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RESEARCH ARTICLE

# Discussion on the Safe Distance Between HVDC Electrode and Pipeline

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**ABSTRACT** The safe distance is an important reference for the mutual avoidance and interference reduction between the pipelines and HVDC electrodes in the planning stage. However, the definition of pipe-to-electrode safe distance in existing standards and researches is still not clear yet. In order to study the reasonable value of safe distance, firstly, the influencing factors of safe distance is analyze through simulation. Soil structure, pipeline length, coating surface resistivity and grounding current are the main factors while electrode type and pipe size are the minor ones. Then, taking touch voltage and DC corrosion rate as the limit respectively, the pipe-to-electrode safe distance is analyzed under different parameter combinations. When touch voltage is taken as the limit, the safe distance to meet the 70V limit is 11km~25km ($I$ = 3000A) and 16km~52km ($I$ = 6000A); The safe distance to meet the 35V limit is 16km~52km ($I$ = 3000A) and 24km~87km (I=6000A). When DC corrosion is taken as the limit, the safe distance to meet the 0.1mm/a limit is 14km~38km ($I$ = 3000A) and 20km~56km ($I$ = 6000A); The safe distance to meet the 0.0254mm/a limit is 32km~65km ($I$ = 3000A) and 44km~70km ($I$ = 6000A); The safe distance to meet the 0.01mm/a limit is 44km~70km ($I$ = 3000A) and 52km~72km ($I$ = 6000A).In order to solve the problems of unknown parameters, uncertain limit standards, and too-large safe distance, the acceptable safe distance is further extracted. The indicator $\kappa$ =0.8 is suggested. The acceptable safe distance of 100km short pipeline is 13km ($I$ = 3000A), 19km ($I$ = 6000A) while that of 700km short pipeline is 25km ($I$ = 3000A), 27km ($I$ = 6000A). For the case where the grounding current and pipeline length are also unknown, it is recommended to take the acceptable safe distance of 30km. In addition, the safe distance or acceptable safe distance of long pipelines can be valued according to that of the short ones after segmentation. The acceptable safe distance of 100km short pipelines is 18km.

**INDEX TERMS** Safe distance, pipeline, HVDC electrode, touch voltage, DC corrosion.

## I. INTRODUCTION

With the increasing demand of optimal energy allocation, a large number of HVDC transmission projects and oil & gas projects are included in the construction plan every year. When the HVDC system operates in the monopolar mode, the grounding current may induce overvoltage between the coated metal pipe and the soil, leading to touch voltage electric shock or DC corrosion at the defect point [1], [2], [3], [4], [5]. Since the ground potential and pipe-to-soil voltage generated by the DC current attenuates rapidly with the increase of distance, reserving sufficient distance is one of the important ways to reduce the DC interference of the pipeline. The avoidance distance with which the DC interference is suppressed to a certain limit is called the safe distance. Even though the simulation methodology of DC interference generated by HVDC electrode is well-developed and mature and it is easy to carry out differential evaluation of the DC interference [6], [7], [8], [9], [10], [11], [12], planners can only complete the geometric division of the limited space with the safe distance as an approximate direction and the capacity of lines or pipelines may be the only available data in the long-term planning stage. Therefore, it is an important work to determine the pipe-to-electrode safe distance so that a reasonable data reference can be obtained. Some scholars have carried out some

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discussion the pipe-to-electrode safe distance. X. Chi studied the studied the safe distance between coastal grounding electrode and pipeline whose the surrounded soil resistivity is 0.5∼10Ω·m. The safe distance that meet the 1$\mu$A/cm$^2$ limit of current density is 965m [13]. The Chinese standard DL/T 5224-2014 (Technical code for design of HVDC earth return system) pointed out that the impact of DC interference can be ignored when the distance between HVDC electrode and buried metal facilities is more than 10km [14]. Yu and Liu analyzed the safe distance between the Gaoqing HVDC electrode and the nearby pipelines. Results showed that the safe distance that satisfied the limit of 100mV positive offset under 6250A is 100km [15]. Meng et al. studied the pipe-to-electrode safe distance with a simplified model and the grounding current is 4000A. He pointed out that the safe distance is 8 km under the limit of 100mV positive offset when the soil resistivity is 50 Ω·m and it increased to 15km when the soil resistivity is 500 Ω·m [16]. Standard CSA Z662 (Oil and gas pipeline system) mentioned that the area affected by HVDC electrode grounding current can reach 70km in specific soil structure [17]. Yang et al. proposed that the distance between HVDC electrode and pipeline should be at least 30km and the 60km around the grounding HVDC should be included in the DC interference estimation [18]. Jiang et al. stated out that as the DC interference is affected by many factors, it is not appropriate to adopt a uniform safe distance. For example, the pipelines suffered severe interference even they were dozens of kilometers away from the electrodes in Guangdong Province in China while interference on pipelines attenuated to a very low level in about 10km in Shanghai Province. He also suggested that several safe distances should be defined according to different risk levels [19].

As the researches on safe distance are always carried out in specific cases and an agreement on the control standard is still not reached, there is large difference among the proposed safe distances. In order to provide a clear data reference for the electrode site selection and pipeline path planning, the pipe-to-electrode safe distance is further discussed in this paper. The influencing factors of pipe-to-soil voltage and safe distance is firstly analyzed. Then the safe distance under different conditions is simulated from the perspectives of human safety and DC corrosion respectively and the control standards are compared. At last, acceptable safe distance is further proposed and optimized to improve engineering applicability.

## II. INFLUENCING FACTORS OF SAFE DISTANCE

In order to clarify the main variables in the safe distance analysis, this paper first studies the influence of the electrode type, soil structure, pipeline length, coating surface resistivity and pipe size on the safe distance. Considering the touch voltage and corrosion rate is positively related to the pipe-to-soil voltage, the pipe-to-soil voltage is mainly analyzed in this section. The simulation model established with CDEGS is shown in Fig.1. Each factor is studied with the control variable method and the non-controlled variables are valued according to Table 1.

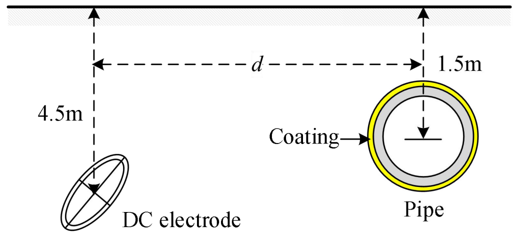


**FIGURE 1.** Simplified simulation model of pipeline and DC electrode.

**TABLE 1.** Simulation parameters.

| Parameters | Value |
|---|---|
| Current | 6000A |
| Electrode type | three-runway electrode |
| Pipe-to-electrode distance | 5km |
| Pipe size | Φ1016mm×17.9mm |
| Pipeline length | 700km |
| Coating type | 3PE |
| Soil | Soil 4 |

### A. ELECTRODE TYPE

As shown in Fig.2, single-ring electrode, double-ring electrode, two-runway electrode and three-runway electrode with different sizes are selected for comparative analysis. The single-ring electrode is a fictitious type, which is built to obtain a larger range of grounding resistance, enhancing the universality of the results.

The parameters of five grounding electrodes and the comparison results of pipe-to-soil voltage under different pipe-to-electrode distance are shown in Table 2. Due to the difference in the length of feeder rods of each electrode type, the difference in grounding resistance is significant, with the maximum of 4.39 Ω and the minimum of 0.39 Ω, indicating that the underground current field near each electrode varies wildly. However, as the pipeline gradually moves away from the electrode, the difference of pipe-to-soil voltage calculated with different electrode types becomes smaller. When pipe-to-electrode $d$ = 1km, the maximum difference is 17V, and when $d$ > 5km, and the maximum difference is less than 1V, which can be ignored for DC corrosion or human safety. Therefore, the electrode can be treated as a point source to reduce the model size and save computing resources in the discussion of safe distance.

