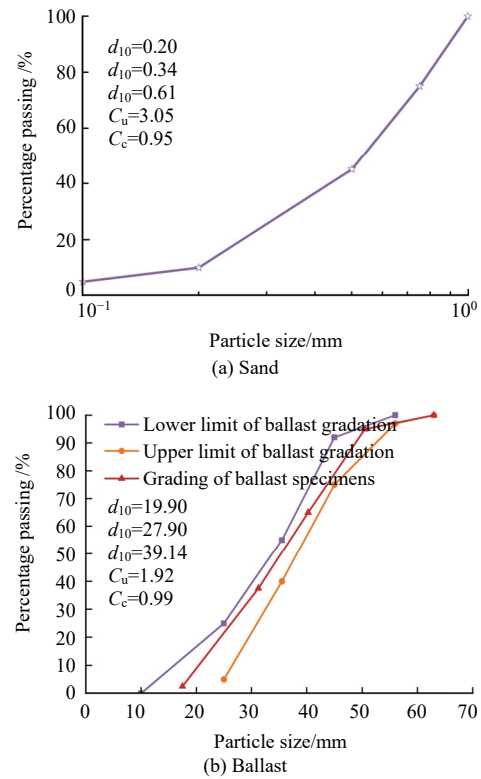
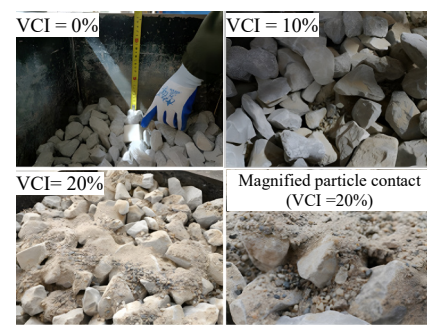


Fig. 2 Sand and ballast gradations



(a) Preparation of samples with different VCIs



(b) Sensors arranged at equal intervals along the shear direction

Fig. 3 Sample preparation and sensor arrangement

(GB/T 50123–2019) and existing test studies, we set the maximum shear displacement to 80 mm^[30–33]. Once the shear displacement reaches 80 mm (corresponding maximum shear strain is 13.33%), the horizontal displacement warning value set by the instrument will be reached, indicating that the shear experiment is complete.

Upon completion of the shear test, the vertical displacement sensor and rear reaction frame strut are disconnected, and the pressure roof is removed. Subsequently, the ballast within the upper and lower shear boxes is removed in layers and subjected to rescreening. This methodology allows for the determination of gradation changes in ballast subjected to shear stress, particularly in the vicinity of the shear plane. Additionally, materials that may be considered contaminants, such as sand and particles of deteriorated ballast, are collected and subjected to screening. The objective was to determine the factors influencing main body fracture, sharp angle fracture, and surface wear during the shear process^[1]. SmartRock sensors are recovered from the shear box and their data is saved on an upper computer.

2.4 SmartRock

During the testing process, according to different working conditions, three SmartRock sensors (S1, S2, S3, corresponding to front, middle, and tail shear planes) were placed within ± 5 cm of the shear plane inside the shear box. The sensors were arranged with an equal spacing of 150 mm between them, and the Y-axis of each sensor was aligned with the shear direction (Fig. 3(b)). This was done to effectively monitor the complete range of particle movement within the aggregate during shear. After burying the sensor, gravel was placed around it and mechanically compacted using a vibratory plate compactor to simulate the density and porosity of a real railway ballast bed.

The SmartRock system incorporates a variety of sophisticated sensors, including accelerometers (ACCs Sensors) and gyroscopes (gyros), along with a high-performance microprocessor and an advanced dynamic solution module. The system is capable of resetting the acceleration direction and error balance in the three-axis direction within the shear box, thereby enabling the rapid determination of the module's current real-time motion posture. The Kalman filtering algorithm is employed to effectively reduce measurement noise. The module is capable of operating for a period of between three and four hours on a full charge. The acceleration range is ± 15 g, the angular velocity range is $\pm 2\ 000(^{\circ})/s$, the angle range in the X/Z direction is $\pm 180^{\circ}$, and in the Y direction is $\pm 90^{\circ}$. The precision of the X and Y axes is 0.2° , while the Z axis exhibits a precision of 1° . Additionally, the signal output frequency is 200 Hz. The dimensions of the device are 40 mm $\times$ 40 mm $\times$ 40 mm. The device's low power consumption and high

performance make it an optimal choice for long-term dynamic data acquisition. In the testing phase, the SmartRock wireless sensor was employed in conjunction with the Bluetooth 5.0 multi-connection adapter for the purpose of transmitting data to a computer-based acquisition device. It was demonstrated that up to four SmartRock wireless sensors could be connected simultaneously and transmitted to the computer via Bluetooth. It was also shown that the basic parameters of the sensor could be monitored, including acceleration, angular velocity, angular acceleration, Euler angles, quaternions, magnetic field, and so forth. Generally, the sensor's basic parameters can be monitored, including acceleration, angular velocity, angular acceleration, Euler angles, quaternions, and magnetic fields.

