EXPERIMENTAL RESEARCHES ON PREVENTION OF ICE COATING GALLOPING USING SMALL-SCALED SIMULATED TRANSMISSION LINE

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Abstract: As there are lots of practical difficulties of researches on ice coating galloping of real transmission lines, North China Grid Co., Ltd constructed a number of small-scale simulated transmission lines and developed researches on galloping. Although these simulated transmission lines are not totally equal to real transmission lines, the research results can also be used to analyze the mechanical characteristics and the prevention methods of galloping. This paper gives a brief introduction of these small-scaled transmission lines, shows some galloping characteristics and presents a modified configuration scheme of phase to phase spacer.

1. INTRODUCTION

At present, the phase to phase spacer is adopted in the prevention of galloping of 500kV compact transmission line and double-circuit transmission line, even applied in 220kV and 110kV lines. But unfortunately, there were two flashover accidents caused by galloping in the compact lines which has installed phase to phase spacer separately in April and October in 2010. Therefore, the rationality of spacer installation scheme is drew great consideration. In order to research on the configuration of spacer, two simulated overhead transmission line were built in Shahe experimental station of North China Grid Company Ltd in Changping district of Beijing. Meanwhile, the researches on characteristics and prevention methods of galloping are being developed.

2. RESULTS AND DISCUSSION

The research discovered that there was a range of excitation locations where the galloping easily happened. When the wind force acted on the excitation locations, the conductor galloping was easily to happen with distinct form. When the conductor was confronted with constant wind, the galloping was difficult to happen.

When the angle between the wind direction and the transmission line was among 20~60°, the conductor galloping was easily to happen; When the wind direction was perpendicular to the transmission line, the galloping was less easy to happen than that of the above angle.

As the wind speed increased, the most obvious process of galloping changed from high frequency to low frequency, and the number of half waveform peak points was decreased, but the amplitude of galloping increased.

The galloping was less easy to happen with the increase of conductor tension force.

There exists a fixed frequency which is easily excited by wind force in the conductor and tower system. This frequency is respond to a fixed wave length. At this frequency, the system is probable to resonate with the wind and normal galloping would happen easily. Meanwhile, half-wave length and half-wave number is certain. With the increase of the section span length, the half-wave number would increase only if the new span is big enough to create a new half-wave. This viewpoint is verified by the video record. In the video, when the span distance is around 250-300m, the form of galloping is like a sine wave with two half-waveform, when the span distance is increased to 550m, the form of galloping is like two sine waves with four half-waveform.

Resonate galloping easily happens when spans have similar length.

Finally, we developed some new configuration of phase to phase spacer to prevent galloping. We recommend triangle arrangement of spacers in the compact transmission line while in-line arrangement in double-circuit transmission line. Prevention effect is better when the material of the spacers is harder.

3. CONCLUSION

There was a range of excitation locations where the galloping easily happened.

The number of half waveform or the number of peak point under most obvious galloping form is relevant to the wind energy absorbed. While the energy is higher, the number is fewer.

One hypothesis: there exists a fixed frequency which is easily excited by wind force in the conductor and tower system. And the distance between every adjacent peak points of conductor may be restricted to a range at this frequency.

Triangle arrangement of spacers in the compact transmission line while in-line arrangement in double-circuit transmission line are better than staggered arrangement.

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Experimental Researches on Prevention of Ice Coating Galloping Using Small-scaled Simulated Transmission Line

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***Abstract*—In China, there was a large-area ice coating galloping of transmission line from October to April in the last year, which caused great cost to national grid. Therefore, State Grid Corporation of China (SGCC) develops lots of researches on this area and plans to transform some transmission lines to avoid or decrease ice coating galloping. While the cases of ice coating galloping happened several times on transmission lines operated by North China Grid Company Ltd. (NCGC), the subsidiary of SGCC from 2007. As a result, NCGC adopted some measures to prevent galloping and has accumulated experience in this field.**

Because there are lots of practical difficulties of researches on ice coating galloping of real transmission lines, NCGC constructed a number of small-scaled simulated transmission lines and developed researches on ice coating galloping of transmission line. Although these simulated transmission lines are not totally equal to real transmission lines, the research results can also be used to analyze the mechanical characteristics of ice-coating lines and the prevention methods of galloping can be applied to real transmission lines as a reference. This paper gives a brief introduction of these small-scaled transmission lines, shows galloping characteristics and presents the advantages and disadvantages of different configuration with phase to phase spacers.