### B. SOIL STRUCTURE

According to the grounding theory, the soil resistivity and soil structure directly affect the magnitude and attenuation law of the underground current field and the ground potential. As large numbers of soil models can be built with different resistivity and thickness combinations even for horizontal

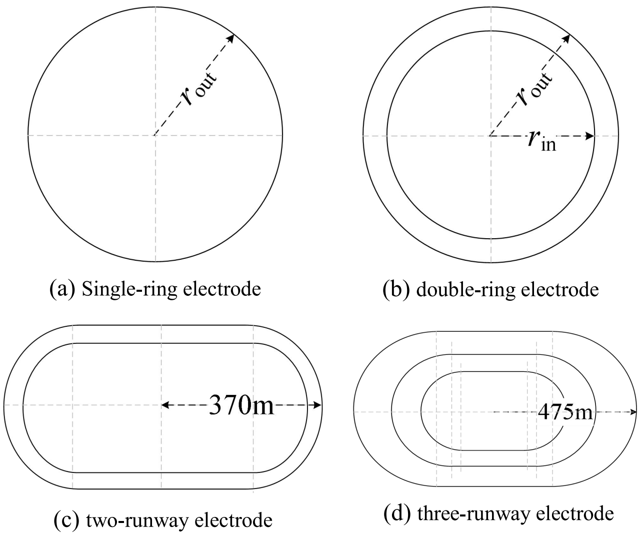


**FIGURE 2.** Typical types of HVDC electrode.

**TABLE 2.** Simulation results with different DC electrode type.

| | Type | (a) | (a) | (a) | (b) | (c) | (d) |
|---|---|---|---|---|---|---|---|
| | $r_{in}$/m | - | - | - | 340 | - | - |
| | $r_{out}$/m | 2 | 25 | 50 | 470 | - | - |
| | $L_f$/m | 13 | 157 | 314 | 5152 | 3422 | 5528 |
| | $R_g$/Ω | 4.39 | 1.09 | 0.81 | 0.39 | 0.45 | 0.41 |
| $U_p$ /V | $d$=1km | 1472 | 1472 | 1472 | 1477 | 1470 | 1460 |
| | $d$=5km | 621 | 621 | 621 | 622 | 621 | 621 |
| | $d$=10km | 332 | 332 | 332 | 332 | 332 | 332 |
| | $d$=15km | 202 | 202 | 202 | 202 | 202 | 202 |
| | $d$=20km | 130 | 130 | 130 | 131 | 130 | 130 |
| | $d$=25km | 87 | 87 | 87 | 88 | 87 | 87 |
| | $d$=30km | 60 | 60 | 60 | 60 | 60 | 60 |
| | $d$=35km | 42 | 42 | 42 | 42 | 42 | 42 |
| | $d$=40km | 30 | 30 | 30 | 30 | 30 | 30 |

$L_f$: feeder rod length, $R_g$: grounding resistance, $U_p$: maximum pipe-to-soil voltage, $r_{in}$:inner radius, $r_{out}$: outer radius, $d$:electrode-to-pipeline distance

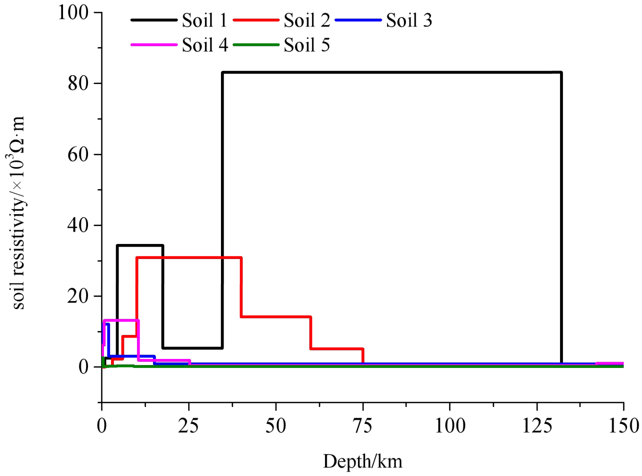


**FIGURE 3.** Soil models of five DC electrodes.

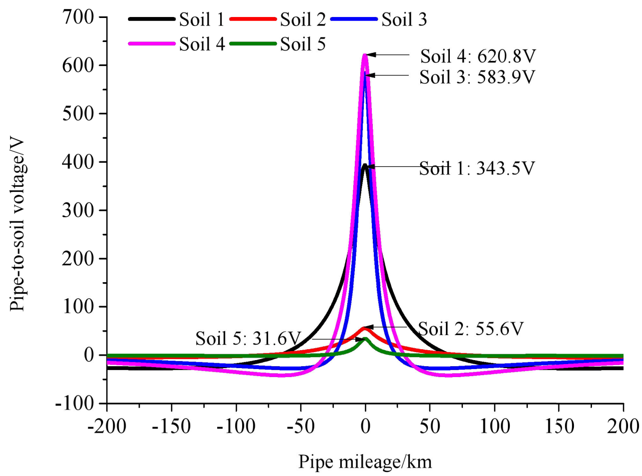


**FIGURE 4.** Pipe-to-soil voltage distribution under different soil models.

layered structure, it is difficult to take all kinds of soil structures into consideration. Thus, five typical electrode soil structures are selected from the HVDC projects that have been built/are being built in China for research here.

The parameters of each soil structure is shown in Fig.3, which is obtained by measure and inversion with the Wenner's four probe method, AMT method and MT method. The high resistivity layer of Soil 1 mainly locates below 35km underground, that of Soil 2 mainly locates at the middle layer at about 10km∼40km underground. For Soil 3 and Soil 4, the high resistivity layer locates main locates at the upper layers above 2km underground. For Soil 5, the highest resistivity layer locates at the surface with a resistivity of 2643 Ω and thickness of 352m and the overall conductivity is better than the other soil models.

The pipe-to-soil voltage distribution calculated with the 5 soil models is shown in Fig.4. It can be seen that the magnitude and spatial distribution of the pipe-to-soil voltage obtained from each soil model are significantly different, indicating that these five soil models are representative to some extent. The above five soil models are mainly taken into consideration in the analysis of safe distance.

### C. PIPELINE LENGTH

When the HVDC electrode operates in monopolar mode, the metal pipeline with low resistivity plays a role in drawing the remote potential and near potential closer. Thus, the remote potential and the pipe-to-soil voltage will also change if the pipeline length is different.

The relationship between maximum pipe-to-soil voltage and pipeline length is shown in Fig.5. Considering that soil structure also has a great influence on remote potential, the results simulated with different soil models are also given. When the pipeline is short, the pipe-to-soil voltage increases rapidly along with the pipeline length, and it may reach the saturation at about 700km, where the the rate of change is

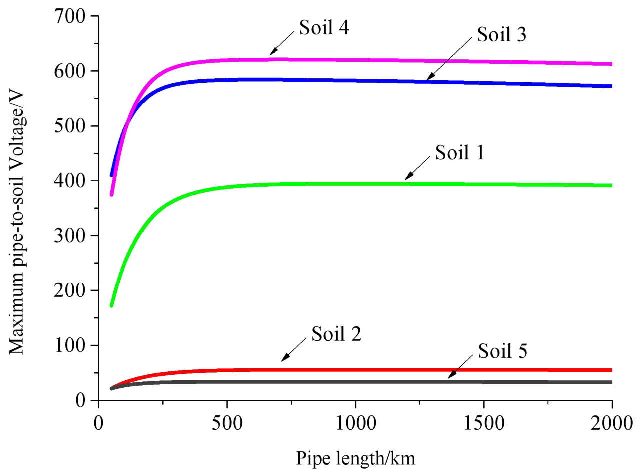


**FIGURE 5.** The influence of pipeline length on maximum pipe-to-soil voltage.

less than 1V/100km. Therefore, the difference between short pipeline and long pipeline should be considered in the analysis of safe distance. Besides, the length of pipelines longer than 700km can be uniformly treated as 700km in simulation.

### D. SURFACE RESISTIVITY OF COATING

The anti-corrosion coating is the corrosion prevention of buried pipelines for avoiding direct contact between the metal pipeline and the corrosive soil. Since the 1930s, the coal tar enamel coating was applied to buried pipelines for the first time.Then, petroleum asphalt, fusion-bonded epoxy (FBE), polyethylene tape, 2-layer PE and 3-layer PE (3PE) has been applied successively. As anti-corrosion materials are often strong insulating materials at the same time, the coating builds a high resistance layer between the pipeline and soil so that high potential difference is induced between the both sides, resulting in high corrosion current at the coating defect points and touch voltage.

The resistance characteristics of the anti-corrosion coating is mainly determined by its resistivity and thickness. It can be uniformly described by the parameter of surface resistivity, which is defined by $\rho L$ (resistivity × thickness), representing the normal resistance per unit area of a specific coating material. We have investigated the surface resistivity of commonly used anti-corrosion coating, which is shown in the Table 3.

