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Effects of soil resistivity on currents induced on pipelines

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Abstract

The goal of cathodic protection is to prevent corrosion by maintaining buried pipelines at a constant potential with respect to the surrounding soil. In practice, however, the implementation is very complicated since many factors can contribute to the current flowing off the pipe. Design requires characterization of the parameters impacting the corrosion process, such as soil resistivity, size of the pipe and quality of the coating.

In the present paper, we have studied the effect of geomagnetic fields on the pipe-induced currents considering it as an additional cause of corrosion. A theoretical method implemented to model the induced currents was tested in a previous work and the effect during disturbed days was quantified. This theoretical model indicated that the intensity of the current induced in a pipeline by the varying geomagnetic field depends on the intensity and rate of change of the field and the electrical resistivity of the soil. This induced current is in equilibrium with the host current and there is no current drainage between the pipeline and the host until, along the length of the pipeline, the host resistivity becomes different. At that point, current must flow between the pipe and host in order to establish a new equilibrium. It is this drainage current, flowing between the pipeline and the host, which causes corrosion problems.

Following these results, experimental tests were performed in Tierra del Fuego. In this zone, a geophysical study was made to determine the discontinuities in soil resistivities and simultaneous measurements of the geomagnetic field and the drainage of current were recorded at different sites. The results obtained from the correlation of the data are consistent with the theoretical predictions.

Keywords: Cathodic protection; Corrosion in pipelines; Telluric effects in pipelines

1. Introduction

The protection of buried iron pipelines against corrosion is a complex process. Since the corrosion of metals is of an electrochemical nature, differences of potentials must be compensated as pipes cross terrains with different conductivities. A non-corrosive coating is used to prevent damage, and additional protection is applied by means of cathodic protection (CP) in order to control galvanic current in such a way as to avoid anodic current flow from the pipe to the soil. CP can be accomplished by two widely used methods: sacrificial anodes and impressed-current systems. A rectifier or galvanic anode is used to create a complete circuit between

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the anode and the pipe, throwing current through the ground and creating chemical reactions on the pipe surface to prevent corrosion. The voltage differences in sacrificial anode systems are limited to approximately 1 V, while impressed-current systems can use larger voltage differences, producing more efficient protection. Nevertheless, this current is limited by the thickness of the coating. The usual rule is to maintain the pipeline at a constant potential between −0.850 and −1.3 V (with respect to a copper/saturated copper sulfate electrode).

Although this potential is generally large enough to compensate for most pipeline-induced currents, sporadic large enhancements of the drainage current have been detected, which leave the structure unprotected during such occurrences. Fluctuations in pipeline-induced current have been correlated to geomagnetic activity and enhancements in pipe-to-soil potentials have been observed during days of high magnetic activity (e.g., Campbell, 1986; Boteler and Cookson, 1986; Martin, 1993).

In order to model the effect of these ''telluric'' currents, we implemented a two-dimensional method to calculate the current induced in pipelines buried in a conductive medium assuming the external geomagnetic field as the source of induction (Osella et al., 1998). Through numerical simulations two main theoretical results were obtained.

The first one was the correlation between the external magnetic field and the currents induced in the pipelines. The results indicate that the intensity of these currents depends on the magnetic activity and on the size of the pipe. Thus, currents from 0.1 to 1 A can flow during quiet days, but they could reach several amperes during a geomagnetic storm. This behavior was tested by performing a survey along the Argentine Tierra del Fuego pipeline system (Favetto and Osella, 1999). During a fortnight, simultaneous recordings of the horizontal geomagnetic field and pipeline-induced current were made and it was observed that the induced current pattern followed the external field. Applying the two-dimensional method, the theoretical induced current was calculated, with the measured magnetic field as the induction source, and the result was compared with the measured currents. The close agreement between them confirmed the capability of the theoretical method to predict the geomagnetic induction effects successfully.

The second theoretical result was the dependence of the induction effect on the resistivity of the host medium, this effect being increased for more resistive soils. This result is contrary to the common classifications (e.g., Feliú and Andrade, 1991). Since ground-bed is usually considered to be one of the most significant sources of resistance in the entire CP circuit, soils with high conductivity ($\sigma > 0.04$ S/m) are considered ''dangerous'' and when pipelines run along such terrains, protection is intentionally increased. Nevertheless, our results can be explained taking into account that, as the medium becomes more conductive, larger currents are induced in the soil, resulting in a decrease of the current in the pipe. In contrast, for more resistive soils, larger currents are induced in the more conductive pipeline. So, it is clear that significant corrosion effects should occur in pipeline burial terrains having large conductivity contrast. If the pipeline crosses the media of different conductivities, the discontinuities at the boundaries should produce an escape of current, which can behave in the same manner as a corrosion current.