Keywords-galloping; simulated transmission line; phase to phase spacer; configuration

I. INTRODUCTION

Galloping is an oscillatory process of the conductors of transmission lines influenced by wind. The frequency of galloping is generally between 0.1-3Hz with the highest amplitude of 10m [1-2]. There are many reports about galloping in the USA, Japan, Canada, etc and these countries have the history of 80 years researches on galloping [3]. However, the records of galloping in China just began in 1950s and the relevant researches started from the galloping accident of Zhongshankou large span overhead transmission line in Hubei province in 1987 [4]. In order to research on the characteristic of galloping, Den Harto, McDaniel, Nigol, etc developed relevant experiments and present important theories of galloping [5-8]. Then, the technician from Canada, France, Japan built several experimental real-lines and did further researches on galloping [9-12]. However, the formation of galloping is complicated and caused by the resonance of the frequency of the wind-force and the system frequency of conductor and tower. So far, the principle of galloping has not been fully explored and the prevention methods were still in study at home and abroad.

A large area of galloping happened in the spring of 2010 in China which was harmful to the safety of transmission line operation. Therefore, State Grid Corporation of China (SGCC) pays great attention to the prevention and cure of galloping and encourages in installment of anti-galloping device to decrease the adverse impact of galloping. As the sub company of SGCC, North China Grid Company Ltd (NCGC) carried out relevant researches in the last 3 years and adopted some prevention methods including installment of double pendulum anti-galloping device or phase-to-phase spacer in the important transmission lines. Therefore, no flashover and tower-conductor damage happened in lines operated by NCGC in the spring of 2010 when widespread galloping existed in China. Based on the experience of prevention of galloping, NCGC thought that phase to phase spacer is more useful. At present, the spacer is adopted in the prevention of galloping of 500kV compact transmission line and double-circuit transmission line, even applied in 220kV and 110kV lines. But unfortunately, there were two flashover accidents caused by galloping in the compact lines which has installed phase to phase spacer separately in April and October in 2010. Therefore, the rationality of spacer installation scheme is drew great consideration. In order to research on the configuration scheme of spacer, two simulated overhead transmission line were built in Shahe experimental station of NCGC in Changping district of Beijing. Meanwhile, the researches on characteristics and prevention methods of galloping are being developed. This paper gives a brief introduction of the researches. For several reasons, the details about some experimental results are not listed in this paper.

II. CONSTRUCTION OF SMALL-SCALED SIMULATED TRANSMISSION LINE

A. Construction of Transmission Line

Regarding the researches on galloping, the experimental results would be more accurate if the real transmission line is used. However, meteorological condition is required in the adoption of real line which is difficult to control. Although part of the meteorological condition can be controlled by using wind tunnel, the investment would be very high. Therefore, real line is hard to use in the research. In order to achieve the principles and prevention methods of galloping, NCGC built a 500kV simulated compact transmission line and double-circuit transmission line respectively in the scale of 1:50 in Shahe experimental station. The photos of the above two lines are shown in Fig.1 and Fig.2.

Figure 1. Small-scaled Simulated Compact Transmission Line

Figure 2. Small-scaled Simulated Double-circuit Transmission Line

The arrangement of 3-phase conductor in the real 500kV compact transmission line is inverted regular triangle and each phase conductor is 6 split with the split diameter of 0.75m like a regular hexagon. Each conductor has been hung by two clusters of V-style insulators. The phase distance is 6.7m. The structure of tangent tower used in small-scaled simulated compact transmission line is the same as the real tower. The terminals of line are fixed by spring instead of strain tower, so as to observe the change of tensile force in the process of galloping. The conductor structure in small-scaled line is the same as it in the real line and the material is steel-cored wire whose modulus of elasticity is similar with the real conductor. The total length of small-scaled simulated compact line is 36m, divided into 3 segments by 2 towers. The length of each section and height difference of tangent tower can be adjusted freely. To make sure the flexibility of conductor, the ratio of the terminal tensile force to gravity of the conductor in the small-scaled simulated line is similar to that of real line.