**TABLE 3.** Surface resistivity of typical coating.

| Coating type | Surface resistivity/Ω•m² |
|---|---|
| Coal tar eposy | 5000 |
| Petroleum asphalt | 10000 |
| Plastic | 50000 |
| FBE | 50000 |
| 3PE | 100000 |

Taking the surface resistivity of the coating as 5000 $\Omega \cdot m^2 \sim$ 100000 $\Omega \cdot m^2$, the relationship between the maximum pipe-to-soil voltage and the surface resistivity is shown in Fig.6. As the insulation performance of the coating is improved, its ability to isolate the potential of the pipeline and the soil is enhanced and a significantly increase in the pipe-to-soil voltage is also found. Thus, it is necessary to consider the resistance characteristics of coating as an important variable for discussion in safe distance analysis.

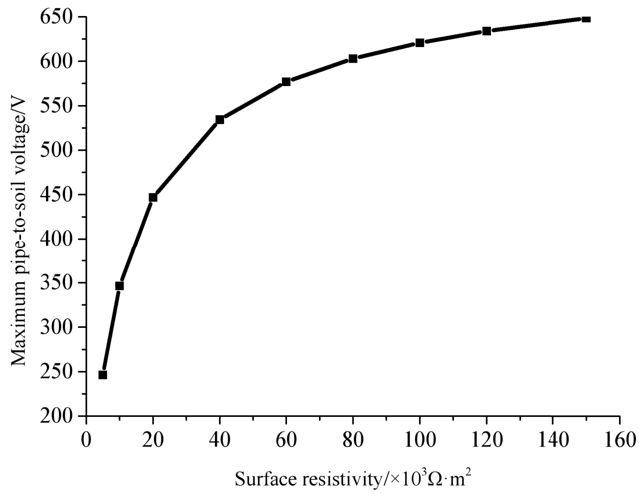


**FIGURE 6.** The influence of coating surface resistivity on maximum pipe-to-soil voltage.

### E. PIPE SIZE

As shown in TABLE 4, the pipeline type and pipe size of some existing buried pipelines are investigated. The external diameter of oil pipelines ranges from 508mm to 1219mm, with the thickness of 11.9mm~27mm and the external diameter of gas pipelines ranges from 610mm to 1016mm, with the thickness of 8.8mm~26.2mm. The external diameter of 1219mm, 1016mm, 813mm, 508mm and the thickness of 11.9mm, 17.9mm, 27.0mm are taken for comparison and the result of maximum pipe-to-soil voltage is shown in Fig.7.

It can be seen from the results that the change of pipe-to-soil voltage under different pipe size is about 5%, indicating that the pipe size has a certain influence on safe distance. However, considering that the influence of pipe size is far less than other factors, and in order to reduce the number of the variables to simplify the safe distance analysis, the pipe size will be fixed to Φ1016mm × 17.9mm to represent the average situation.

In summary, soil structure, pipeline length, and coating insulation performance are the main factors while pipe size and electrode type are the minor ones. Besides, the grounding current of the HVDC electrode is the source of DC interference on the pipeline which should as also be considered. As the law that all interference are proportional to the grounding current in resistive network is obvious, we do not further discuss in this section.

**TABLE 4. Statistics of pipe size in common use.**

| Nation | Line Name | Medium | Size | Material |
|---|---|---|---|---|
| China | West-to-east | Gas | D1219×22<br>D1219×18.4 | X80 |
| | Moda | oil | D813×16~17 | X65 |
| | Ruzhi | Gas | D1016×21 | X70 |
| | Taian | Gas | D1016×21<br>D1016×17.5 | X70 |
| | Lancheng | oil | D610×16.9 | X60 |
| | Buxin | Gas | D914×14.7 | |
| | Zhongmian | Gas | D1016×15.3 | X80 |
| | Zhongmian | oil | D813×9.5 | X70 |
| | Guangnan | Gas | D1016×14.6 | X70 |
| | Shanggu | Gas | D508×14 | L360 |
| | Yong-hu-ning | oil | D711×11.1 | L415 |
| | Changqing | oil | D813×8.8<br>D813×11 | L415 |
| | Minyue | Gas | D813×17.5 | L485 |
| Turkmenistan | Turkmenistan | Gas | D1016×14.3 | X70 |
| | | | D1219×14.3<br>D813×11.9<br>D914×14.3 | |
| Myanmar | Myanmar pipeline | oil/Gas | D1016×26.2<br>D813×14-20.3 | X70 |
| Iraq | Halfaya pipeline | Gas | D813×11.1 | X70 |
| Kazakhstan | Kazakhstan C | Gas | D1219×27 | X80 |
| Netherlands | Norgron | Gas | D1219×15.01<br>D1219×17.87 | X70 |

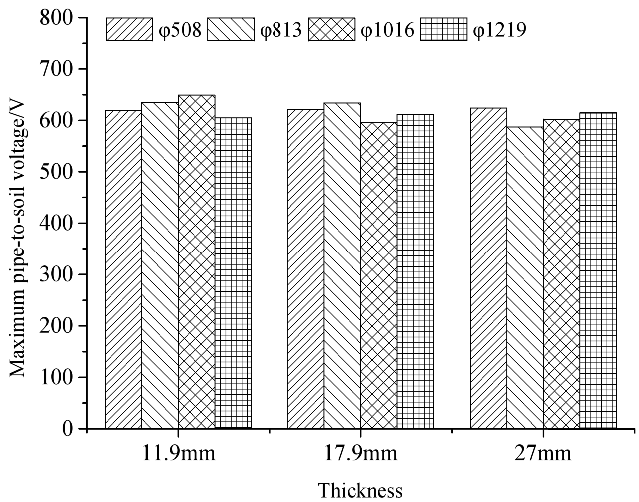


**FIGURE 7. The influence of pipe size on maximum pipe-to-soil voltage.**

## III. SAFE DISTANCE ANALYSIS WITH TOUCH VOLTAGE AS THE LIMIT

### A. THE LIMIT OF TOUCH VOLTAGE

As shown in Fig.8, when the DC current enters the earth through the electrode, large potential difference is induced between the pipeline and the soil. Human body may suffer the potential difference between the body and the feet, which is the touch voltage, if people touches the pipeline accessories.

At present, there is still no standard for touch voltage risk of HVDC interference. However, there are some other relevant values for reference in other standards. Chinese standard GB/T3805-2008 (Extra-low voltage (ELV)-Limit values) states that the steady-state DC safety voltage of human body is 70V for dry environment, and 35V for wet

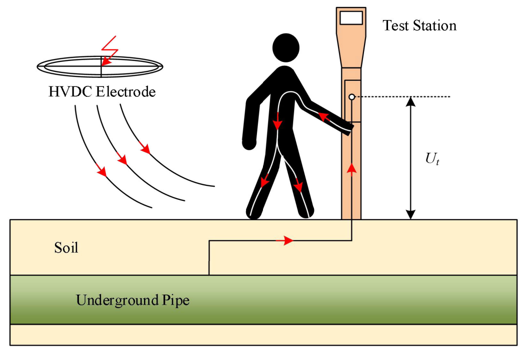


**FIGURE 8. Process of electric shock after personal touch with pipeline system caused by grounding current.**

environment where skin impedance reduces [20]. Since the monopolar operation the DC system often last for several hours, the steady-state limit above can be used as a reference for the touch voltage. Similarly, IEC Standard 479 (effects of current passing through the human body) mentions that the touch voltage limit is 37.5V [21].

Besides, the DC steady-state touch voltage limit can also be estimated with the human body withstand current. As stated in [19], according to human body reaction, the current can be divided into perception current, escape current and fatal current whose ranges are 0.7mA∼1mA, 10mA∼16mA, and 30mA∼50mA respectively. According to the test results of Dalziel, IEEE points out that the hand-to-hand power frequency impedance of human body is 2330Ω, and the hand-to-hand one is 1130Ω [22]. Taking the fatal current 30mA and substituting power frequency impedance 1130Ω for DC impedance, we can get the human body's DC safety voltage is 33.9V, which is close to the 35V limit under the wet condition in the Chinese standard and the 37.5V limit in the IEC Standard 479. For higher human body impedance like 3000 Ω, we can get the human body's DC safety voltage of 90V, which is close to the 75V limit under the dry condition in the Chinese standard. On the whole, the DC safety voltage limit for human body can divided into 2 conditions: 35V∼37.5V and 75V∼90V. The former is applicable to the environment with long-term rainy season or high air humidity, while the latter is applicable to the environment with long-term dry season or low air humidity. It is necessary to discuss the pipe-to-electrode safe distance of the two limits respectively. The limits of the two conditions are chosen 35V and 70V according to GB/T3805-2008 in this paper.