2.5 Test program

In order to facilitate the preparation of specimens with the corresponding VCI ratio during the experiment and ensure the reliability of parallel tests, the mass of the sand was calculated in advance according to Eq. (1) and added to the specimen in multiple stages to ensure consistency. Furthermore, in order to simulate the pressure state of the ballast at the depth of contamination, normal pressure values of 30, 50 kPa and 75 kPa were selected, respectively^[34–35]. The specific test conditions are detailed in Table 1.

Table 1 DST conditions

VCI/%	Normal stress/kPa
0	30, 50, 75
10	30, 50, 75
20	30, 50, 75

3 Analysis of the test results

3.1 Shear strength analysis

Figure 4 depicts the stress-strain curves of the samples with varying VCI values. Due to the irregular geometry and rough surface of the ballast particles, an external force applied to the system results in interlocking of the particles, creating an 'interlocking effect' that restricts relative movement and exhibits shear strength. When subjected to a normal pressure σ_n of 30 kPa, the peak shear strength of VCI=10% and VCI=20% specimens decreased by 23.5% and 34.5% respectively compared to the VCI=0% specimen. When subjected to a normal pressure of 50 kPa, the peak shear strength of the VCI=10% and VCI=20% specimens decreased by 18.0% and 25.8%, respectively, compared to the VCI=0% specimen. When subjected to a normal pressure of 75 kPa, the peak shear strength of the VCI=10% and VCI=20% specimens decreased by 23.2% and 27.5% respectively compared to the VCI = 0% specimen. Under the same normal pressure conditions, the samples in each group show the same

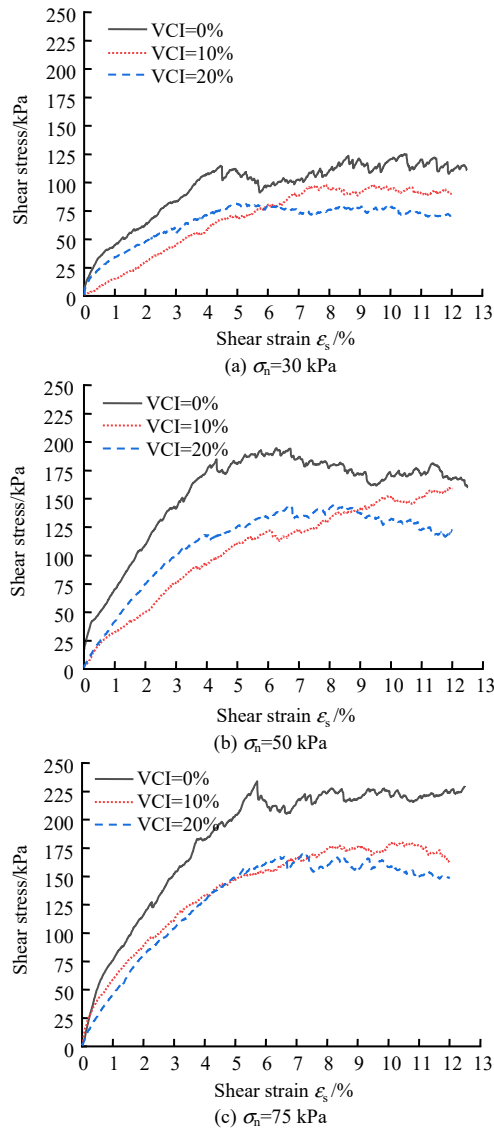


Fig. 4 Shear strength-horizontal shear strain curves of ballast under different normal pressures