The arrangement of conductors in the real 500kV double-circuit transmission line is in vertical distribution and each phase conductor is made up of 4 sub-conductors in regular quadrangle hanged by clusters of V-style insulators. The phase distance is between 11 and 12m. The design mentality of small-scaled simulated double-circuit transmission line used in the experiment is similar with the small-scaled simulated compact line mentioned above, considering the material, mechanical characteristic, etc. The length of small-scaled simulated double-circuit transmission line is 50m, divided into 4 sections and the length and height of tower can be adjusted freely. The rulers are installed beside the lines to observe the amplitude of galloping.

The persistent and stable wind force for these experimental lines is supplied by 5 blowers and the area of wind letout is 0.7×0.6m2 which is enough for covering all phase of conductors. The location and elevation of the blowers can be adjusted according to requirement. In order to absorb the wind force, there are several wind blades installed on the conductors so as to stimulate the influence of asymmetric ice covering to the conductors. The wind blade is rectangular and the width is 2 times of the split diameter. The location of the wind blade can be adjusted based on requirements.

Observing pots are allocated in average and the galloping images are recorded by camera. The oscillating amplitude of each pot is measured by image processing software to analyze the characteristic of galloping and test the effect of anti-galloping device.

B. Discussion of the Equivalence of Small-scaled Simulated Transmission Line and Real Line

The dimension of small-scaled transmission line is in fixed scale to real line and the material, conductor characters and structure are all similar with real line. However, the relationship of tension and the wave characteristic with the real transmission line is not clear during galloping. Still, in order to be close to the real conductor form during galloping, we can adjust the parameters of the small-scaled transmission line and wind force and wind blade dynamically based on the video records of the galloping condition of real transmission line. But the records can not reflect all galloping conditions, so the simulation must be one of them. By means of comparison of multiple records, we can consider it as the typical galloping condition and the simulation results can be used in the relevant research.

At present, the small-scaled line cannot be demonstrated completely equivalent to real transmission line and the experimental results can't be directly applied to the anti-galloping work of real transmission line. However, the experimental results are still useful for finding out the principles of galloping and the effectiveness of prevention methods of the galloping.

Researches on the equivalence of small-scaled transmission line and real transmission line will be carried out this year.

III. Observation on Galloping of Small-scaled Line

A. *Influence of Wind on Galloping*

As the difference of location, direction and the force of wind, the difficulty of beginning galloping and the form of galloping of small-scaled line is different. With some time work, we found out some principles of galloping by dynamically adjusting the relevant parameters of blowers in small-scaled line. The experiments were based on the small-scaled simulated compact transmission line, and a section with the span of 20m was selected.

At first, the research paid attention to the influence of the sphere of action of the wind on galloping. In this research, we installed several wind blades averagely in this 20m section and applied the natural wind, usually blew in Shahe station, with the speed of 10m/s to this section. The wind shoe width was more than 20m which means that all section was influenced by this natural wind. The separation angle between the wind direction and the route of transmission line was 70 degree. Due to this wind, three-phase conductors of the small-scaled line were difficult to happen galloping in vertical direction and the windage was mainly occurred. The amplitude of the windage changed with the wind force. Then, one blower was used as the source of wind and the action area was restricted by the dimension of blower letout. The separation angle between the wind direction and transmission line was also 70 degree and the wind speed was set at 10m/s. Several locations were set at every 1.5m from middle to the end of the section. On this condition, we observed different forms of galloping when the blower was laid on different location.

The experiment showed that when the blower was in the middle of section, the windage was mainly in horizontal direction of the three-phase conductors. Galloping in vertical direction was sporadic with small amplitude. When moving the blower into the 1/3 distance to the end of section, the galloping happened frequently with long lasting. But the average amplitude was small. When moving the blower into the 1/6~1/4 distance to the end of section, conductor galloping happened quickly with the highest amplitude. Three-phase conductors collided with each other and multi-frequency galloping exists evidently. When moving the blower closer to the end, there was only high frequency conductor galloping with small amplitude.

