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Research Article

Improvement on the Key Element of Flexible U-Shaped Steel Support and Its Field Applications

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In China, there are a significant numbers of soft rocks roadways in underground coal mines. The roofs of these roadways are generally highly fractured, and traditional bolt installation does not provide sufficient supporting capacity. Hence, U-shaped steel support has gained popularity, and the key influential factor of steel support is the lock unit between its mechanical structures. The commonly used two-slotted splint lock unit can experience eversion and splitting and resulted in overall instability. To overcome the limitation, a "surface snap-in" lock unit was developed. Based on experimental results, it was found that the relationships of bearing capacity and deformation of two lock unit types were similar under same loading conditions. The ultimate bearing capacity of surface snap-in lock unit was lower than the two slotted splint unit. Although, its overall stability and flexibility were better. On the other hand, screw bolts of both unit types exhibited increase or decrease with the compressional deformation of steel support. The maximum stress along the screw bolt of two-slotted splint lock unit was 1.6 to 1.8 times of the surface snap-in lock unit. Based on the findings, the combination of two lock unit types was proposed and used at Peigou coal mine. Results show that the proposed design can effectively manage the roadway deformation while preventing the steel support damage. This in turn can reduce the associated supporting cost as the steel support can be recycled.

1. Introduction

The maintenance of support structure in soft rock roadways has always been a major technical problem in Chinese coal mines. Bolts and steel supports are commonly used supporting elements underground [1–3]. Rock and cable bolts can provide active support and support resistance earlier, which is beneficial to reducing the labor intensity, the associated support and maintenance costs, as well as simplifying the retreatment process. Therefore, it is widely used in underground operations [4–6]. However, the supporting performance does not always meet the requirements, particularly under soft and fractured rock [7, 8]. Other extreme conditions can also influence the effectiveness of bolting, including water-bearing, softening and expanding rock roadway, deep roadway under high stress, and crushed surrounding rock. In the short-range multiseam mining, the rock and cable bolts cannot provide sufficient support, such that the steel support is pivotal to ensure the underground stability [9, 10].

Steel supports are divided into rigid supports and yielding supports in China [11]. Rigid supports are usually made from I-steel with a simple structure and a simple processing technology [12]. There are three kinds of standard I-steel, namely, Nos. 9, 11, and 12. In response to high in situ stress at depth, Chinese researchers [13–16] recently developed concrete-filled steel tube supports, in which concrete is injected into a circular steel tube. In field practice, the effect of concrete steel tube has been examined. However, this support method is only suitable for roadway development and preparation. For the longwall retreat roadway with short service term, it is not cost effective to recycle support once the longwall face ends, and this may subsequently influence the retreating speed. Yielding supports generally adopts the steel beam of U section, in which the common types are U25, U29, and U36. Comparing with rigid support, the overlapped segment of the elastic support can move relatively. When the stent experiences overpressure, the contraction of the stint and the bracket can reduce the pressure acting on itself. This prevents the bearing capacity of support from stress-induced failure due to support material breakage and bracket deformation. Thereby, it also retains the capacity of the support. In recent years, a modified steel support beam was introduced by Chinese researchers [17] to increase the supporting strength. This was achieved by cutting the beam section into Ū type during the welding the steel plates and subsequently filling concrete. This change retains the flexibility of the support and increases the support capacity. However, the improvement only considers the strength of the steel beam itself while ignoring the strength of the lap segment.

The connecting element is the key part to make steel supports yielding, which not only determines the yielding energy of the support but also provides support resistance. Every connecting element contains a lock unit and a friction unit. The lock unit binds the overlapping part of two segments in the support and offers compressive force. To improve the mechanical properties of steel supports, different lock units were developed. According to the structural form, lock unit types can be divided into bolt type (Figure 1(a)) and wedge type (Figure 1(b)) [11]. During the installation of the lock unit, it is necessary to tighten the bolts so that the overlapping part between the top beam and the leg beam IS compressed, which is usually referred to as the pretightening force or locking force. As the preload increases, the internal force of the support increases. When the surrounding rock continues to deform, it is required to overcome the friction resistance between the connecting element to reach failure. To fully utilize the steel supports, it is essential to ensure that the locking force is stable at a certain value. This paper improved the capacity of the existing lock unit based on the review of the practical damage situation of the lock unit, as well as introduced a new wedge connecting element (Figure 1(c)). By using the new lock unit, the damage quantity of U-shaped steel support can be effectively reduced, the number of roadway repair can be reduced, and the operation cost of coal mine can be reduced.

2. Review of Existing Wedge Connecting Elements

The lock unit (Figure 1(a)) was widely used in China since 1970s. Due to its simple structure and installation, as well as competitive price, the elements are still used to date. Wedge-type unit (see Figure 1(b)), originally development in Germany, was introduced and popularized in China in 1960s, consists of double U-shaped clamping plates and pushing bolt. Compared with the bolt-types unit, it has higher strength and stiffness. Thereby, its working resistance is relatively stable during installation.

However, in field applications, the failure of the lock units occurred before the U-shaped steel supports was damaged, as shown in Figure 2. The failure of wedge connecting element is shown as (i) damage and sliding of the upper lock unit (Figure 2(a)); ii) deformation and bending of bolts under combined tension and shear (Figure 2(b)); and (iii) breakage of bolts and falling off of the U-shaped clamping plates (Figure 2(c)); the U-shaped clamping plates broke under cactavbomplex working conditions (Figure 2(d)). In general, the main reasons for bolt failure include (i) the width of double U-shaped clamping plates is too narrow, such that it is easy to turn over in the process of relative slippage; (ii) irregularity of bolt. The tensile stress concentration on one side will cause the bolt fracture under axial loading; and (iii) limited number of screw bolts, such that the shear resistance is insufficient. On the other hand, the main reason for the damage of the lock unit is low strength of the U-shaped clamping plates.

Based on the shortcomings of wedge connecting element, a new wedge connecting element (NWCE) was developed, as shown in Figures 1(c) and 2(d). Comparing with the traditional wedge connecting element, NWCE has a number of advantages, including (i) utilization of normal screw bolts to rereduce local concentration of load due to bolt shape and (ii) the area between double U-shaped clamping plates and the number of bolts is increased. In this way, the bearing capacity of lock unit can be effectively improved. Meanwhile, the overturning degree of the clamping plates is reduced, such that the shear force subjected to the bolt is reduced. Subsequently, the preload force of the lock unit is increased, which in turn improves the stability of the connecting element.

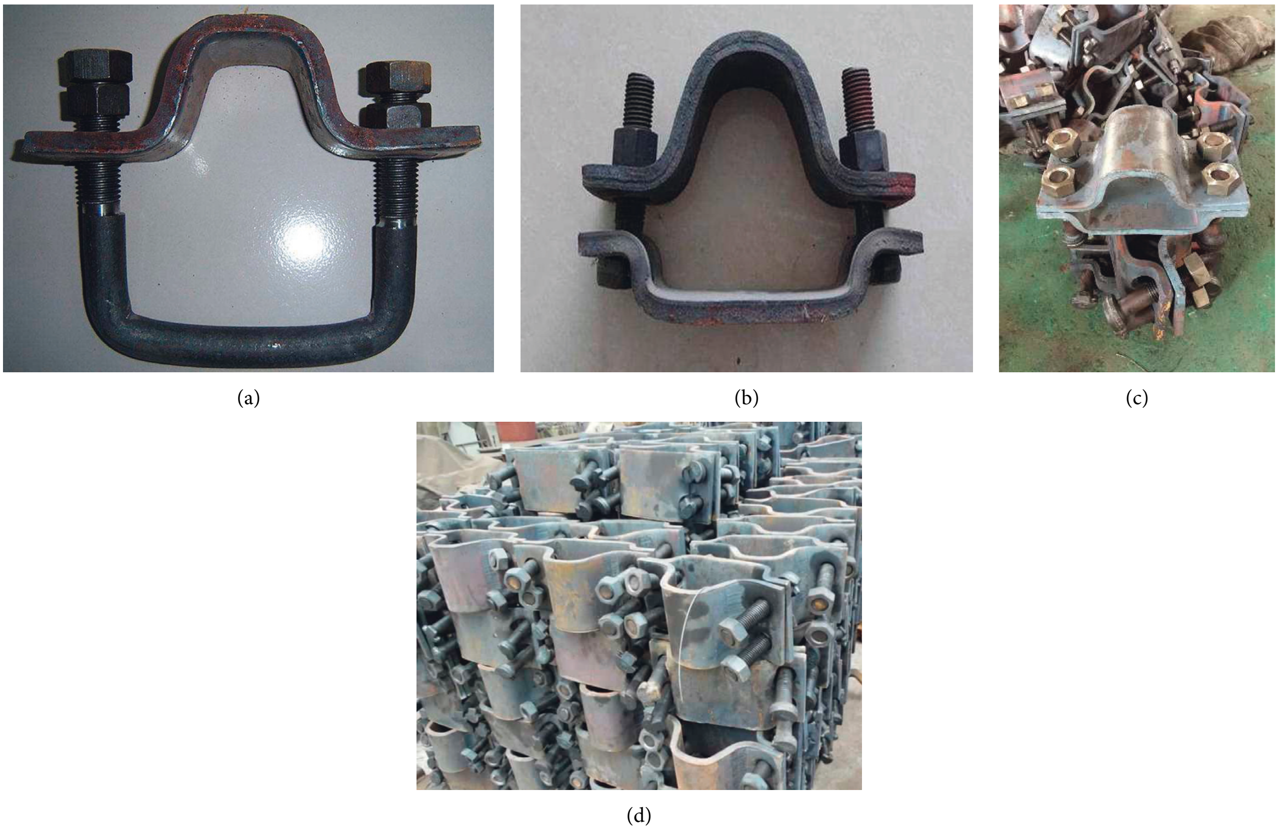
3. Experimental Study of NWCE Influence on the Support Bearing Capacity