trend of change as the degree of contamination increases, i.e. as the VCI increases, the peak shear strength of the ballast gradually decreases^[36]. The shear strength decreases more under the condition of lower normal pressure (30 kPa), showing that sand contamination is not conducive to the formation of the shear strength of the ballast sample. As the sand adhere to the surface of the ballast particles, the intergranular bite effect is weakened. The ‘lubricating effect’ of the sand promotes relative translation and rotation between the ballast particles, thereby reducing the shear strength of the ballast aggregate^[37]. The shear strength of ballast increases rapidly in the range of 0%–7% shear strain. Under low normal pressure, the shear stress basically reaches the peak of shear strength when the shear strain exceeds 8% and strain softening occurs. Under high normal pressure, the peak shear strain is in the range of 10%–12%. In addition, at the early stage of shearing, the shear strength of the VCI=0% specimen increased significantly compared to the VCI= 20% specimen, while the shear stress of the VCI= 10% specimen was lower. At VCI= 10%, the internal skeletal structure of the specimen is shown in Fig.5(b). Some ballast blocks still have contact forces and interaction forces, such as translational sliding, rolling and hopping. Concurrently, the same time, the sand inside the specimen acts as a lubricant during the movement of the ballast blocks and fills their voids, causing the overall specimen to expand, so that the shear strength of the VCI = 10% specimen is lower than that of the pure ballast (VCI = 0%) and the higher contaminated (VCI = 20%) specimen^[5]. The above fluctuations in the shearing process are mainly caused by the rearrangement and local crushing of the ballast particles^[38].

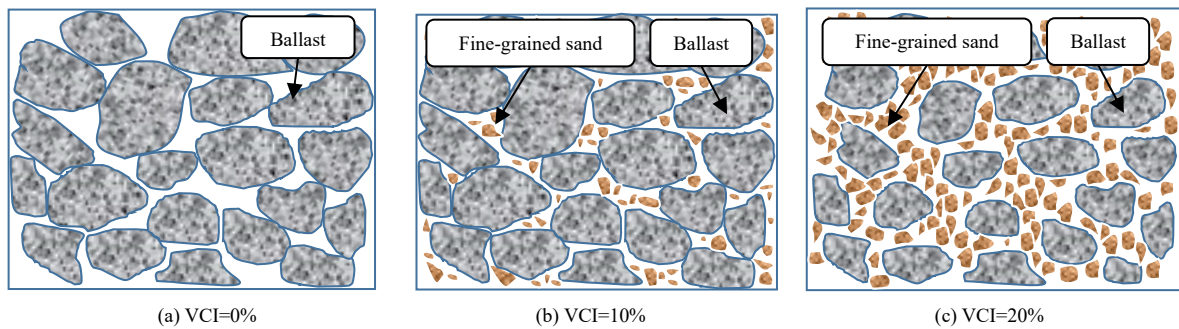


Fig. 5 Internal skeleton structure of SCB under different VCI levels^[5]

Gundavaram et al.^[39] performed DST on ballast aggregates contaminated with coal dust. They found a non-linear relationship between shear strength and normal stress. Therefore, the definition and description of the shear strength for the SCB at the fracture surface using the Mohr-Coulomb strength theory needs to be more accurate. Figure 6 shows the relationship between shear strength and normal stress

for SCB with different VCI values. These curves are all regressed using a power function to plot the envelope of shear strength and normal stress.

Shear strength is given by Eq. (2):

$$\frac{\tau_{\text{peak}}}{\sigma_c} = m \left(\frac{\sigma_n}{\sigma_c} \right)^n \quad (2)$$

where τ_{peak} is the peak shear strength of the specimen, σ_n is the normal stress, σ_c is the uniaxial compressive strength of the ballast block ($\sigma_c = 120$ MPa), m and n are dimensionless fit coefficients, and the results of the fit are given in Fig. 6.