### B. SAFE DISTANCE FOR TOUCH VOLTAGE RISK

Taking grounding current $I$ = 3000A, 6000A, pipeline length $L_p$ = 100km, 700km, coating surface resistivity $\rho_c$ = 5000Ω·m$^2$, 5000Ω·m$^2$, and 100000Ω·m$^2$, the pipe-to-electrode safe distance under five typical soil resistivity for the 35V limit and 75V limit is studied. On the basis of the model in Fig.1, the pipe-to-electrode distance is gradually increased until the maximum pipe-to-soil voltage reaches

35V or 70V so that the safe distance is obtained. Corrosion prevention measures like sacrificial anode and cathodic current protection are not considered so that only the relationship between safe distance and touch voltage is reflected.

Fig.9~Fig.16 shows the change of touch voltage with pipe-to-electrode distance under different parameters and the safe distance is extracted in TABLE 5. Results show that when $I = 6000$A, the safe distance for 70V is 16km~52km while that for 35V is 24km~87km; When $I = 3000$A, the safe distance for 70V is 11km~25km while that for 35V is 16km~52km. As the value range of safe distance under different conditions is large, it is difficult to give an unified value that satisfy all the conditions.

According to TABLE 5, the severity of the 70V limit and the 35V limit differs greatly. The difference between the two increases with the pipeline length, coating surface resistivity, and grounding current. The selection of touch voltage limit may lead to tens of kilometers difference in safe distance. Thus, a better way is to choose the safe distance limit according to the environment around the pipeline section near the electrode. However, there are too large safe distances which even reach 87km under sever conditions, which is difficult to use in engineering. A set of acceptable safe distance will be further proposed in section V.

**TABLE 5.** Safe distance in consideration of the risk of touch voltage.

| case | $I$/kA | $L_p$/km | $\rho_c$/Ω·m$^2$ | $d_{70V}$/km | $d_{35V}$/km |
|---|---|---|---|---|---|
| 1 | 6000 | 100 | 5000 | 16 | 24 |
| 2 | | 100 | 10000 | 21 | 31 |
| 3 | | 100 | 100000 | 22 | 33 |
| 4 | | 700 | 5000 | 19 | 33 |
| 5 | | 700 | 10000 | 40 | 70 |
| 6 | | 700 | 100000 | 52 | 87 |
| 7 | 3000 | 100 | 5000 | 11 | 16 |
| 8 | | 100 | 10000 | 15 | 21 |
| 9 | | 100 | 100000 | 16 | 23 |
| 10 | | 700 | 5000 | 13 | 18 |
| 11 | | 700 | 10000 | 20 | 39 |
| 12 | | 700 | 100000 | 25 | 52 |

$d_{70V}$: pipe-to-electrode distance when touch voltage reach 70V; $d_{35V}$: pipe-to-electrode distance when touch voltage reach 35V.

## IV. SAFE DISTANCE ANALYSIS WITH DC CORROSION AS THE LIMIT

### A. THE LIMIT OF DC CORROSION RATE

There are many evaluation standards for metal DC corrosion, including soil potential gradient, potential offset, current density, corrosion rate, etc. [26]. Considering that it is often difficult to obtain the specific polarization curve and to carry out complex iterative solution to obtain the potential offset, corrosion rate is a more intuitive parameter. Besides, current density and soil potential gradient are also variables related to corrosion rate. Therefore, the DC corrosion rate is selected as the main control standard. GB/T 21448-2017 (Specification of cathodic protection for underground steel pipelines) and ISO 15589-1: 2015 (Proleum, petrochemical and natural gas industries-Cathodic protection of pipeline systems-Part 1: On-land pipelines, NEQ) specify that the DC corrosion should be controlled below 0.01mm/a [23], [24]. In NACE SP0169-2013 (Control of external corrosion on underground or submerged metallic piping systems), the limit is loosened to 0.0254mm/a [25]. The Chinese standard SY/T 0087.4 (Standard of steel pipeline and tank corrosion assessment-Part 4: Steel pipeline direct current Interference corrosion assessment) holds that the the above limits of 0.01mm/a and 0.0254mm/a are too strict in the initial planning stage as they are used to evaluate the corrosion level after installation of anti-corrosion measures. Too strict limit standard may cause the problem of overdesign, increasing the difficulty in site/path selection and reducing the flexibility of planning.

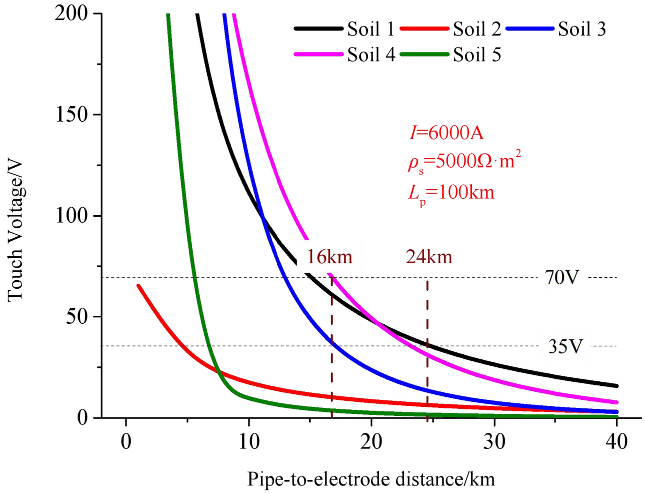


**FIGURE 9.** Relationship between touch voltage and pipe-to-electrode distance (I=6000A, $\rho_s$ =5000Ω·m$^2$, $L_p$ =100km).

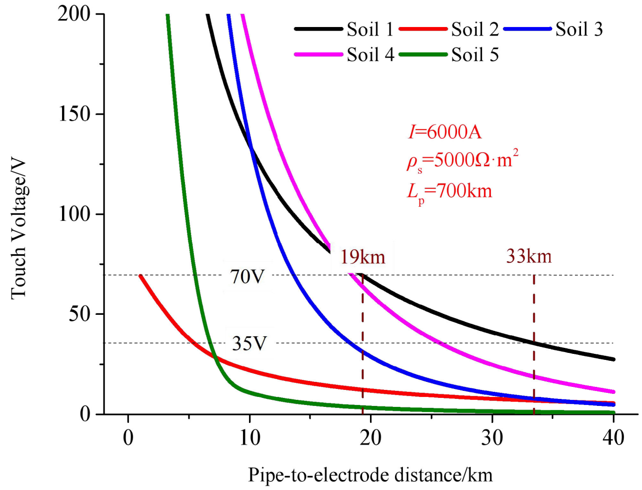


**FIGURE 10.** Relationship between touch voltage and pipe-to-electrode distance (I=6000A, $\rho_s$ =5000Ω·m$^2$, $L_p$ =700km).

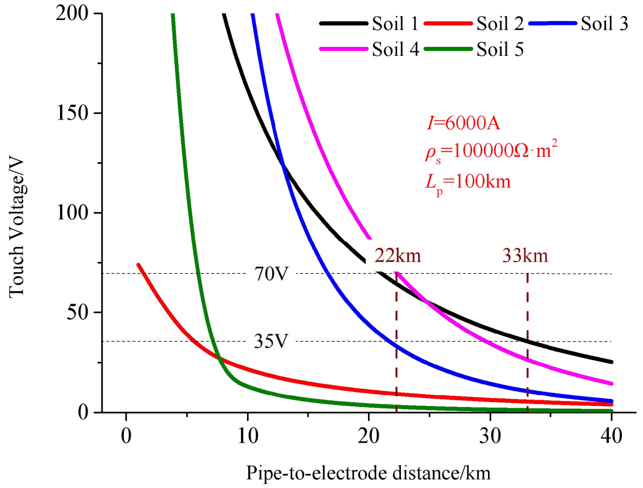


**FIGURE 11.** **Relationship between touch voltage and pipe-to-electrode distance (I=6000A, $\rho_s$ =100000Ω·m$^2$, $L_p$ =100km).**

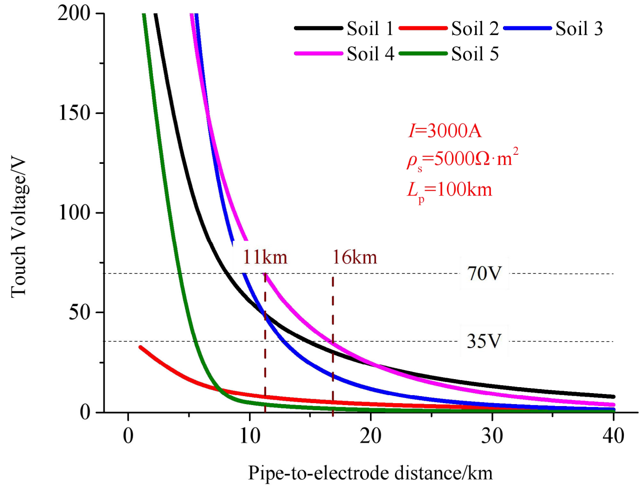


**FIGURE 13.** **Relationship between touch voltage and pipe-to-electrode distance (I=3000A, $\rho_s$ =5000Ω·m$^2$, $L_p$ =100km).**