The research also studied on the influence of the separation angle between the wind direction and the line to the probability of galloping. The blower was located at 1/6 distance to the end of section and the wind speed was set at 10m/s. The separation angle between the wind direction and the line was changed at every 10 degree. It was discovered that when the angle was between 20 and 60 degree, the three-phase conductor galloping happened easily and the amplitude was relative high; when the angle was below 20 degree, conductor was almost not influenced by the wind force; when the angle was between 60 and 90 degree, conductor galloping still happened but lasting time was short and amplitude was smaller. When the angle was between 20~90 degree, the galloping peak point was basically fixed in the same position no matter how much the angle is. The results were almost the same with the opinion in paper [9].

In this research, the relationship between the wind speed and the biggest amplitude was studied when the blower was located at 1/6 distance to the end and the separation angle was 60 degree. During the wind speed of 4~15m/s, the biggest amplitude of the conductor galloping enhanced with the increase of the wind speed. As the wind speed increased, conductor galloping changed from high frequency to multi frequency with low frequency, and the number of half waveform peak points was decreased. The low frequency with few peak points galloping was more difficult happened than high frequency galloping.

B. *Influence of Line Parameters on Galloping*

We still used the same module mentioned above to study the influence of line parameters on galloping. The blower was located at 1/6~1/4 distance to the end and the angle was set at 60 degree with the wind speed of 8m/s. This experiment focused the change of galloping form when the tensile force of conductor and section distance changed. At the beginning, tensile force of conductors was adjusted to 7N. Then we observed each phase had three distinct galloping peak points with high amplitude. Other peak points still existed, but not clear as the above three points. Among these three peak points, the first point was just against the blower and the distance to the end was 3.5m. The second peak point was 6m distant to the first point and the third point was 7m distant to the second point. The distance of each peak point was bigger as the distance to excitation point increased. When the tensile force was adjusted to 30N, each phase had six distinct galloping peak points with very low amplitude and the galloping was not obvious. The distance of adjacent two peak points was between 3~3.5m. Paper [4] gave part of the explanation.

Then, tensile force was again adjusted to 7N and the section distance increased to 30m. While located the blower at 3.5m to the end and keep the same angle and wind speed. It was discovered that in the research each phase conductor had 5 distinct galloping peak points and the frequency was close to that in the 20m section. The distance between peak points was smaller near the excitation point and sag point.

The research also showed that resonate galloping was easily triggered when the length of the adjacent section was similar with the excitation section.

C. Summary

We can draw some conclusions and presumed some viewpoints from the above research:

1) The research discovered that there was a range of excitation locations where the galloping easily happened. When the wind force acted on the excitation locations, the conductor galloping was easily to happen with distinct form. When the conductor was confronted with constant wind, the galloping was difficult to happen.

2) When the angle between the wind direction and the transmission line was among 20~60°, the conductor galloping was easily to happen; When the wind direction was perpendicular to the transmission line, the galloping was less easy to happen than that of the above angle.

3) As the wind speed increased, the most obvious process of galloping changed from high frequency to multi-frequency with low frequency, and the number of half waveform peak points was decreased, but the amplitude of galloping increased.

4) The galloping was less easy to happen with the increase of conductor tension force.

5) There exists a fixed frequency which is easily excited by wind force in the conductor and tower system. This frequency is respond to a fixed wave length. At this frequency, the system is probable to resonate with the wind and normal galloping would happen. Meanwhile, half-wave length and half-wave number is certain. With the increase of the section span length, the half-wave number would increase only if the new span is big enough to create a new half-wave.

6) Resonate galloping easily happens when spans have similar length.

The viewpoint 5 above is verified by the video record. In the video, when the span distance is around 250-300m, the form of galloping is like a sine wave with two half-waveform, when the span distance is increased to 550m, the form of galloping is like two sine wave with four half-waveform.

IV. CONSIDERATION ON THE CONFIGURATION OF SPACER

Based on small-scaled simulated line, we studied the effect of galloping prevention of the phase to phase spacer in different material and different configuration, and advised a better configuration of spacer.

A. Material of Spacer

We thought that the softness of the spacer had an influence on galloping prevention. In the research, we measured the softness of three kinds of the spacer models made of different material and also measured the softness of the phase to phase spacer used in real line. The material of the first kind spacer was binding wire, which was a kind of soft iron wire with the diameter of 0.2mm; the second one was stranded copper wire with plastic insulated cover. The third one was nylon wire, whose softness was similar to the soft spacer developed by NCGC. The material of the phase to phase spacer used in real transmission line in China is fiberglass mostly. No outside force in horizontal direction, the middle point of the real spacer (diameter 30mm and distance of 5.7m) drooped at 38cm under gravity force. In the above simulated material, the softness of the second one is similar to the real spacer used widely at present, while the first one is harder and the third one is softer. The comparison of softness of three materials is referred in Fig.3.