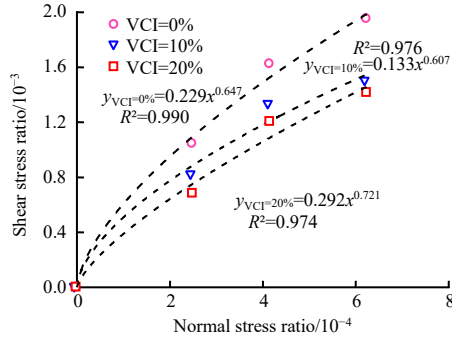


Fig. 6 Shear strength envelope of SCB with different VCI values

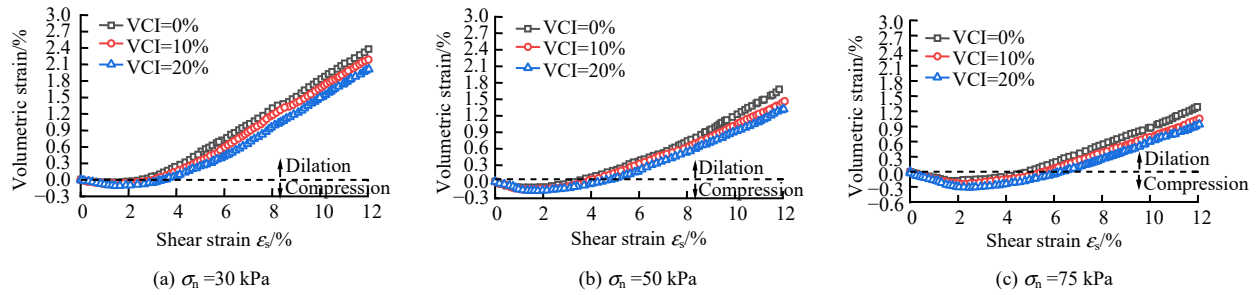


Fig. 7 Curves of volumetric strain versus shear strain under different normal stresses

Table 2 Development law of maximum volumetric strain and critical shear strain of the SCB

Normal stress/kPa	Horizontal shear strain at maximum volumetric strain/%			Horizontal shear strain at critical shear strain/%		
	VCI = 0%	VCI = 10%	VCI = 20%	VCI = 0%	VCI = 10%	VCI = 20%
30	2.591	3.068	3.471	4.759	4.373	4.025
50	3.359	2.925	2.642	3.546	3.920	4.462
75	2.571	2.100	1.875	5.027	5.666	6.445

Upon entering the zone of shear dilation, the pattern of volumetric strain development is approximately linear. The critical shear strain corresponds to the shear strain at zero volumetric strain. However, it can be observed that as the VCI value increases, so does the value of the shear strain required to reach the critical point in the shear expansion zone (see Table 2).

The relationship between the maximum volumetric strain of the SCB, the critical shear strain, and the normal stress is illustrated in Fig. 8. A power function fitted equation can be used to predict the macro-mechanical behavior of the SCB when the VCI value varies in the range of 0%–20%. This is achieved through regression analysis of the relationship.

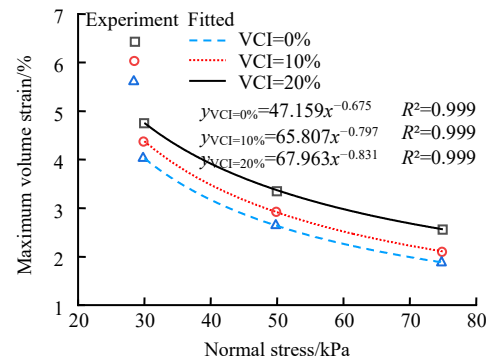
3.3 Motion characteristics analysis of SmartRock on the shear plane

The configuration of the SmartRock sensors is illustrated in Fig. 9. The direction of shear on the shear

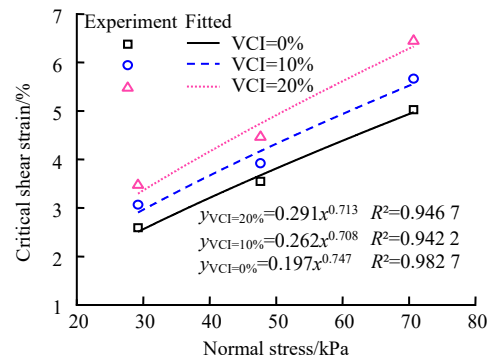
It can be observed that as the sand content of the SCB increases, there is a notable downward shift in the curve between peak stress and normal stress, accompanied by a reduction in peak strength.

3.2 Volumetric strain analysis

Figure 7 illustrates the variation in the vertical displacement of the top plate during the shear test. In the shear test, the greater length of the lower shear box relative to the upper shear box maintains the same shear area. Consequently, when shear compression occurs, the vertical displacement of the top plate is negative; conversely, when shear expansion occurs, the vertical displacement of the top plate is positive. The maximum volumetric strain of the sample is approximately -0.15% when the normal stress is 30 kPa, while it is approximately -0.3% when the normal stress is 75 kPa.