3.1. Tesing Purpose. To study the performance of surface snap-in lock unit and two-slotted splint lock unit, a laboratory testing was designed. The main objectives of the test include

(1) Investigate the mechanical properties and deformation of different types of cable in the bearing process of support.

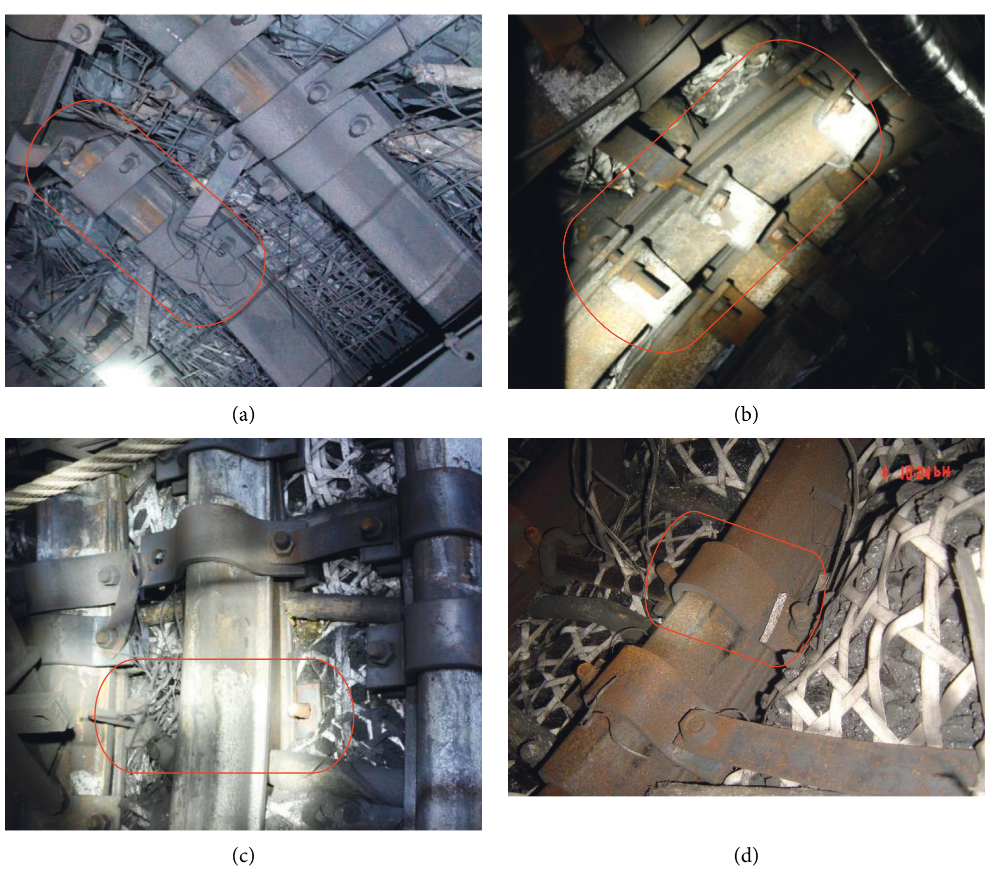
(2) Study the influence of different cable types on the bearing performance of supports under the same load.

3.2. Testing Methods. This test used roadway steel support performance test system in State Key Laboratory of Coal Resources and Safe Mining at China University of Mining and Technology. This test system is capable of examining mechanical performance indicators of roadway steel support. The details of the system are shown in Figure 3. The system consists of hydraulic control console, computer servo control system, hydraulic Jack, protection device, displacement sensor, force sensor, and resistance strain gauge. The system can independently control each hydraulic module, monitor and collect the load, and deformation of the support and cable surface stress and bolt axial force to



(a) (b) (c) (d)

Figure 1: Lock unit physical drawing. (a)Bolt-types lock unit, (b)wedge-type lock unit., (c)new wedge-type lock unit, (d)new wedge-type lock unit.



(a) (b) (c) (d)

Figure 2: The deformation and failure of the wedge connecting element. (a) U-shape clamping plates slip failure, (b) bolts bending damage, (c) bolt breakage, (d) fracture of splint.

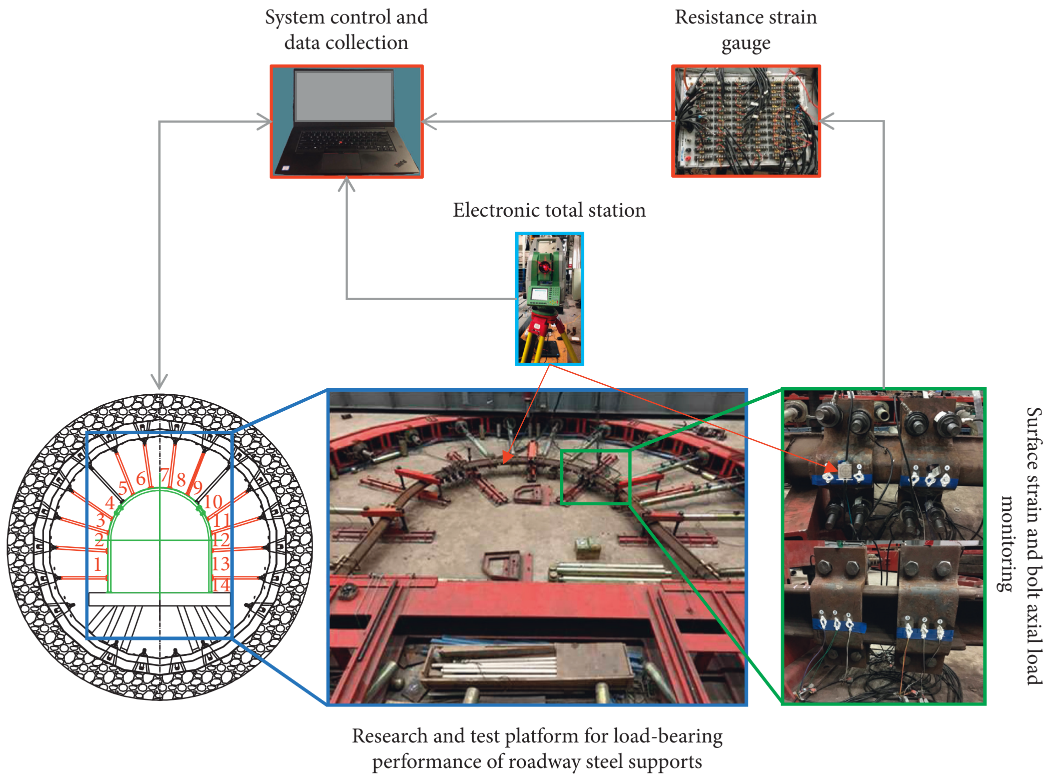


Figure 3: Performance test system of roadway support.

meet the requirements of this test. In addition, strain gauges were mounted onto the cable surface to monitor the deformation and axial load of cable bolts. A total station was used to record the displacements of the cable and U-shaped steel support. The material type of U-shaped steel is 16 MnK, the yield strength is 325 MPa, and the tensile strength is 490 MPa.

3.3. Testing Scheme. Based on different field conditions, the loads of the supports can be divided into two types: symmetric and asymmetric, as shown in Figure 4. The symmetrical loading can be further classified into three categories, i.e., static pressure, side pressure coefficient greater than 1, and side pressure coefficient less than 1. For asymmetrical load, the case of high pressure on one shoulder and low pressure on the other shoulder is adopted. The four types of load distribution are shown in Figure 4. In this test, symmetrical load with lateral pressure coefficient of 1/3 and 3 and right-side partial load were adopted as shown in Figure 5 and Table 1.