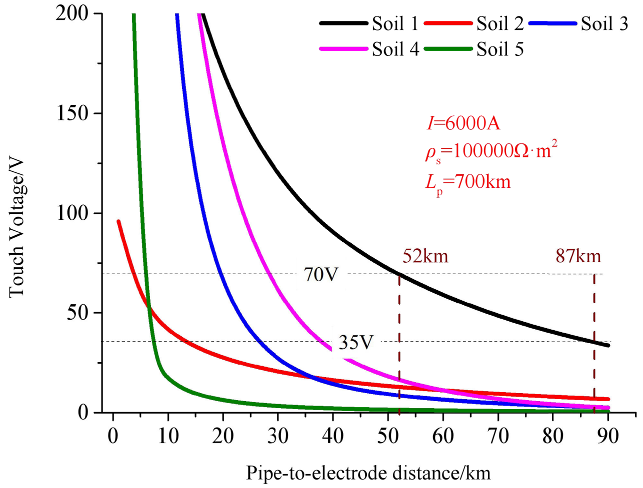


**FIGURE 12.** **Relationship between touch voltage and pipe-to-electrode distance (I=6000A, $\rho_s$ =100000Ω·m$^2$, $L_p$ =700km).**

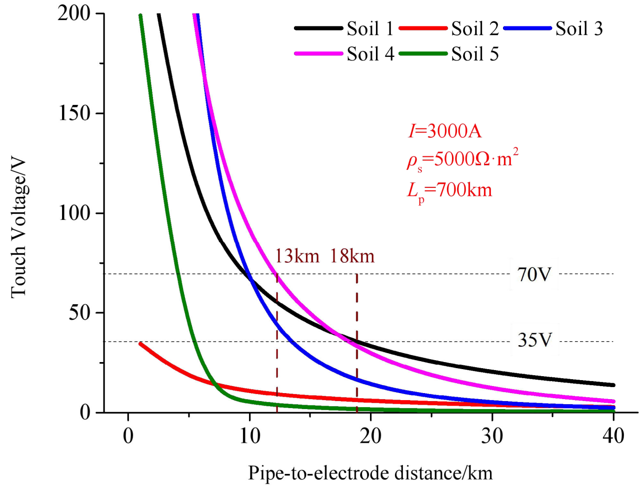


**FIGURE 14.** **Relationship between touch voltage and pipe-to-electrode distance (I=3000A, $\rho_s$ = 5000Ω·m$^2$, $L_p$ = 700km).**

It is recommended that 0.1mm/a is more suitable for the planning stage as reserving distance is only the initial measure to reduce the interference [27].

### B. CALCULATION METHOD OF DC CORROSION RATE

#### 1) THE RELATIONSHIP BETWEEN DC CORROSION RATE AND CURRENT DENSITY

According to [28], the corrosion rate of 1 A/m$^2$ DC current density on steel is 1.168mm/a. Thus, we can describe the relationship between DC corrosion rate and current density as in (1).

$$\upsilon_c = 1.168 \times j \times \eta \tag{1}$$

where $\upsilon_c$ is the DC corrosion rate of pipeline; $\eta$ is the probability of electrode operating in monopolar mode; $j$ is the current density of defect point on the pipeline during the monopolar operation of the HVDC electrode.

Fig.17 shows the the statistics of the magnitude and duration time of the grounding current during monopolar operation of HVDC electrodes in China Southern Power Grid from 2011 to 2016. The data in Fig.17 is further processed with (2) to convert the actual duration time to the duration time under rated current so that all cases are treated under the state of rated current $t_{eq}$. By summing $t_{eq}$, we can get the total equivalent monopolar time of electrodes is 270h and the probability $\eta$ in (1) is 0.5%. It should be noted that with the continuous improvement in maintenance technology of HVDC system in recent years, the total equivalent operation time as well as the probability $\eta$ will be reduced.

$$t_{eq} = \frac{I_n \cdot t_n}{I_r} \tag{2}$$

where $t_{eq}$ is the equivalent duration time under rated current; $I_n$ and $t_n$ are the grounding current and duration time during

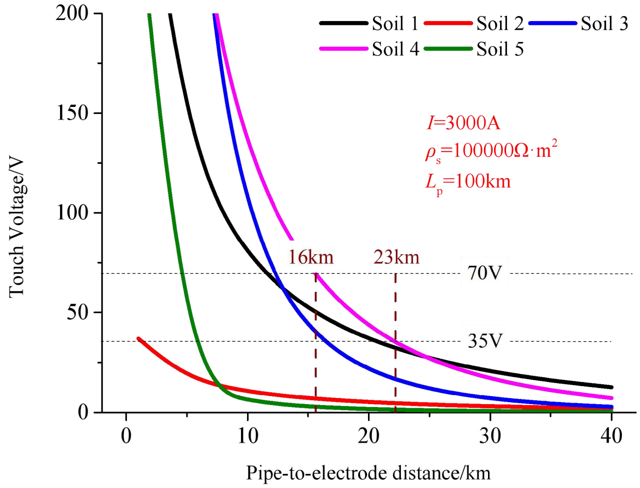


**FIGURE 15.** Relationship between touch voltage and pipe-to-electrode distance (I=3000A, $\rho_s$ = 100000Ω·m$^2$, $L_p$ = 100km).

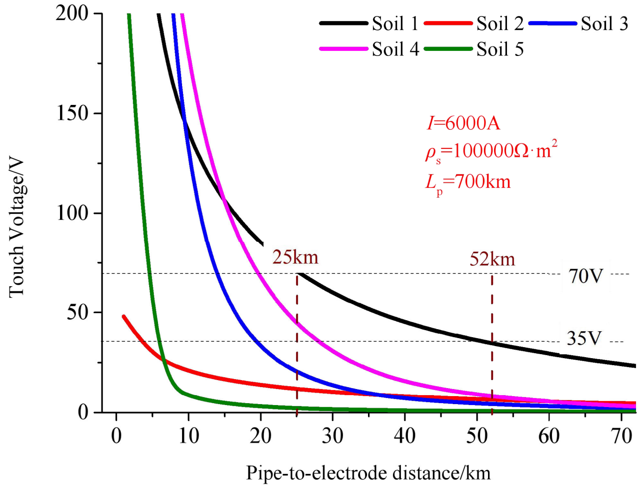


**FIGURE 16.** Relationship between touch voltage and pipe-to-electrode distance (I=3000A, $\rho_s$ = 100000Ω·m$^2$, $L_p$ = 700km).

the nth monopolar operation respectively; $I_r$ is the rated current of the HVDC electrode.

### 2) THE CALCULATION AND CORRECTION OF CURRENT DENSITY

Supposing that the shape of the defect points on pipelines is circle, the current density can be obtained by (3), which is the simplified form for the ratio of pipeline potential to the grounding resistance and area of the defect point. In Chinese standard SYT-0029-2012 (Specification of application for underground steel coupons), test pieces with an area of 6.5cm$^2$~50cm$^2$ is suggested to represent the pipeline defect point [29]. Besides, the size range of defect points in the statistics in [7] is 6cm$^2$~8cm$^2$. Thus, the area of defect point is chosen 6.5cm$^2$, whose corresponding diameter of is $d_a$ = 28.77mm, in this paper to represent a more

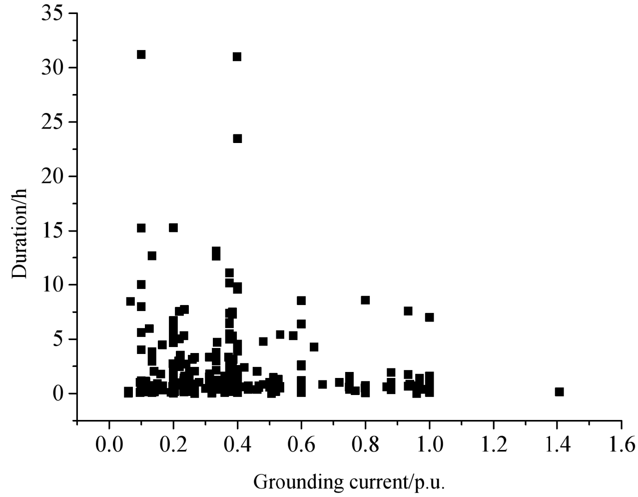


**FIGURE 17.** Statistics of monopolar operation parameters of DC electrodes in China Southern Power Grid from 2011 to 2016.

severe condition.

$$j = \frac{8V_p}{\rho_s \pi d_a} \tag{3}$$

where $V_p$ is potential of the pipeline where the defect point locates; $\rho_s$ is the resistivity of the surrounded soil around the defect point; $d_a$ is the diameter of the defect point.