(a) Maximum volumetric strain at the end of shear test



(b) Fitted critical shear strain curves during dilatancy and shear contraction

Fig. 8 Fitted curves of peak volumetric strain, critical shear strain versus normal stress of samples with different VCI values

plane is aligned with the positive Y -axis of the coordinate system in which the sensors are placed. The three-axis angles of the sensor represent the rotation vectors around the X , Y , and Z axes in the spatial coordinate system. The right-hand rule is employed as the convention, whereby a clockwise rotation is regarded as positive and a counterclockwise rotation is regarded as negative. During the shearing process, a positive X -axis angle indicates that the corresponding particle is rotating in a clockwise direction around the X -axis, which aligns with the trend of shear strain development. Conversely, a negative value indicates the opposite direction of rotation.

As presented in Fig. 10(a), 10(b), 10(d), 10(e), 10(g), 10(h), the angular rotation of S1~S2 around the X -axis and Y -axis is more pronounced, whereas the angular rotation around the Z -axis exhibits fluctuations around 0° and a lack of discernible angular increment. The angular change values of S3 in each axis in Fig. 10(c), 10(f), 10(i) are observed to be smaller than those of S1

and S2. Figure 11 illustrates the box shear front view (X -plane) and side view (Y -plane) projections of the ballast particle motion pattern. In the event of shear behaviour occurs, the ballast moves mainly in the X -plane in the direction of shear strain growth. This movement results in individual particles rub against the surrounding ballast, thereby generating contact forces^[40].

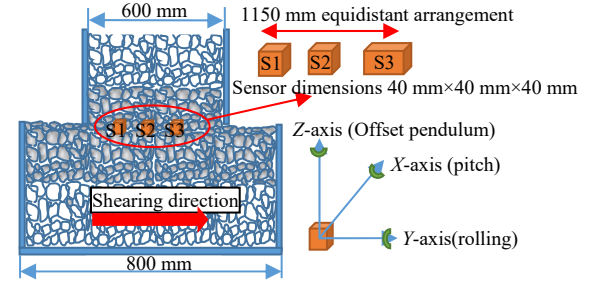


Fig. 9 SmartRock layout area and its spatial coordinate attitude angle regulation