The specific installation procedures are as follows:

(1) Install the U-shaped steel supports, U-shaped clamping plate strain gauge, and load sensor as depicted in Figure 5.

(2) Apply 5 kN contact force between each hydraulic rod and the support, by then, load other parts of the support as specified in Table 1.

(3) During the loading process, when the bracket reaches the following conditions the test must be stopped: (i) the bearing capacity is extremely low and continues to shrink; (ii) the deformation of the steel supports exceeds the protection range of the safety device; (iii) the out of plane deformation of the U-shaped steel support; (iv) the stroke of the loading cylinder exceeds the predetermined value; and (v) the displacement and the overload of the load sensor.

4. Results and Discussion

4.1. Analysis of the Load-Bearing Capacity of U-Shaped Steel Supports under Different Lock Units. Figure 6 shows the deformation of steel support under various loading conditions. It can be seen that the gradients first increases then fluctuates. Based on the deformation curve of new wedge-type lock unit of steel support (see Figure 6(a)), loading increased gradually in yellow section. This indicates that during this phase, the support deformation was dominated by material deformation. On the other hand, loading decreased dramatically in red section, suggesting that the support deformation was mainly from deformation of overlapping sections. The combination of the two deformation sources forms the overall deformation of the steel support.

The ultimate bearing capacity of steel support is determined by material properties of support parts and lock unit types. Prior to the compression of compressible u-shaped steel support, its load–displacement curve is similar to the rigid support. This suggests that the support performance at this stage was largely controlled by the support structure and mechanical properties of steel, while the influence of lock

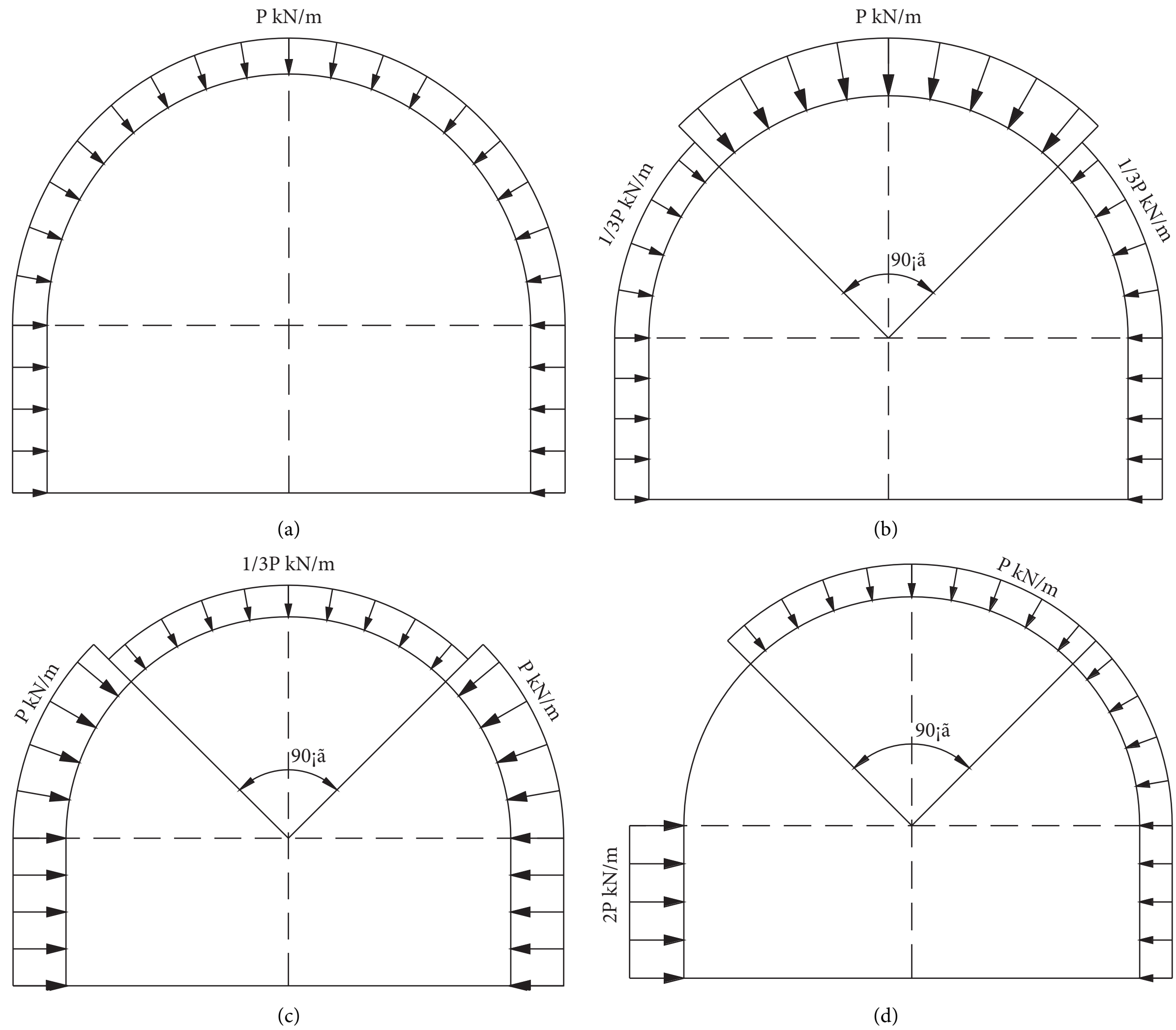


FIGURE 4: Load condition of steel supports. (a) Static pressure, (b) lateral pressure coefficient of 1/3, (c) lateral pressure coefficient of 3, (d) right-side partial load.

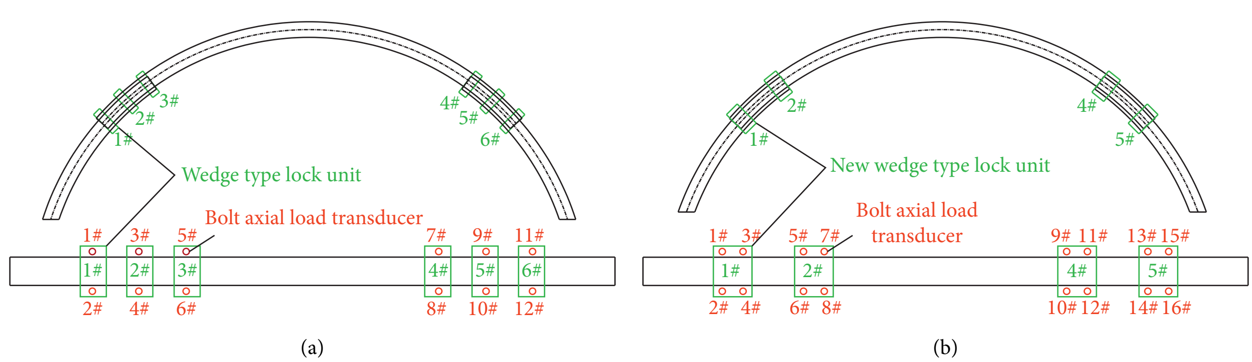


FIGURE 5: Schematic diagram of lock unit and load sensor installation locations. (a) Wedge-type connection element number and load sensor number and (b) two-slotted splint connection element number and load sensor number.

unit types was negligible. Subsequently, the capacity was influenced by lock unit type as the mechanical structure could not take much load due to slippage between linking parts. Therefore, the appropriate lock unit type can effectively utilize the capacity of the mechanical structure while preventing the components from failure due to excessive loads.

According to Figure 6(a), it can be seen that the initial compressional resistance of the support with two-slotted splint lock unit for wedge connection element was high, and

Table 1: Loading parameters of experimental system.

Serial number of hydraulic cylinder		Lateral pressure coefficient of 1/3		Lateral pressure coefficient of 3		Right-side partial load	
		Load (kN)	Loading rate (kN/min)	Load (kN)	Loading rate (kN/min)	Load (kN)	Loading rate (kN/min)
1	Leg	50	1	150	3	300	6
2		50	1	150	3	300	6
3	Shoulder	50	1	150	3	0	0
4		50	1	150	3	0	0
6	Arch	150	3	50	1	150	3
7		150	3	50	1	150	3
8		150	3	50	1	150	3
9		150	3	50	1	150	3
11	Shoulder	50	1	150	3	150	3
12		50	1	150	3	150	3
13	Leg	50	1	150	3	150	3
14		50	1	150	3	150	3

the maximum slippage of the support was larger than new wedge-type lock unit. ◦ The initial compressional resistance and the ultimate bearing capacity of the support with new lock unit were 93% and 90% of the original units, but slippage of the support was more frequent. Thereby, the slipping resistance of the support was always lower than the initial compressional resistance.