Equation (3) is derived based on the assumption that the soil resistivity is constant, and the obtained current density is the maximum one ever reached during the monopolar operation.

In fact, during DC interference, a series of physical and chemical reactions will occur near the defect point due to the DC electric field, resulting in changes in soil properties and current density. As shown in Fig.18, the time-domain current density of Φ18 mm×3 mm X80 steel was tested after DC source was applied in this paper. Reddish-brown clay with different water content was selected as the medium, whose main contents were NaCl, $CaCl_2$, $MgCl_2$, $NaHCO_3$, $Na_2SO_4$, KCl, and $NaNO_3$. The change of current density shown a significant three-stage process: At the first stage, the current density of the defect point reached the maximum as soon as the source was applied. Then, it came to the second stage in which the current density decreased rapidly. The third stage appear at about 10min~20min and the current density reached the saturation state. The change of current density can be explained as follows: After stray current flowed in or out of the defect point for a period of time, the soil near the defect point were heated and became dry, resulting the rise in soil resistivity and the decrease in current density in the second stage. Then, as the DC electric field broken the coexistence of ions at the soil/electrode interface, the processes of ion aggregation, ion electromigration and water diffusion appear simultaneously. When they came to the balance, the current density reached a saturation state in the third stage. As shown in Fig.19, the change of loop impedance and the ratio of steady-state current density $J_1$ to peak current density $J_2$ are further extracted. As the initial water content of soil increased, the influence of water evaporation and water migration reduced. The difference between the initial loop impedance and final loop impedance became smaller and the current density ratio $J_2/J_1$ is much closer to 1.

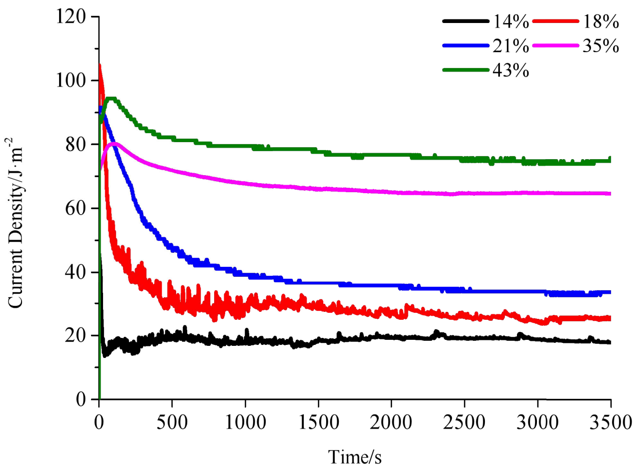


**FIGURE 18. Three-stage process of current density under DC interference.**

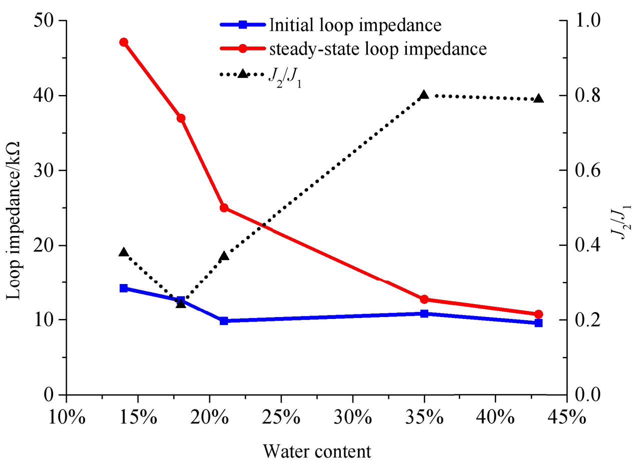


**FIGURE 19. Change of impedance and current density.**

Considering that the current anti-corrosion coating of pipeline is often 3PE with good insulation performance, the corrosion process is more affected by the third stage. In order to take the change of soil properties into consideration, the current density in (3) is modified by adding the coefficient *k*, which is as (4), to reflect the difference between the initial current density and the steady-state one. The $k = J_2/J_1$ in Fig.19 also shows a large span, which ranges from 0.24 to 0.80. In order to simplify the analysis safe distance, *k* is fixed to 0.8 as the local soil conditions are difficult to predict.

$$j = k\frac{8V_p}{\rho_s \pi d_a} \tag{4}$$

In order to determine the representative value of soil resistivity, two pipelines in China are selected to carry out nearby soil resistivity measure (Fig.20). The nearby soil resistivity along pipeline 1 ranges from 14Ω·m to 1256Ω·m, with an average of 210Ω·m, and that along pipeline 2 ranges from 15Ω·m to 368Ω·m, with an average of 140Ω·m. Although the span of soil resistivity is large, the soil environment for pipeline construction is generally good. Besides, as high current density occurs in areas with low soil resistivity according to (4), the situations in which the soil resistivity is high are not needed to be discussed. Thus, soil resistivity of 100Ω·m∼200Ω·m are mainly taken into consideration in safe distance analysis. Moreover, extreme cases such as lakes, rivers and depressions, where soil resistivity is below 100Ω·m, can not represent the overall resistivity of pipeline. It is recommended to ignore these cases at the planning stage, but analyze them based on specific soil data after the pipeline is put into operation to avoid overdesign.

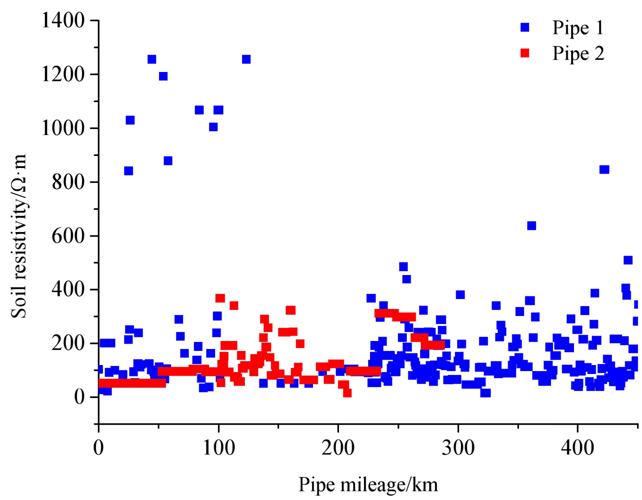


**FIGURE 20. Surface soil resistivity measure results along the two pipelines.**

### C. SAFE DISTANCE FOR DC CORROSION

When $k = 0.8$, $d_a = 2.887$cm, and the soil resistivity around the defect point $\rho_s = 100\Omega\cdot$m, the pipeline potential corresponding to the limit of 0.1mm/a, 0.0254mm/a, and 0.01mm/a are 24V, 6V, and 3V respectively. Besides, in order to better compare the differences between different standards, the pipe-to-soil voltage, which close to the touch voltage, is used here to replace the pipeline potential and it also represents a more severe situation. The safe distance for DC corrosion can be further extracted in TABLE 6 according to the results in Fig.16∼Fig.19. Similarly, when the soil resistivity around the defect point $\rho_s = 200\Omega\cdot$m, the pipeline potential corresponding to the limit of 0.1mm/a, 0.0254mm/a, and 0.01mm/a are 24V, 6V, and 3V respectively. The safe distance for DC corrosion is as in TABLE 7.

Results show that when the soil resistivity $\rho_s = 100\Omega\cdot$m, 30 out of 36 obtained distance is more than 40km, accounting

**TABLE 6.** Safe distance in consideration of DC corrosion ($\rho_s$ = 100Ω·m).

| case | $I$/kA | $L_p$/km | $\rho_c$/Ω·m$^2$ | $d_{0.1mm/a}$ | $d_{0.0254mm/a}$ | $d_{0.01mm/a}$ |
|---|---|---|---|---|---|---|
| 1 | 6000 | 100 | 5000 | 32 | 52 | 55 |
| 2 | | 100 | 10000 | 40 | 54 | 57 |
| 3 | | 100 | 100000 | 41 | 55 | 57 |
| 4 | | 700 | 5000 | 43 | 59 | 62 |
| 5 | | 700 | 10000 | 60 | 68 | 70 |
| 6 | | 700 | 100000 | 65 | 72 | 73 |
| 7 | 3000 | 100 | 5000 | 20 | 44 | 52 |
| 8 | | 100 | 10000 | 26 | 49 | 54 |
| 9 | | 100 | 100000 | 27 | 50 | 55 |
| 10 | | 700 | 5000 | 26 | 54 | 59 |
| 11 | | 700 | 10000 | 49 | 66 | 68 |
| 12 | | 700 | 100000 | 56 | 70 | 72 |

$d_{0.1mm/a}$: pipe-to-electrode distance when touch voltage reach 0.1mm/a;
$d_{0.0254mm/a}$: pipe-to-electrode distance when touch voltage reach 0.0254mm/a;
$d_{0.01mm/a}$: pipe-to-electrode distance when touch voltage reach 0.01mm/a.