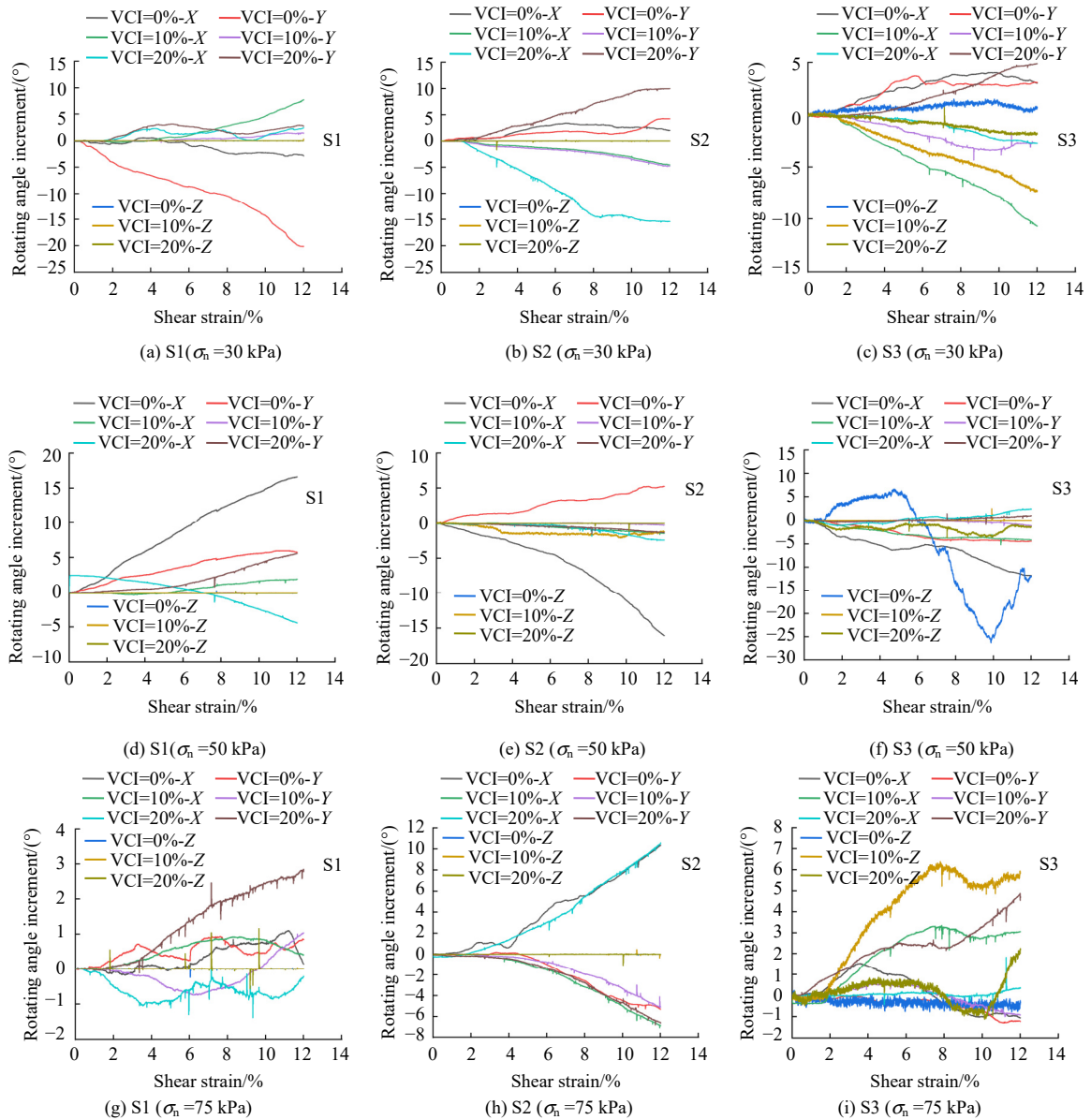


Fig. 10 Angle change of SmartRock under different normal stresses

As the ballast progresses through the Y -plane, the forces and moments generated by contact with the particles cause the particles to change their angle with respect to the Y -axis, which is perpendicular to the shear direction. This results in a rearrangement between the particles that exhibits an increase or decrease in volumetric strain on a macroscopic scale^[41]. In conclusion, the ballast particles within the shearing box can be defined as a typical form of motion in the Z -plane, exhibiting positive and negative angular changes around the X -axis and Y -axis.

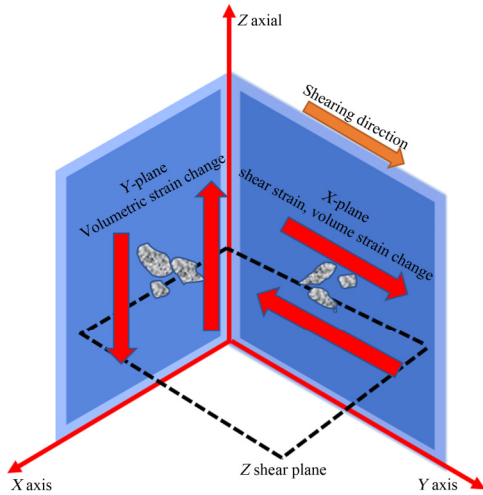


Fig. 11 Shear strain and volumetric strains caused by particle motion during shearing

As illustrated in Fig. 10(g), 10(i), there is a notable discrepancy in the angular trajectories of the particles under high normal stress ($\sigma_n = 75$ kPa) at different shearing stages. S1 and S3 correspond to the shear plane's front and tail. The angle changes a lot when shear strain develops. The curve demonstrates the presence of burr waves, and both positive and negative values are reflected during the development of shear strain. In contrast, the growth rate of the angle change value of S2 particles, as illustrated in Fig. 10(h), is maintained at a constant interval without any apparent decrease. This phenomenon can be attributed to the shear position corresponds to the front of the shear plane, and the tail is close to the rigid boundary (direct shear box sidewalls). Therefore, the particle-particle action can be defined as a point-to-point contact occurring along the shearing plane as the particles move. In contrast, the motion of some particles is in contact with a rigid boundary, and the particle-rigid plate interaction is a point-plane contact and a plane-plane contact. As a consequence of the ongoing alterations in mode and attitude, the compression and misalignment between particles give rise to considerable fluctuations in the turning angle. S2, situated in the central position of the shearing plane, is not affected by the rigid plate. Nevertheless, the particles on either side of S2 are affected by the boundary effect of the side walls of the direct shear box due to its width being more

significant than three times the maximum particle diameter. The particles at S2 demonstrate a consistent rotational direction in the shearing direction and exhibit a cooperative forward trend within a specific range of shear strain, as illustrated in Fig. 10(h). The positive rotation angle of the particles (S2) around the X -axis at this position is indicative of reduced shear resistance.