As seen from Figure 5(b), the bearing capacity of the support first increased and then decreased and then stabilized at around 700 kn. The initial compressional resistance force and maximum support force of the mounting surface snap-in lock unit were both 109% of the two-slotted splint lock unit, see Table 2. In the subsequent load bearing process, the installation of new lock unit significantly increased the number of slippage of support comparing with the old unit. In addition, the support resistance did not decrease substantially, indicating that the new lock unit can effectively improve the support slippage while maintaining the support resistance.

Figure 6(c) shows that when the support was in the sliding stage, the peak load was larger than the initial compressive load. The bearing capacity of the bracket with two-slotted splint lock unit fluctuated greatly, while the minimum value was close to 0. The support with new lock unit had considerable slippage, as shown in Table 2. Although the maximum sliding resistance was smaller than that of the old unit, the support resistance did not fluctuate and the minimum value was stable and above 300 kN. It shows that under the partial load, the support with the new lock unit can still ensure the stability of steel support under the most unfavorable condition.

To sum up: 1), when different types of cable are selected, the relationship between load and deformation of the support before slippage was roughly the same under the same type of load; (2) under the same type of load, the initial compressive force and ultimate bearing capacity of the support with two-slotted splint lock unit selected were greater than the initial compressional resistance of the support with old lock unit; and (3) the support of new lock unit is better than the old one.

Based on the observation during the experiment, it can be seen that in the case of less use of two lock units, the bearing capacity of the surface snap-in lock unit was similar to that of the two-slotted splint lock unit while the yielding capacity was better than that of the two-slotted splint lock unit. It is suggested to use the combination of two in the field to maximize the bearing capacity of the support and stability of the roadway. Investigation on the lock unit screw bolt under various loading conditions.

4.2. Investigation on the Lock Unit Screw Bolt under Various Loading Conditions. This section analyzed the axial load change of lock unit screw bolt under various loading conditions. When installing lock unit, pretension is generally applied to 300 N•m, corresponding to 50 kN axial load on the screw bolt [18]. Figure 7 shows the axial load change of screw bolt during support bracket slippage, which the top section is 3D image and the bottom section is the plane view. X-axis is the slippage displacement of support because this slippage resulted in support structural change. Y-axis is the screw bolt number. In this experiment, all applied load onto support is in the same plane, and screw bolts numbers and locations are symmetrical in this plane. Hence, the deformation on each corresponding pairs should be the same. Therefore, only the screw bolts with even numbers were selected for analysis. Z-axis represents the axial load, the higher the load, the darker the color. Within the black line, color changed dramatically. This indicates there was a sudden change in the screw bolt axial load, which is due to the compressive deformation of the steel support.

4.2.1. Change of Axial Load of Screw Bolt under High Confining Pressure. Under high confining pressure, there are a number of characteristics can be seen on axial load of screw bolts: (i) axial loads of screw bolts on the rib leg were greater than the ones on the roof and (ii) instant decrease in axial load of some screw bolts when there was compressional movement of the support, as displayed in the black box in the figure. This suggests that during compressional

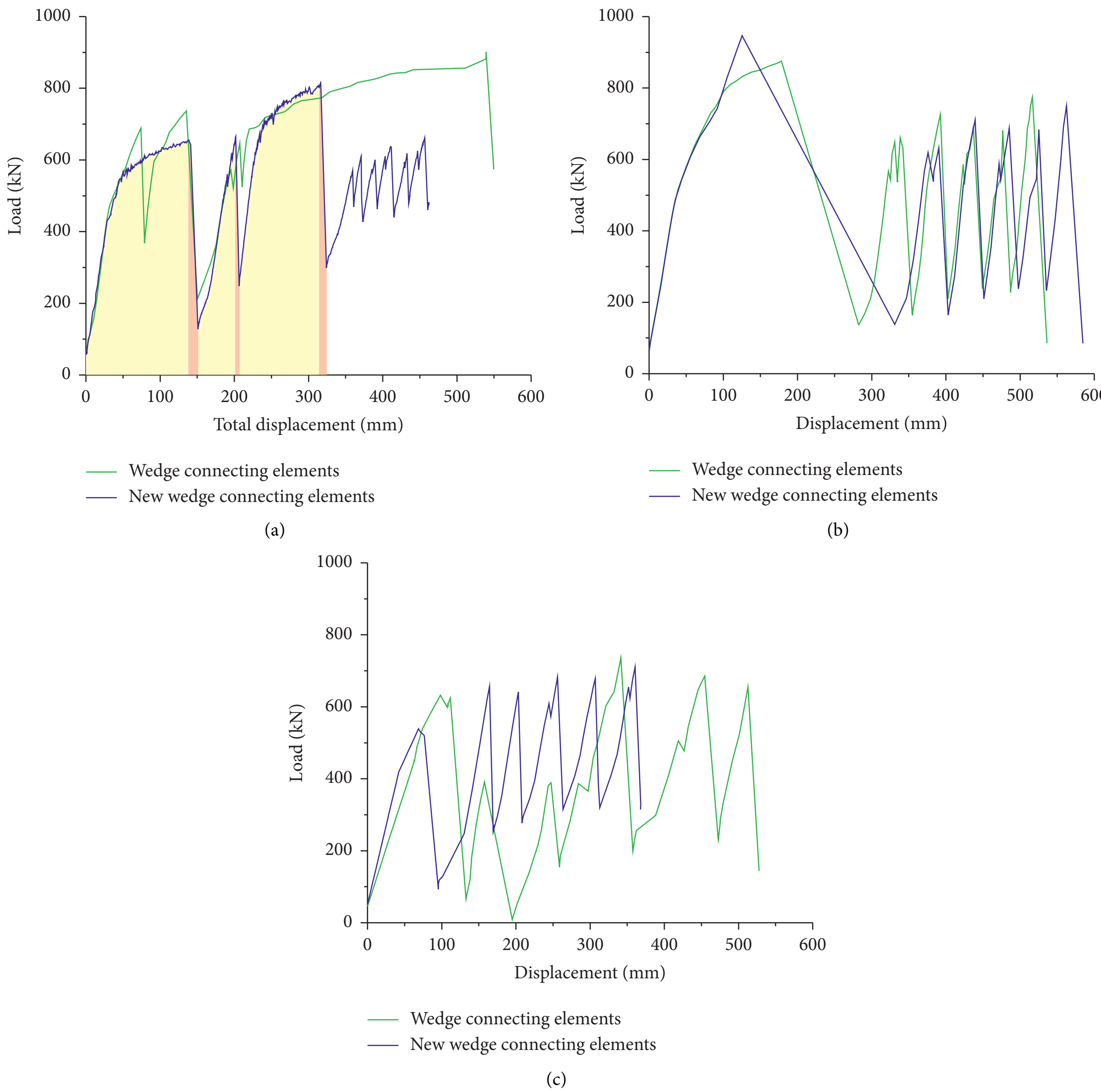
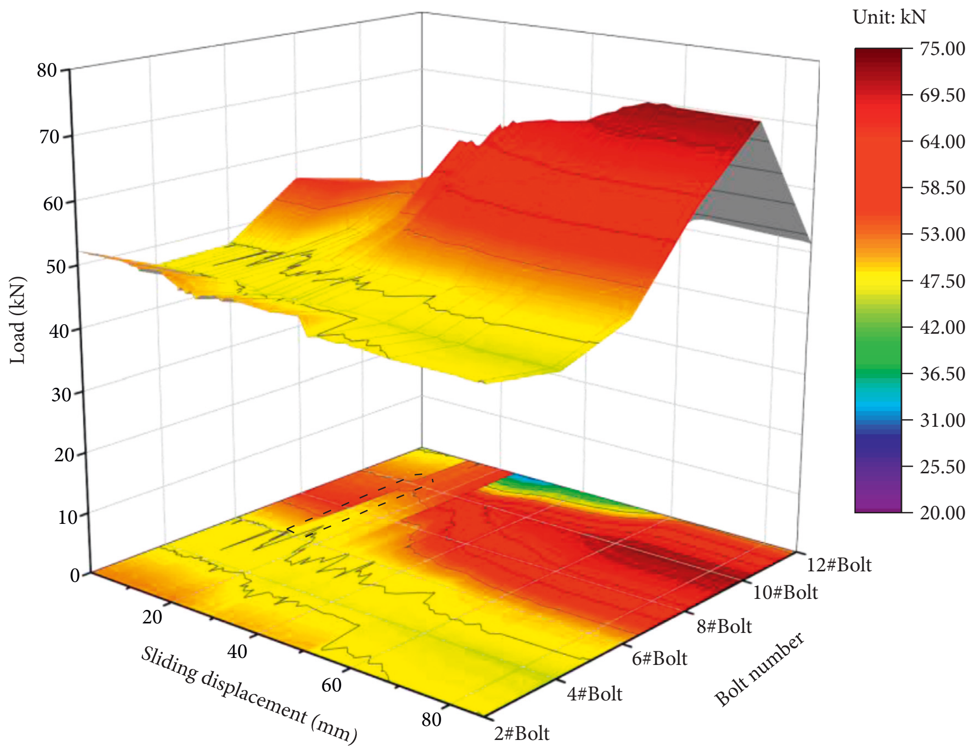


Figure 6: Relation between bear acting force and frame deformation with different types of lock uint. (a) High leg loadact, (b) high arch load (c) partial load.