**TABLE 7.** Safe distance in consideration of DC corrosion ($\rho_s$ = 200Ω·m).

| case | $I$/kA | $L_p$/km | $\rho_c$/Ω·m$^2$ | $d_{0.1mm/a}$ | $d_{0.0254mm/a}$ | $d_{0.01mm/a}$ |
|---|---|---|---|---|---|---|
| 1 | 6000 | 100 | 5000 | 20 | 44 | 52 |
| 2 | | 100 | 10000 | 26 | 49 | 54 |
| 3 | | 100 | 100000 | 27 | 50 | 55 |
| 4 | | 700 | 5000 | 26 | 54 | 59 |
| 5 | | 700 | 10000 | 49 | 66 | 68 |
| 6 | | 700 | 100000 | 56 | 70 | 72 |
| 7 | 3000 | 100 | 5000 | 14 | 32 | 44 |
| 8 | | 100 | 10000 | 18 | 40 | 49 |
| 9 | | 100 | 100000 | 19 | 41 | 50 |
| 10 | | 700 | 5000 | 15 | 43 | 54 |
| 11 | | 700 | 10000 | 29 | 60 | 66 |
| 12 | | 700 | 100000 | 38 | 65 | 70 |

$d_{0.1mm/a}$: pipe-to-electrode distance when touch voltage reach 0.1mm/a;
$d_{0.0254mm/a}$: pipe-to-electrode distance when touch voltage reach 0.0254mm/a;
$d_{0.01mm/a}$: pipe-to-electrode distance when touch voltage reach 0.01mm/a.

for 83%; When $\rho_s$ = 200Ω·m, the number of safe distance over 40km is 24, accounting for 67%. In order to make the safe distance implementable and provide more space for further discussion of on safe distance, the result of $\rho_s$ = 200Ω·m are mainly discussed.

The safe distance to meet the 0.1mm/a limit is 14km∼38km ($I$ = 3000A), 20km∼56km ($I$ = 6000A); The distance to meet the 0.0254mm/a threshold is 32km∼65km ($I$ = 3000A), 44km∼70km ($I$ = 6000A); The distance to meet the 0.01mm/a threshold is 44km∼70km ($I$ = 3000A), 52km∼72km ($I$ = 6000A). Therefore, when DC corrosion is taken as the limit, it is still difficult to give a unified safe distance that meets all conditions due to the large span and large values. The two limits of 0.0254mm/a and 0.01mm/a are too strict for planning as all safe distances exceed 40km when $I$ = 3000A and they exceed 50km when $I$ = 6000A. In general, the 0.1mm/a proposed by the Chinese standard is more suitable in the planning stage while the other two limits are more suitable for the design of anti-corrosion measures.

### D. COMPARISON BETWEEN THE TOUCH VOLTAGE LIMITS AND DC CORROSION LIMITS

Based on the analysis in Section II and Section III, the severity of each limit is as follows: 70V>0.1mm/a> 35V>0.0254mm/a>0.01mm/a ($\rho_s$=200Ω·m). The touch voltage limit of 70V is the most loose while the DC corrosion rate limit of 0.01mm/a is the most strict and the severity of the touch voltage limit of 35V is between the two corrosion rate limits of 0.1mm/a and 0.0254mm/a. The question of whether human safety or DC corrosion determines the safe distance mainly depends on the selection of standard. Besides, the pipe-to-soil voltage corresponding to 0.1mm/a and 0.0254mm/a are 12V and 6V, which are far less than 70V, 48V and 35V required by other standards. The comparison among safe distances of case 1 with different limits is shown in Fig.21. As the limits of 0.0254mm/a and 0.01mm/a are too strict, there is a big gap between the first three safe distances and the last two ones. For example, the safe distance obtained with the 0.0254mm/a limit is 175% and 83% more than that obtained with the 70V limit and 225% and 117% more than that obtained with the 35V limit. Thus, it is not suggested to use the 0.01mm/a and 0.0254mm/a limits, which are used for the evaluation of the corrosion level after anti-corrosion measures are installed.

At present, some scholars have been arguing about the value of pipeline safety limits during the monopolar operation of HVDC electrode. Electric power companies tend to use the touch voltage limit of 70V, because too harsh control limit will lead to difficulties in the control of HVDC system and site selection of electrodes. On the contrary, pipeline companies tend to use the 35V limit, as it can avoid safety accidents in the pipeline system to the maximum extent, ensuring the safety of the pipeline system. Some others prefer the DC corrosion rate limit of 0.1mm/a, emphasizing the corrosion of pipeline.

In fact, these approaches are one-sided as each standard has specific applying scenario. For dry environment, priority is suggested to be given to DC corrosion with the limit of 0.1mm/a, while for wet environment, priority suggested to be given to touch voltage risk with the limit of 35V.

## V. ACCEPTABLE SAFE DISTANCE

### A. THE DEFINITION OF ACCEPTABLE SAFE DISTANCE

Planners can look up specific safe distance in electrode site selection and pipeline path designing according to TABLE 5 and TABLE 7. But there are inevitable problems:

(1) The parameters of soil structure, pipeline length, and coating type etc. for pipelines and grounding electrodes are often unknown in the planning stage. So it is often difficult to differentiate the safe distance by table lookup. Besides, as the large-scale environment is a factor that is difficult to quantify, it is hard to give a clear control standard for safe distance selection.

(2) Some of the safe distance results in Table 5 and Table 7 are too large. The purpose of reserving safe distance between

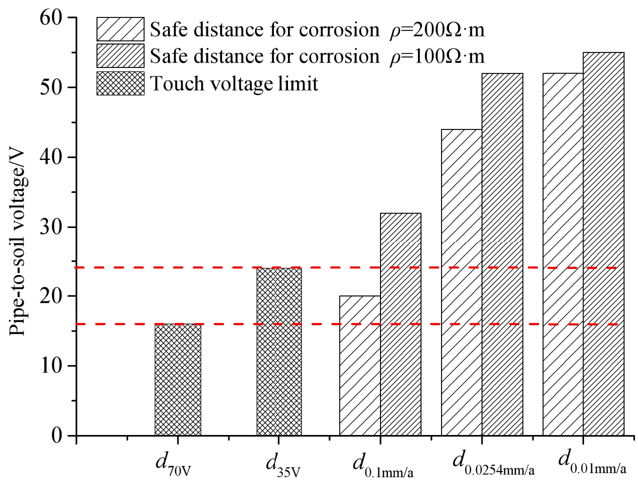


**FIGURE 21.** Safe distance under five limits.

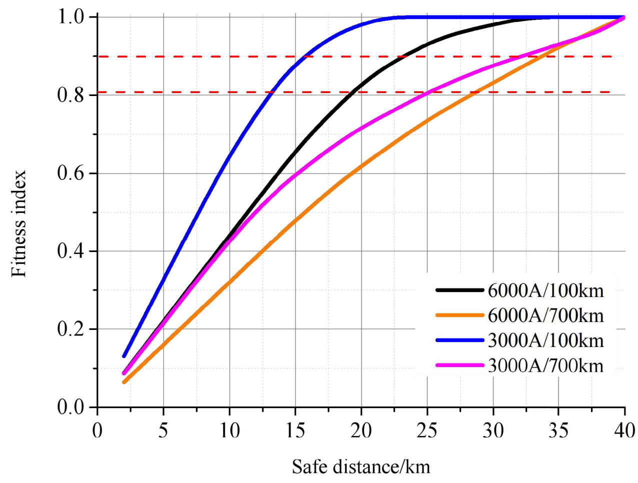


**FIGURE 22.** Fitness indicator under different safe distance $d_r$.

the pipe and electrode is to reduce the DC interference within a reasonable range in the design stage, but it does not mean complete elimination. As other protective measures may be added to achieve higher protection requirements after the pipeline is put into operation, it is not reasonable to enlarge the safe distance to meet all limit requirements, especially for severe conditions like high soil resistivity and high coating insulation performance, in which the the attenuation of potential is slow. Thus, a more reasonable way is that the selected safe distance can make the interference very small in most cases, but at the same time, the interference under extreme conditions is allowed to exceed the touch voltage limits or the DC corrosion rate limits.