In discrete element numerical simulations, a common method for analyzing internal shear patterns during the shear test is to place measurement spheres inside the model and then measure the porosity of the aggregate in a local area by equivalent particle size substitution. Moreover, the distribution of particles rotating along the major axis in the shear direction and undergoing positive and negative angular deflections can be analyzed to investigate the detailed motion patterns at local locations in the shear zone^[42]. The SmartRock technique, as illustrated in this paper, enables the capture of the particle rotation angle of the shear zone along both the shear direction spindle (Y -axis) and the plane rotation spindle (X -axis).

Figure 12 demonstrates the motion patterns of SmartRocks in shear strains at $\varepsilon_s = 2.5\%$, 5.0% , and 7.5% . The mean and median of the rotation angles around the X -axis and Y -axis can reflect these motion patterns for S1, S2, and S3. When the normal stress is 30 kPa, an increase in the VCI value results in a reduction in shear strength in the strain range of $\varepsilon_s = 2.5\%$ to 5.0% when SmartRock rotates from negative to positive. Conversely, in the region of $\varepsilon_s = 5.0\%$ to 7.5% , an increase in shear strength is observed. When the normal stress is 50 kPa, the compactness of the sample increases and the shear strength exhibits a rapid decline in the region of $\varepsilon_s = 5.0\%$ to 7.5% . When contamination level is high, it is possible that particle rearrangement and an increase in regional shear strength may occur at a normal stress of 30 kPa. Nevertheless, the shear strength of the sample at a normal stress of 50 and 75 kPa is observed to diminish, while the extent of particle confinement is seen to decline (with positive values emerging) within the $\varepsilon_s = 5.0\%$ to 7.5% region. As evidenced in Fig. 12(a), an increase in VCI values at low normal stress levels ($\sigma_n = 30$ kPa) results in a shift in the rotation angle of particles around the X -axis at S1 (shear strain $\varepsilon_s = 2.5\%$) changes from -1.123° to 1.165° . The substance in question lubricates the contact between particles, reduces the shear resistance between them, and decreases the confinement of the particles due to the increased sand content.

4 Conclusion

In order to gain insight into the shear performance of SCB and comprehend the nature of particle motion, a series of DSTs were conducted. The findings of these studies led to the following conclusion:

(1) At normal pressures of 30, 50 kPa and 75 kPa, the peak shear strength of SCB with VCI = 10% decreased