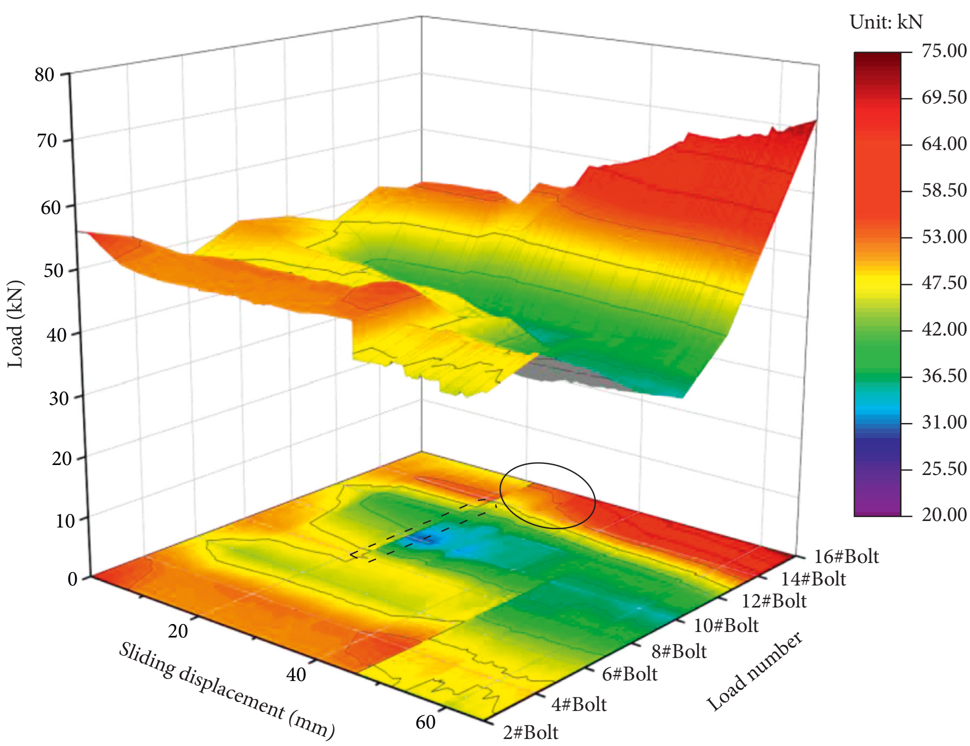
Table 2: Initial compressional resistance force, maximum compressional force, and slippage numbers of yieldable U-shaped steel supports with different types of lock unit.

Load type	Lock unit type	Initial retraction resistance force/kN	Maximum retraction force/kN	Retraction times
Large arch load	Wedge-type lock unit	875.66	875.66	7
	New wedge-type lock unit	721.18	721.18	16
Large leg load	Wedge-type lock unit	688.85	892.69	4
	New wedge-type lock unit	655.12	814.67	8
Partial load	Wedge-type lock unit	632.30	735.76	7
	New wedge-type lock unit	539.02	710.33	9

movement, resistance of the lock unit would decrease; (iii) screw bolts near the roof experienced axial load below initial pretension conditions. Overall, it can be found that the lock units at different location of the support exerted different loads. During compressional movement of support, resistance of some lock units suddenly decreased and then



(a)



(b)

Figure 7: The relationship between bolt force and frame slippage on overlapping parts. (a) Axial load of two-slotted splint lock unit and (b) axial load of surface snap-in lock unit.

gradually increased, while others did not drop and increased (see black circles). This ensured the steel support was able to provide sufficient capacity during compressional movement.

Maximum axial loads of two-slotted splint and surface snap-in lock units were 73.61 kN and 71.59 kN. Comparing with the screw bolts on two-slotted splint lock unit, the screw bolts on surface snap-in lock unit had less axial load. This was because the two-slotted splint lock unit had more screw bolts, such that the load was distributed to more elements. The results in turn suggested that screw bolts on surface snap-in lock unit were under better condition than those on the two-slotted splint lock unit, so that the possibility of screw-bolt breakage induced support failure can be reduced.

4.2.2. Change of Axial Load of Screw Bolt under High Vertical Pressure. The maximum and minimum axial loads of screw bolts on surface snap-in lock unit were 67.3 kN and 27.96 kN under high symmetrical vertical pressure. Axial loads of screw bolts near the rib leg were higher than those near the roof, while the axial loads of screw bolts near the roof were always lower than the initial pretension. Axial loads of screw bolts near rib leg exhibited "increase-sudden decrease-increase" trend. Screw bolts on the roof only had one sudden increase, while others all showed gradual decrease. When the steel support experienced compressional movement, pretension on the lock units had different trend. For instance, axial loads of nearby screw bolts showed completely opposite trends, see Figure 8(a). Hence, it can be seen that the resistance provided by lock unit is higher near the rib leg. However, when the resistance of lock unit near the rib legs decreased, the lock unit resistance on the roof would increase.

The maximum and minimum axial loads of screw bolts on two-slotted splint lock unit were 67.87 kN and 22.57 kN under high symmetrical vertical pressure. The change of axial load in screw bolts is rather stable for two-slotted splint lock unit except sudden changes in the early phase. The axial loads of screw bolts on left ribs gradually increased and reached stable, while the screw bolts on the roof fluctuated. In addition, axial loads were stable on the right rib. This suggests that the surface snap-in lock unit can provide stability although support experiences sudden dramatic compressional movement.

Overall, surface snap-in lock unit can provide more stability when the support experiences slippage or sudden compression, especially under high vertical pressure. Screw bolts near the rib can provide more sliding resistance regardless of the pressure conditions as higher tensions were observed.

Experimental results also showed that the maximum and minimum values of different screw bolts types were similar under the same loading condition with same steel support. Based on previous experience, stress distribution along the bolt can be different with different bolt shapes under the same loading condition. In this experiment, surface snap-in lock unit used regular screw bolts while two-slotted splint lock unit used irregular shaped screw bolts. To assess the axial load change and stress distribution of these two types of bolts, numerical simulation via ABAQUS was carried out. 3D synthetic bolts were simulated and subjected to same boundary conditions at five different axial loadings, see Figure 9, rod parameters of symmetrical bolt: $\varphi 22 \times 100$ mm, bolt head parameters: $\varphi 44 \times 100$ mm, rod parameters of asymmetric bolt: $\varphi 22 \times 100$ mm, and bolt head parameters: 44×100 mm. The mesh property of the numerical model is c3d10, the yield strength is 325 MPa, and the tensile strength is 490 MPa. The bolt load is applied on the bolt rod body by adding fixed constraints at the bottom of the bolt and the nut part, respectively.