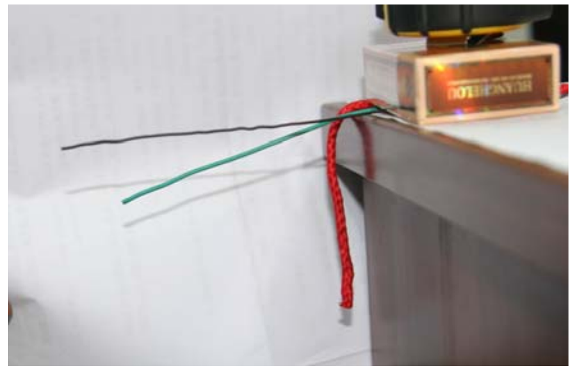

Figure 3. Comparison of Softness of Three Materials

B. Selection of Configuration of Spacers

According to the configuration suggested by SGCC, the configurations of phase to phase spacers in 500kV compact transmission line and double-circuit transmission line are shown in Tab.1 and Tab.2 respectively.

TABLE I. CONFIGURATION OF PHASE TO PHASE SPACERS IN 500KV COMPACT TRANSMISSION LINE

Span Distance L/m	**Quantity (piece)**	**Installation location**		
		upper phase A-lower phase B	***upper phase A- upper phase C***	***upper phase C- lower phase B***
L≤300	2	1/3L	/	2/3L
300≤L<500	3	1/4L	1/2L	3/4L
500≤L<700 #	5	2/9L、3/5L	1/2L	2/5L、7/9L
700≤L<1000	6	1/7L、4/7L	1/4L、5/7L	2/5L、7/8L
L≥1000	7	1/7L、4/7L	1/4L、1/2L、5/7L	2/5L、7/8L

TABLE II. CONFIGURATION OF PHASE TO PHASE SPACERS IN 500KV DOUBLE-CIRCUIT TRANSMISSION LINE

Span Distance L/m	**Quantity (piece)**	**Installation location**	
		Upper phase-middle phase	***middle phase –lower phase***
L≤300	2	1/3L	2/3L
300≤L≤500	3	1/4L、3/4L	1/2L
500≤L≤800 *	5	2/9L、1/2L、7/9L	2/5L、3/5L

L＞800	7	1/7L 、 2/5L 、 3/5L、7/8L	1/4L、1/2L 、3/4L

The above configuration can be summarized as a staggered arrangement method in order to control more galloping peak points using less spacer. In the above configuration, no matter how long the span distance is, 1 half waveform with 1 peak point, 2 half waveform with 2 peak point and multi half waveform galloping are all possible to happen. Less peak point galloping is more possible in short distance span and more peak point galloping is more possible in long section distance. Only below 4 peak points galloping is need to be controlled when the span distance is more than 800m. The rationality of the above configuration is not validated yet as the research on galloping need to be in detail. But after spacer installation based on the above configuration, the galloping is still happened several times in the Guyuan-Taiping compact transmission line. Therefore, we reconsider the rationality of the above configuration.

Based on our experiment, this paper recommends that the spacers installed in triangle in compact transmission line, and upper phase, middle phase, lower phase are connected by two spacers in double-circuit transmission line. Staggered arrangement is not recommended in neither above two arrangements. The special configurations are shown as Tab.3 and Tab.4.

TABLE III. SPACER ARRANGEMENT IN TRIANGLE IN 500KV COMPACT TRANSMISSION LINE

Span Distance L/m	**Quantity (piece)**	**Installation location**		
		upper phase A-lower phase B	***upper phase A-lower phase B***	***upper phase A-lower phase B***
L≤300	2	1/2L	/	1/2L
300≤L ＜ 500	3	1/2L	1/2L	1/2L
500≤L ＜ 600##	5	1/3L，2/3L	1/2L	1/3L，2/3L
600≤L ＜ 700	6	1/3L，2/3L	1/3L，2/3L	1/3L，2/3L
700≤L	9	1/4L ， 1/2L，3/4L	1/4L ， 1/2L，3/4L	1/4L ， 1/2L，3/4L