In order to solve the problems of unknown parameters, uncertain limit standards, and too-large safe distance, the acceptable safe distance is further extracted based on the data in TABLE 5 and TABLE 7:

(1) Firstly, the safe distance larger than 40km is treated as 40km to minimize the influence of extreme working condition.

(2) In order to deal with the problems of unknown parameters and uncertain control limits, the safe distance obtained with the limits of 35V, 70V, and 0.1mm/a are merged into dataset$D$, in which only the grounding current and pipeline length are retained as the main variables.

(3) A specific safe distance $d_r$ is chosen and the matching indicator $\kappa$ is calculated with (4)(5). The second item in (4) represents the proportion of the part that exceeds $d_r$ in dataset $D$. Indicator $\kappa$ shows the degree that the $d$r meets the safe distance in dataset $D$. The closer indicator $\kappa$ is to 1, the higher is the matching degree and the lower is the risk level under all working conditions. The relationship between $\kappa$ and $d_r$ is shown in Fig.22.

$$\kappa = 1 - \frac{\sum_{i=1}^{n} \eta\left(d_i - d_r\right)}{\sum_{i=1}^{n} d_i} \tag{5}$$

$$\eta\left(x\right) = \begin{cases} x & x > 0 \\ 0 & x \leq 0 \end{cases} \tag{6}$$

In order to make full use of the inhibition effect of safe distance and to suppress the influence of extreme conditions, it should be ensured that the safe distance can be implemented in engineering while $\kappa$ is as close to 1 as possible. $\kappa = 0.8 \sim 0.9$ is taken in this paper and the corresponding $d_r$ are defined as the acceptable safe distance. According to Fig.22, when $\kappa$ =0.8, the acceptable safe distance of 100km short pipeline is 13km ($I = 3000$A), 19km ($I = 6000$A) while that of 700km short pipeline is 25km ($I = 3000$A), 27km ($I = 6000$A); When $\kappa$ =0.9, the acceptable safe distance of 100km short pipeline is 16km ($I = 3000$A), 23km ($I = 6000$A) while that of 700km short pipeline is 32km ($I = 3000$A) and 34km ($I = 6000$A). As the acceptable safe distance obtained with $\kappa = 0.9$ is 21%∼28% larger than that obtained with $\kappa = 0.8$, the acceptable safe distance obtained $\kappa = 0.8$ is recommended. For the case where the current and pipeline length are also unknown, it is recommended to take the average value of the acceptable safe distance of the long pipeline, which is 30 km. With the improvement of operation and maintenance technology, the monopolar time will be shortened and the safe distance can be further reduced.

### *B. METHOD TO SHORTEN THE SAFE DISTANCE*

According to the previous analysis, the pipeline length has a great influence on the selection of safe distance or acceptable safe distance. Thus, if all pipelines can be treated as short pipelines, the utilization of space and the flexibility of planning can be greatly improved.

As shown in Fig.23 and Fig.24, the pipe-to-soil voltage distribution and its relationship with pipe-to-electrode distance of 700km non-segmented pipeline, 700km segmented pipeline and 100km non-segmented pipeline are compared. For 700km segmented pipeline, the 100km section close to the HVDC electrode is segmented with insulation flange.

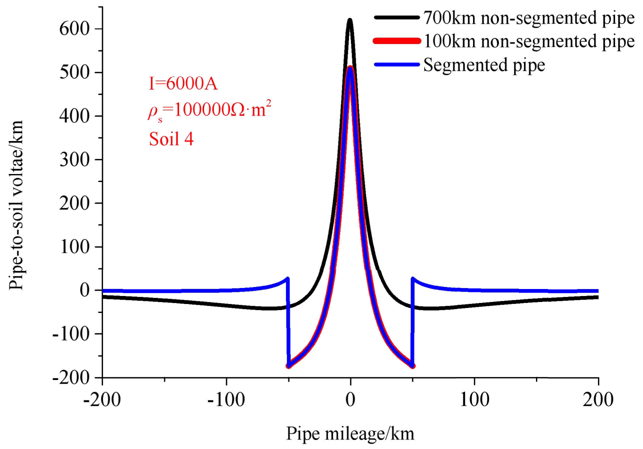


**FIGURE 23.** Comparison of pipe-to-soil voltage distribution between non segmented pipeline and segmented pipeline.

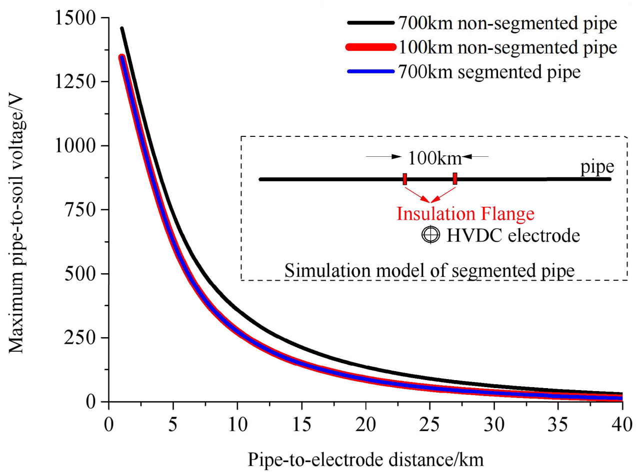


**FIGURE 24.** Relationship between maximum pipeline-to soil voltage and pipe-to-electrode distance of segmented pipeline and non-segmented pipeline.

Results show that the distribution and change law of the pipe-to-soil voltage of the 100km insulated section on the 700km pipeline are completely consistent with that of the 100km non-segmented short pipeline. So the safe distance or acceptable safe distance of long pipelines can be valued according to that of the short ones, which is 18km when the current and pipeline length are also unknown, after segmentation.

## VI. CONCLUSION

This paper carries out discussion on the safe distance between pipelines and HVDC electrodes, which is used for HVDC electrode site selection and pipeline path design in the planning stage. The main conclusions are as follows:

(1) Soil structure, pipeline length, coating insulation performance and grounding current are the main factors that affect the pipe-to-soil voltage and safe distance while the type of electrode and pipe size are the minor ones.

(2) When touch voltage is taken as the limit, the safe distance to meet the 70V limit is 11km~25km ($I = 3000$A) and 16km~52km ($I = 6000$A); The distance to meet the 35V limit is 16km~52km ($I = 3000$A) and 24km~87km ($I = 6000$A).

(3) When DC corrosion is taken as the limit, the safe distance to meet the 0.1mm/a limit is 14km~38km ($I = 3000$A) and 20km~56km ($I = 6000$A); The distance to meet the 0.0254mm/a limit is 32km~65km ($I = 3000$A) and 44km~70km ($I = 6000$A); The distance to meet the 0.01mm/a limit is 44km~70km ($I = 3000$A) and 52km~72km ($I = 6000$A).

(4) The severity of each limit is as follows: 70V>0.1mm/a>35V>0.0254mm/a>0.01mm/a ($\rho_s = 200\Omega\cdot$m). It is not suggested to use the 0.01mm/a and 0.0254mm/a limits, which are used for corrosion estimation after supplementary anti-corrosion measures are installed. For dry environment, priority should be given to DC corrosion with the limit of 0.1mm/a, while for wet environment, priority should be given to touch voltage risk with the limit of 35V.

(5) In order to solve the problems of unknown parameters, uncertain limit standards, and too-large safe distance, the acceptable safe distance is further extracted. The indicator $\kappa = 0.8$ is suggested. The acceptable safe distance of 100km short pipeline is 13km ($I = 3000$A) and 19km ($I = 6000$A), and that of 700km short pipeline is 25km ($I = 3000$A) and 27km ($I = 6000$A). For the case where the current and pipeline length are also unknown, it is recommended to take the acceptable safe distance of 30 km.

(6) The safe distance or acceptable safe distance of long pipelines can be valued according to that of the short ones, which is 18km when the current and pipeline length are also unknown, after segmentation.

Although the conclusions in this paper are obtained within a limited range of parameters, the selected parameters are representative, and the results can be used as a data reference for most projects. For more severe conditions, planning based on given the acceptable safe distance can also effectively suppress DC interference. The follow-up researches will enrich the results under more soil structures and pipe parameters to verify the rationality of the proposed safe distance and acceptable safe distance.

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