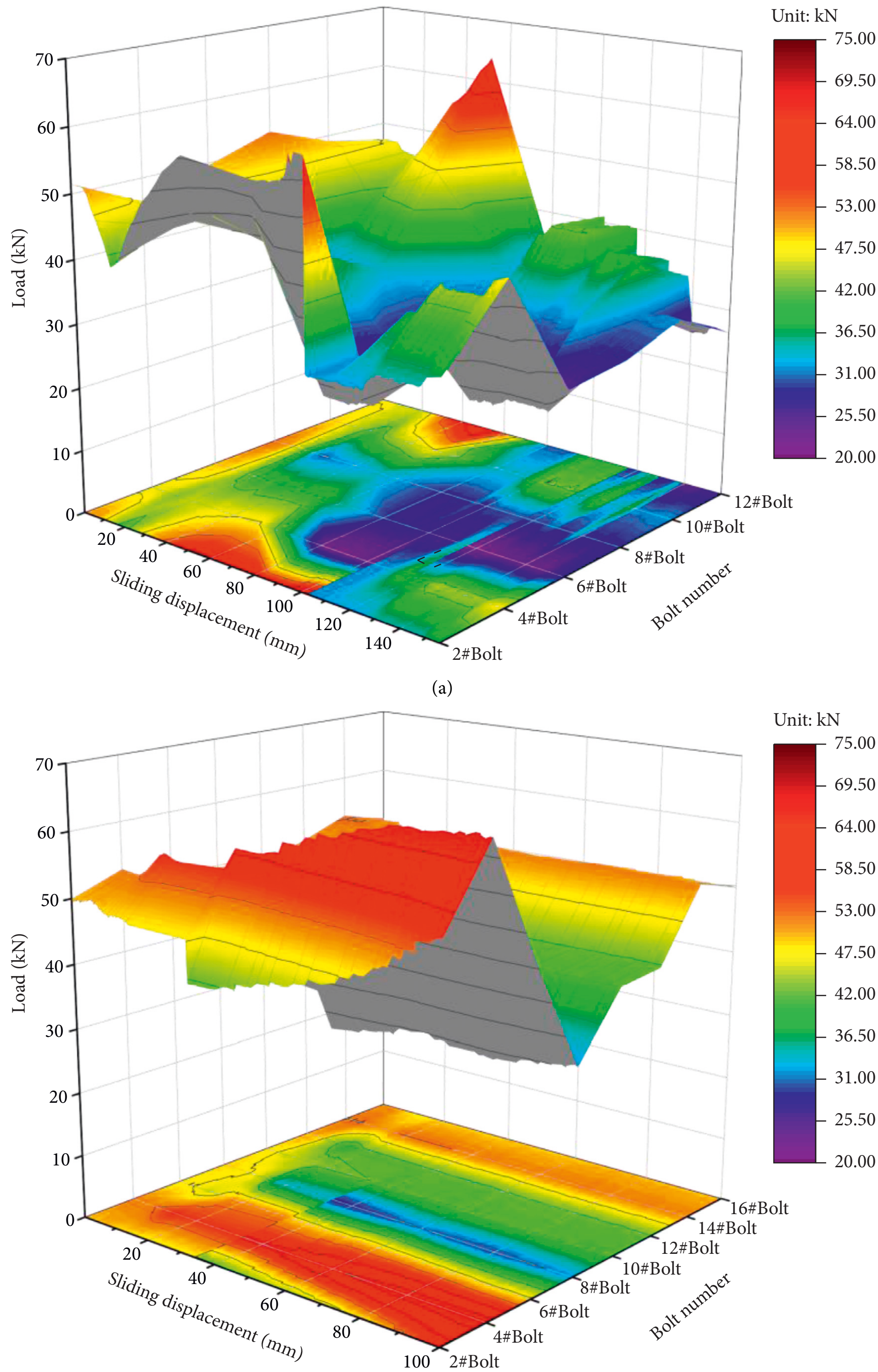
Figure 9 shows that the relationship between the stress threshold of screw bolt with axial load. Based on the figure, axial loads of irregular bolts exhibited a gradient distribution, in which the maximum load rapidly increased and entered plastic deformation. The stress distribution of regular bolts was rather even and increased evenly with the increasing axial load. Therefore, the maximum stress of irregular bolts was 1.6 to 1.8 times of the regular bolts, although the maximum and minimum axial loads were similar. Hence, the utilization of regular bolts can effectively reduce the stress distribution and subsequently prevent bolts from failure.

4.3. Stress Distribution of Lock Units under Various Loading Conditions. This section analyzed the surface stress change of different lock units under various loading conditions. Results can be seen in Figures 10 and 11, in which X-axis is the slippage of connections, Y-axis is the monitoring point number, and Z-axis represents the stress magnitudes. "leg-roof-leg" indicates the monitoring location.

4.3.1. Surface Stress Change of Different Lock Units under High Confining Pressure. The stress of top and bottom surfaces of the lock units increased with the increasing support deformation under high loading, which the sudden change was not observed. The surface stress of two-slotted splint lock unit was higher than the surface snap-in lock unit, indicating two-slotted splint lock unit experienced plastic deformation. Tensile stress on the top surface was lower near the leg and higher away from the leg for two-slotted splint lock unit. Other the other hand, tensile stress on the bottom surface was completely opposite. Figures 10(a) and 10(b) shows the strain change between 1 and 1 to 1–3 and 1–4 to 1.5, this change was due to the eversion of lock unit due to slippage. However, this phenomenon was not observed in surface snap-in lock unit, indicating that this lock unit with four screw bolts can effectively control the eversion.

Stress at different location of the U-shaped steel support was different. For surface snap-in lock unit, stress near the leg was higher than the roof. This was similar to its axial load trend. For two-slotted splint lock unit, the stress exhibited "high-low-high" distribution. However, the axial loads were not significantly different. This suggests that the eversion of lock units was more severe, which led to stress concentration on the surfaces. Therefore, it is recommended to install surface snap-in lock unit on the roof and rib of the roadway to increase stability while reducing the cost.

4.3.2. Surface Stress Change of Different Lock Units under High Vertical Pressure. Stress fluctuated with the support deformation under high vertical stress, see Figure 11. It is noticed that the sudden change in support also resulted in



(a)

(b)

FIGURE 8: The relationship between bolt force and frame slippage on overlapping parts under high vertical pressure. (a)Axial load of two-slotted splint lock unit and (b)axial load of surface snap-in lock unit.

the change in stress. Surface stress of two-slotted lock unit was considerably higher than the surface snap-in lock unit, while the minimum stress was found on the bottom surface of surface snap-in lock unit. For surface snap-in lock unit, stress near the leg was higher than the roof, which was similar to the lock unit under high confining pressure, see

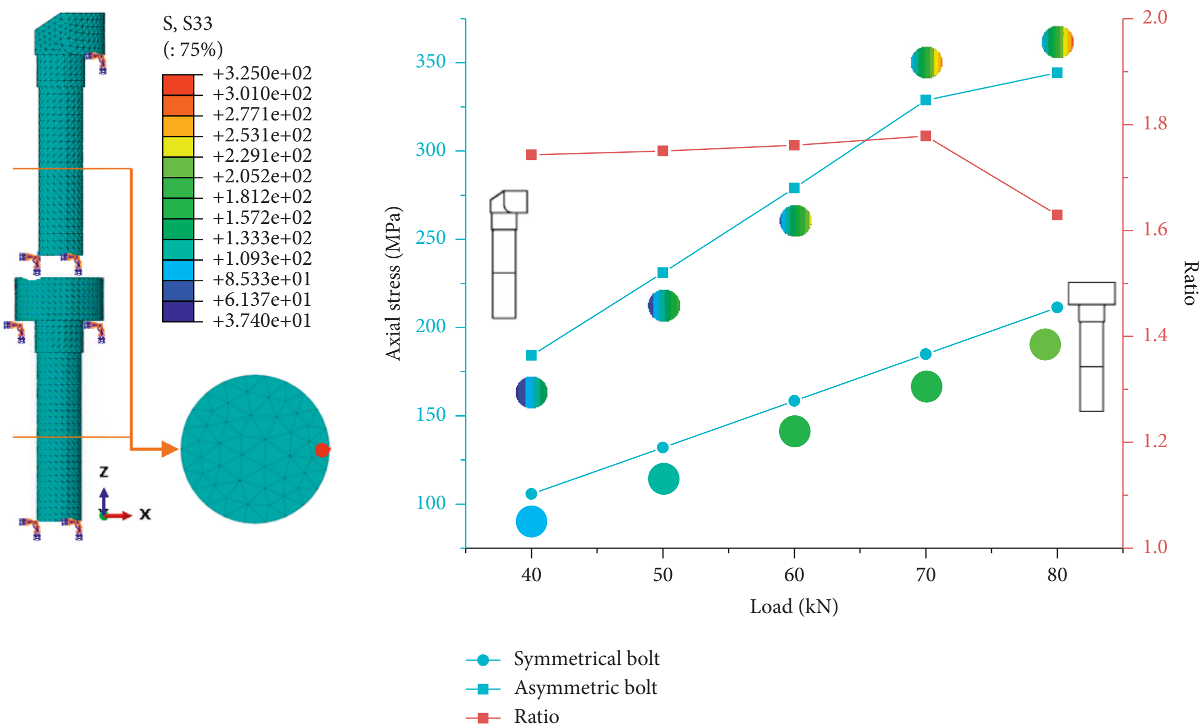


Figure 9: Stress distribution and change on Z-plane of different type of screw bolts under same loading conditions.