TABLE IV. SPACER ARRANGEMENT IN LINE IN 500KV DOUBLE-CIRCUIT TRANSMISSION LINE

Span Distance L/m	**Quantity (piece)**	**Installation location**	
		Upper phase-middle phase	***middle phase –lower phase***
L⩽400	2	1/2L	1/2L
400 ⩽ L ⩽ 600	4	1/3L，2/3L	1/3L，2/3L
600 ⩽ L ⩽ 800**	6	1/4L，1/2L，3/4L	1/4L，1/2L，3/4L
L＞800	8	1/5L ， 2/5L ， 3/5L，4/5L	1/5L，2/5L，3/5L，4/5L

We think that the span distance should be divided according to the fixed half-wave number. The span distance division method shown in Tab.1-4 was based on experience, without evidence support ion.

C. Analysis of the Experimental Results

At first, we compared different configuration qualitatively using the binding wire with the biggest rigidity as the simulated spacer. Then, we compared the different material of spacer after the optimization of experimental results.

The results of the smallest phase distance in different test pots with different configuration of the compact line at 12m section distance and double-circuit line at 15m section distance under the same wind condition are shown in Tab.5 and Tab.6. The section is divided equally by the test pots.

TABLE V. EFFECT OF DIFFERENT CONFIGURATION IN SIMULATED COMPACT TRANSMISSION LINE

Test pot	**the smallest phase distance/mm**	**staggered arrangement according to # in Tab.1**	**Triangle arrangement according to ## in Tab.3**
A	left-right	49	68
	left-lower	75	71
	right-lower	68	53
B	left-right	70	70
	left-lower	70	100
	right-lower	45	75
C	left-right	45	65
	left-lower	85	90
	right-lower	95	110

TABLE VI. EFFECT OF DIFFERENT CONFIGURATION IN SIMULATED DOUBLE-CIRCUIT TRANSMISSION LINE

Test pot	**the smallest phase distance/mm**	**staggered arrangement according to *in Tab.2**	**Line- arrangement according to ** in Tab.4**
A	up-middle	120	100
	middle-lower	55	50
B	up-middle	50	90
	middle-lower	30	80
C	up-middle	120	140
	middle-lower	45	90
D	up-middle	90	120
	middle-lower	120	90
E	up-middle	120	120
	middle-lower	30	60

The above table shows that phase distance after galloping in the original staggered arrangement is smaller than that of the new configuration under the condition of the same section distance and the same quantity of spacers, which increases the risk of phase-phase discharging. Therefore, galloping prevention of the new configuration is obviously better than that of the original one.

In the new configuration, the galloping of different phase maybe happened synchronously. We measured the terminal tension considering that synchronous galloping would increase the terminal force of tower. The research discovered that the terminal force of transmission line during synchronous galloping was almost equal to that during normal galloping. It showed that the new configuration would not make more damages to terminal tower.

Meanwhile, the research focused on the prevention effect of the spacers made of different material under the same configuration. This paper discovers that prevention effect is better when the material of the spacers is harder. The galloping amplitude with the spacer made of binding wire reduces up to 20% than that of the spacer made of the second material.

Of course, the experiment also demonstrates that when the spacers are densely arranged, the prevention effect is better.

V. CONCLUSION

We obtained the following new conclusions based on the research.

The research discovered that there was a range of excitation locations where the galloping easily happened.

The number of half waveform or the number of peak point under most obvious galloping form is relevant to the wind energy absorbed. While the energy is higher, the number is fewer.

Resonate galloping easily happens when spans have similar length.

One hypothesis: there exists a fixed frequency which is easily excited by wind force in the conductor and tower system. And the distance between every adjacent peak points of conductor may be restricted to a range at this frequency.

We recommend triangle arrangement of spacers in the compact transmission line while in-line arrangement in double-circuit transmission line. Prevention effect is better when the material of the spacers is harder.

In the following research, we will detail the above ideas based on small-scaled simulated transmission line. Combining the observation of real line galloping, we can further confirm the relationship of the energy, the number of peak points, the frequency, the wave length and the tension force. Meanwhile, we will develop the research on the galloping form in different terrain and the influence after spacer installation.

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