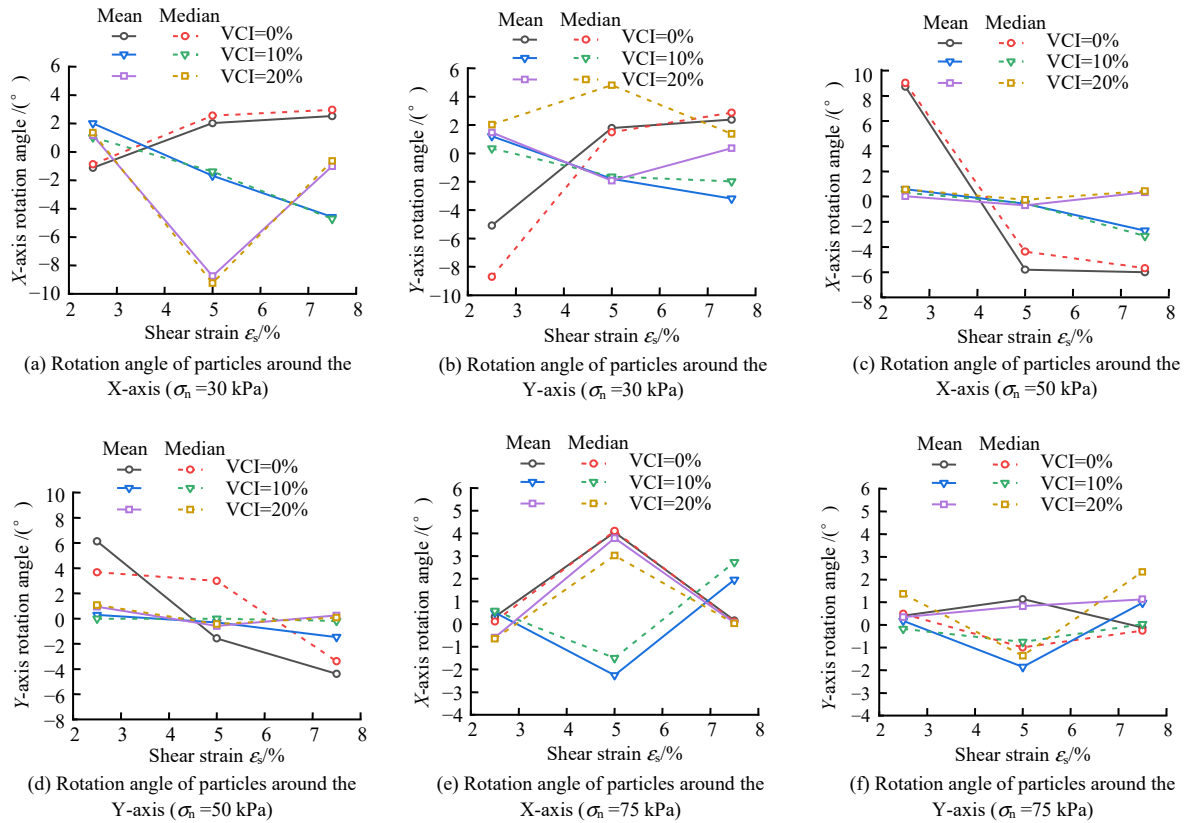


Fig. 12 Angle of rotation of particles around the X- and Y-axes under different normal pressures

by 23.5%, 18.0% and 23.2%, respectively, compared to the uncontaminated condition, while the peak shear strength of SCB with VCI = 20% decreased by 34.5%, 25.8% and 27.5%, respectively. The test results indicate that sand contamination is detrimental to the formation of shear strength in ballast samples. Sand adheres to the surface of ballast particles, weakening the interlocking effect between them. The "lubricant effect" of the sand facilitates the relative translation and rotation between ballast particles, thereby reducing the shear strength of the ballast aggregate. VCI = 0% and 20% correspond to conditions where the ballast is pure and heavily fine-particulate contaminated, respectively. Under these conditions, with normal pressures of 30 kPa and 75 kPa, the contact mode of the ballast particles is characterised by rotation and rolling lift, and the development of shear strain exhibits a strain softening phenomenon of relaxation-compaction-relaxation. In contrast, VCI = 10% represents a condition where some ballast voids are filled with fine particles, resulting in well-graded mixtures. The shear performance of these mixtures demonstrates a strain-hardening behavior with nonlinear growth as shear strain develops.

(2) The envelope curves of peak shear strength of the SCB under different VCI levels were obtained through the application of power function regression equations. The equations are as follows: $y_{VCI=0\%}=0.229x^{0.647}$, $y_{VCI=10\%}=0.133x^{0.607}$, $y_{VCI=20\%}=0.292x^{0.7}$, with corresponding R^2 values of 0.990, 0.976, and 0.974, respectively. The ratio of peak shear strength was

observed to decrease with an increase in VCI at each normal stress level. The greatest reduction in peak shear strength was observed when the VCI value increased from 0% to 10%. The DST revealed a consistent pattern of shear compression followed by shear dilation in SCB across all normal stress levels. The results demonstrated that elevated normal stress and VCI values led to a more pronounced particle displacement, which is a critical factor for achieving shear strength. Furthermore, the critical shear strain corresponding to the transition from shear compression to shear dilation demonstrated an increasing trend with elevated normal stress and VCI values. Concurrently, the volumetric strain within the shear compression zone exhibited a more pronounced behavior. In order to accurately predict these behaviors, a power function nonlinear fitting equation was employed. The R^2 of the maximum volume strain fitting formula was greater than 0.99, and the R^2 of the critical shear strain fitting formula was greater than 0.94, indicating a good fitting effect. This in turn provided a reliable estimate of the critical shear strain and maximum volumetric strain during shear compression-expansion, which provides a certain reference for practical engineering.

(3) It is noteworthy that the SmartRock sensors were able to effectively capture the intricate motion patterns of individual particles within the shear plane. The observations revealed the occurrence of particle rotation in two orthogonal planes perpendicular to the shearing plane, specifically around the X-axis and Y-

axis. There is a significant distinction between the particle angle and movement posture at varying levels of shear strain development. In the context of low normal stress, the area corresponding to a horizontal shear strain of 2.5%–5% demonstrates the most rapid development of shear resistance. Under high normal stress, the shear resistance of the specimen under VCI=0% and 20% contamination showed a tendency to first decrease and then increase with an ε_s of 0%–5%. The opposite was true for VCI=10%. The trend of particle rotation angle experiences a sudden shift when the horizontal shear strain reaches approximately 5%. The real ballast bed under train loads exhibits a multidimensional particle movement pattern, as revealed by direct shear tests. The interaction forces between particles within the ballast bed, in the plane orthogonal to the train's direction of travel, can be characterized by unidirectional shear action.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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