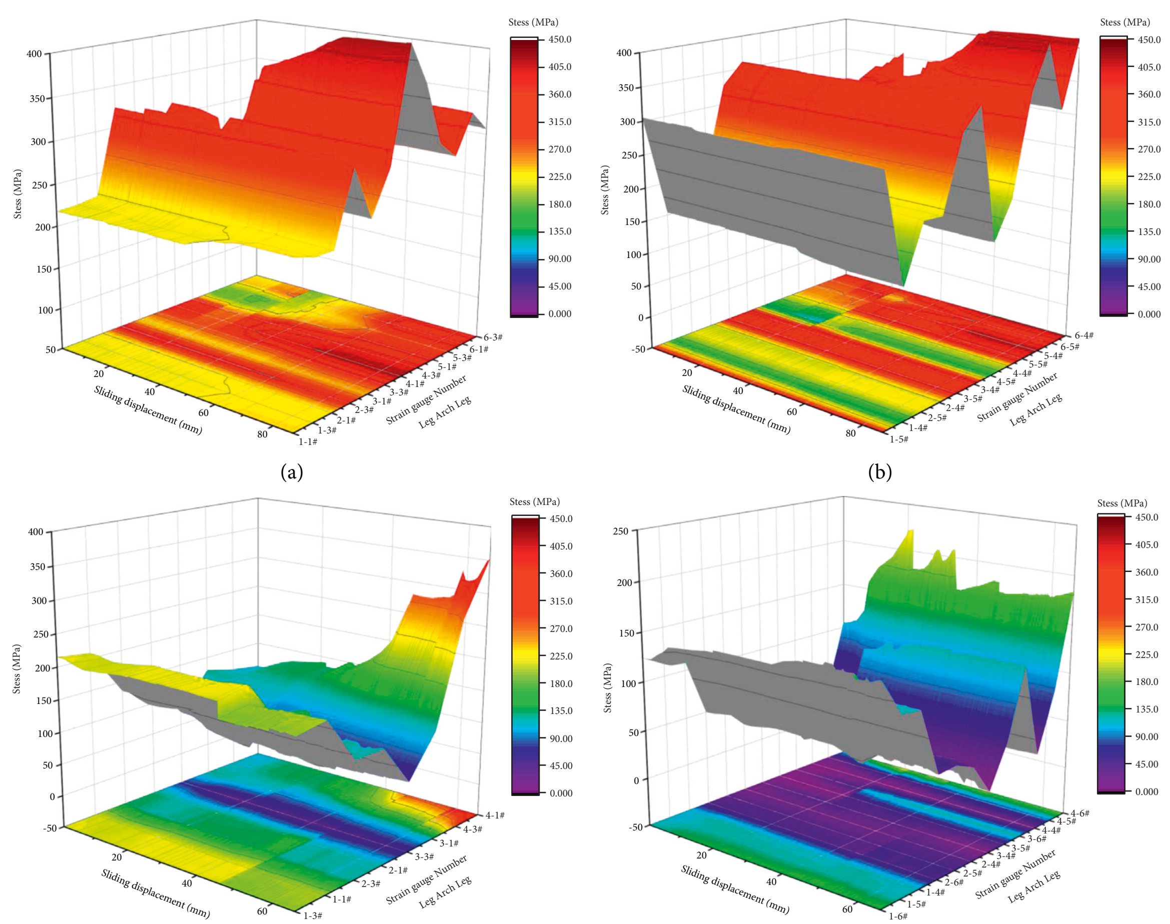


Figure 10: The relationship between surface stress and slippage magnitude of lock units under high confining pressure. (a)Top surface of two-slotted splint lock unit, (b)bottom surface of two-slotted splint lock unit, (c)top surface snap-in lock unit, (d)bottom surface snap-in lock unit.

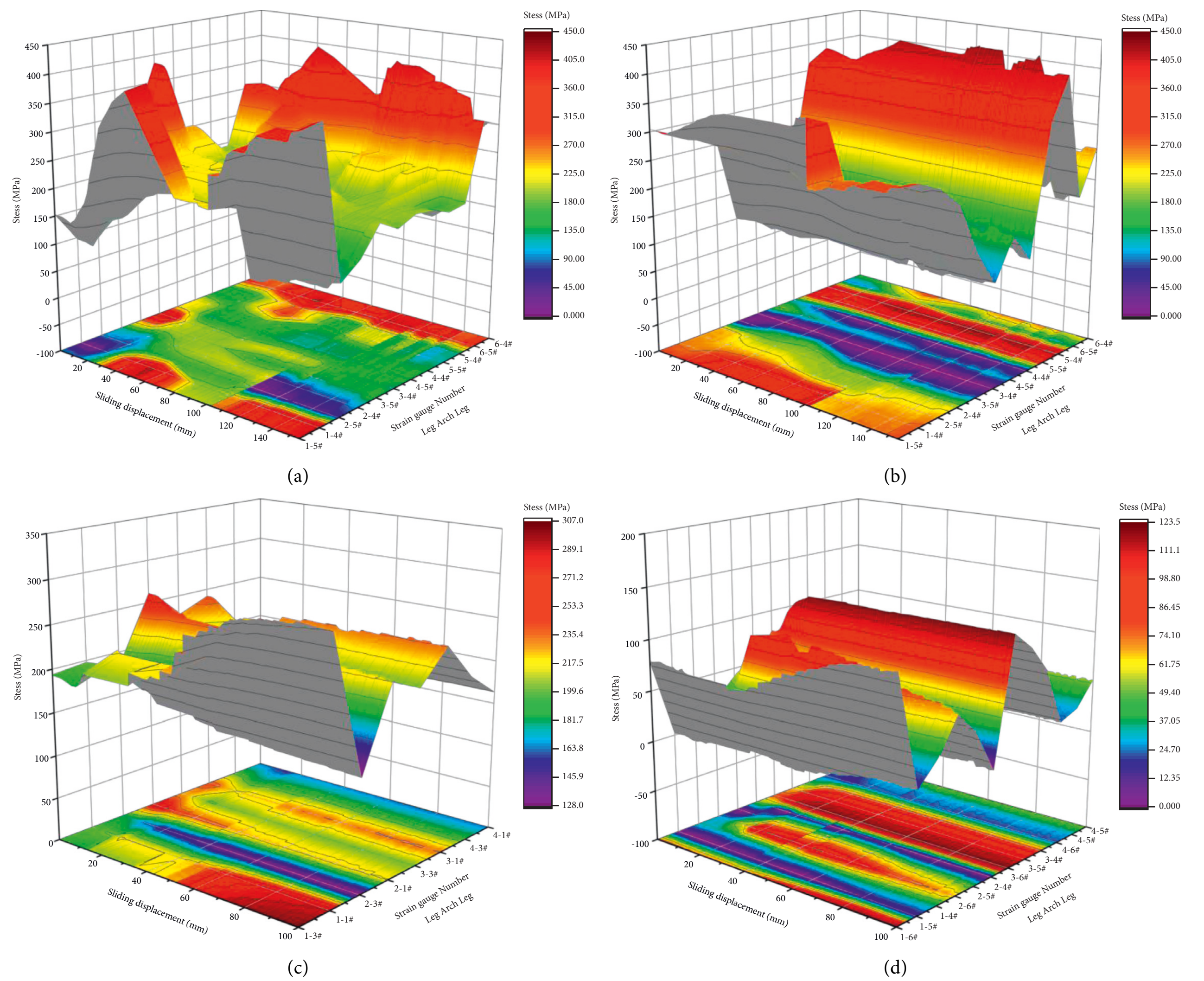


Figure 11: The relationship between surface stress and slippage magnitude of lock units under high vertical pressure. (a)Top surface of two-slotted splint lock unit, (b)bottom surface of two-slotted splint lock unit, (c)top surface snap-in lock unit, (d)bottom surface snap-in lock unit.

Figure 11(c). The stress distribution of two-slotted splint lock unit was similar to the surface snap-in lock unit, see Figure 11. It was also similar to the axial load distribution, suggesting that lock units near the leg provided more resistance under high vertical pressure.

Based on the comparisons, there were three conditions observed: similar stress magnitudes, different stress magnitudes, and completely opposite stress magnitudes. Hence, stress distribution in lock unit in practice is different from the theoretical calculations. This implies that the current theories cannot reflect the behavior of lock units under nonlinear deformation. Thereby, surface snap-in lock units provide higher resistance to eversion and tearing than two-slotted splint lock unit. Lock unit at different locations experience different stress under various conditions and the resistance each lock unit can provide is also different. Overall, an optimized supporting system can be developed by considering the stress conditions and lock unit type.

5. Field Validations

5.1. Conditions of Test Roadway. The depth of cover at Peigou coal mine Longwall 42091 is 507–560 m. Its roadway is a typical “three-soft” roadway type. The immediate roof is highly fractured with slippery surface at an average thickness of 6.7 m. The strength of the roof is $f = 4$–6. The immediate floor is mudstone, in which it turns slurry when filled with water. The thickness and strength of the floor are 11 m and $f = 4$–5. In this type of roadway, the surrounding rock is generally fractured with significant deformation, which bolting cannot provide sufficient support capacity. Therefore, U-shaped steel support is the common supporting type under this condition.

In this study, 29# U-shaped steel support was used with interval between 500 mm and the legs are 5° out. Three-section arch was selected as the support structural since it provides relatively high stability. The overlapping length of the roof and leg was 500 mm. Two sets of surface snap-in and

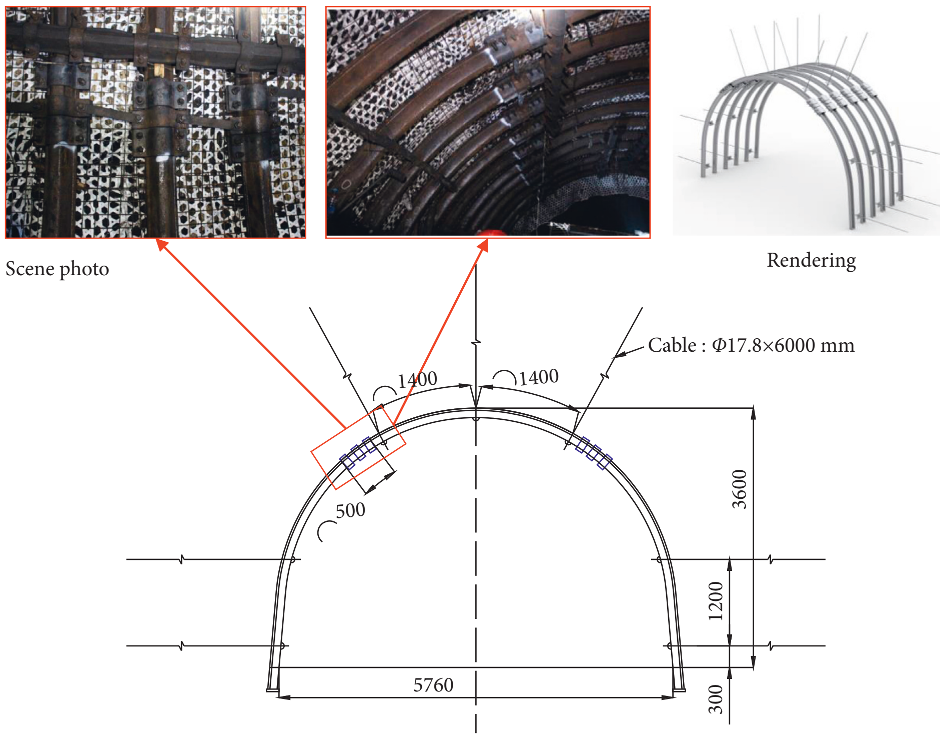


Figure 12: Parameters for support and field view.

one set of two-slotted splint lock units were used along the overlapping length, and the pretension on screw bolts were over 300 Nm, see Figure 12. Two pairs of cable bolts were installed at 300 mm and 1500 mm from the floor and three cable bolts were installed on the roof. Φ17.8 mm 1860 steel strand was used for cable bolts at 6 m length. The distance between the roof bolts was 1400 mm × 1000 mm, whereas distance at rib was 1200 mm × 1000 mm. To ensure the structural stability of steel support while considering the adaptability of cable bolts to host rock deformation, 100 kN pretension was applied. A schematic view can be seen in Figure 12.

5.2. Field Test. To further examine the performance of U-shaped steel support, displacement stations were installed in the roadway to monitor the deformation of roof, floor, and rib. Figure 12 shows the monitored data from the stations.

Based on Figure 13, significant deformation was observed between 0 and 20 days after the roadway expansion. The average displacement rate of roof and floor was approximately 7.6 mm/d, while the average displacement rate of ribs was 4.7 mm/d. This is mainly due to the stress redistribution from roadway expansion, which resulted in rock fracture and rapid shear deformation. After 20 days, the deformation of surrounding rock was controlled effective with diminishing surface displacement rate. After 40 days, the roadway reached stable condition. At that stage, the maximum deformation of roof and floor as well as ribs was 220 mm and 149 mm.

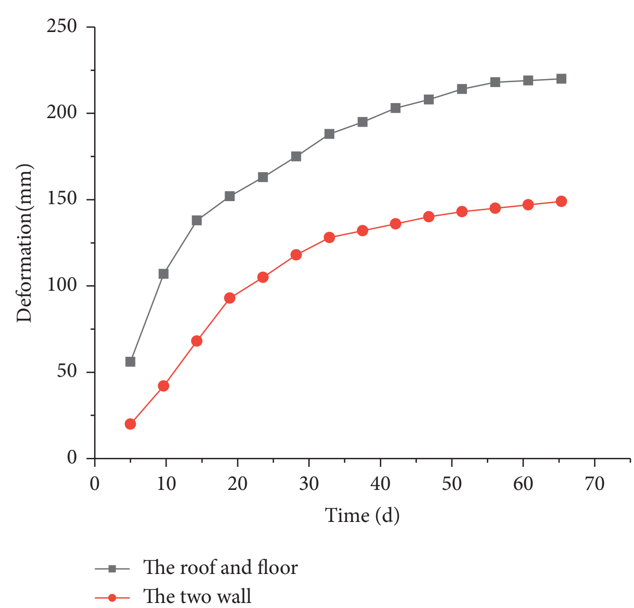


Figure 13: Deformation of roadway.

According to Figure 14, it can be seen that the displacement rate of roof and floor gradually decreased while the displacement rate of ribs did not slow down. This was because the late installation of cable bolts, which was not able to prevent rib deformation in the first place. Although the final displacement rate was negligible. This means since the implementation of the designed support system, the total deformation of surrounding rock was not significant and was able to be managed.

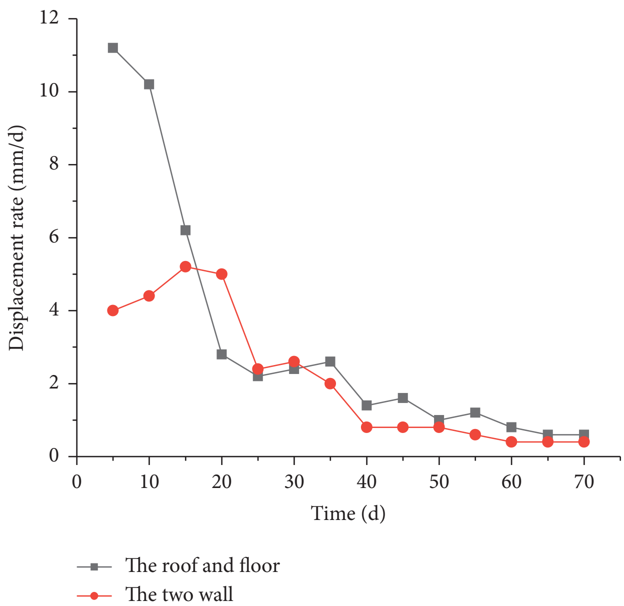


Figure 14: Displacement rate of roadway.

6. Conclusions

This paper studied the deformation and failure process of U-shaped steel support and developed surface snap-in lock unit to overcome the limitation of two-slotted splint lock unit. The experimental and field investigation on two types of lock units revealed that:

(i) The relationships between support capacity and deformation were similar between two types of lock unis under the same loading conditions. The initial compressional force and ultimate bearing capacity of support with two-slotted splint lock unit were greater than the initial compressional resistance of surface snap-in lock unit. However, the two-slotted splint lock unit provides better stability. Under symmetrical load, the two-slotted splint lock unit can offer higher bearing capacity.

(ii) The screw bolts near the leg experience higher load under all conditions. This means these bolts provide more sliding resistance. Under the condition where the overlapping parts slide or suddenly deform, surface snap-in lock unit is more stable, particularly under high vertical pressure. The maximum stress of screw bolts on two-slotted splint lock unit was 1.6–1.8 times of the surface snap-in lock unit.

(iii) When the steel support was under compressional movement, surface snap-in lock unit provides higher resistance on eversion and tearing. Although, the resistance provided by lock units can be different at different locations under various loading conditions.

(iv) Based on a combination of two lock unit types, the eversion of lock unit can be managed and subsequently increasing the stability of steel support. This can also prevent the screw bolt or lock unit from failure using single lock unit type. The performance of the proposed design has also been validated against field conditions and proven effective.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Conceptualization, Zhili Su; data curation, Zhili Su; formal analysis, Xingkai Wang; investigation, Zhili Su; project administration, Wenbing Xie; resources, Wenbing Xie; software, Qingteng Tang; supervision, Wenbing Xie and Shengguo Jing; visualization, Shengguo Jing and Qingteng Tang; writing–original draft, Zhili Su; writing–review and editing, Zhili Su.

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