Within this frame, we completed the study along the Tierra del Fuego pipeline system performing a geoelectrical survey to image the shallow structure of the host media. Forty-five geoelectrical depth soundings were conducted to detect lateral electrical discontinuities, which were correlated with the geological features of the area. Also, drainage of current from pipe to soil, through a Cu–$CuSO_4$ electrode, was measured along the permanent stations located close to some of the sites selected for the electrical soundings, to prove the dependence with the electrical features of the soil. Then, applying two-dimensional modeling, the theoretical induced current was calculated for the different host media to estimate the drainage through the pipe in zones of electrical contrasts and the results were compared with the measurements to confirm our predictions.

2. Geoelectrical prospecting and geologic correlation

2.1. Description of the experimental field work

Geoelectrical depth soundings were performed along a 200-km pipeline route, between Río Grande and Ushuaia, in Tierra del Fuego, to map the shallow electrical layers of the host media. A total of 45 VES (vertical electrical soundings) was conducted, with a distance between soundings of 4–5 km approximately. The sampling density was increased in zones of apparent electrical contrasts (see Fig. 1).

A 2-kW DC power supply was used to inject current through a pair of steel electrodes, separated by a distance *AB*. Potential differences were measured between copper electrodes, *MN* being their separation, following the Schlumberger configuration. These measurements were collected using a data acquisition system, which allows readings with a resolution of 0.33 μV.

2.2. Results

From the measurements of currents and potential differences, curves of apparent resistivity vs. $AB/2$ were obtained for each site. The maximum half-electrode spacing, $AB/2$, was 1000 m. Based on our previous knowledge of the pipe route, we selected VES located about 500 m away from it to minimize any resistivity

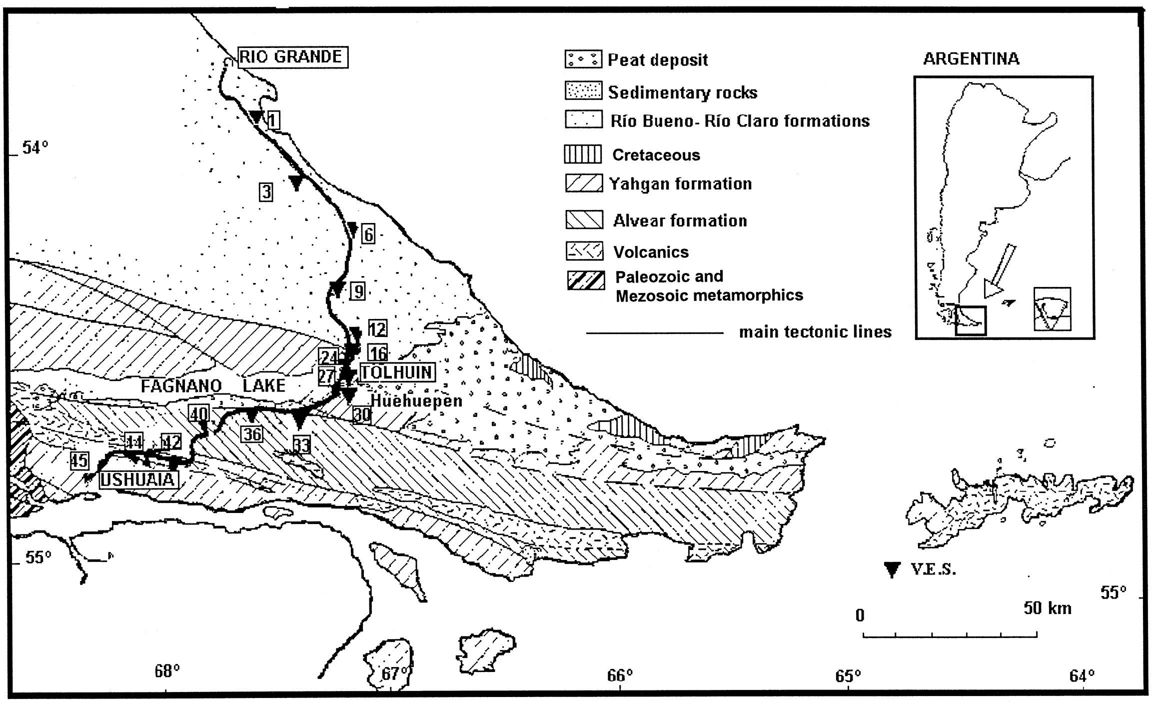

Fig. 1. Route of the Tierra del Fuego pipeline system. The study was carried out from Río Grande (0 km) to Ushuaia (200 km). The principal geological features of the area together with the location of some of the geoelectrical sites are also shown.

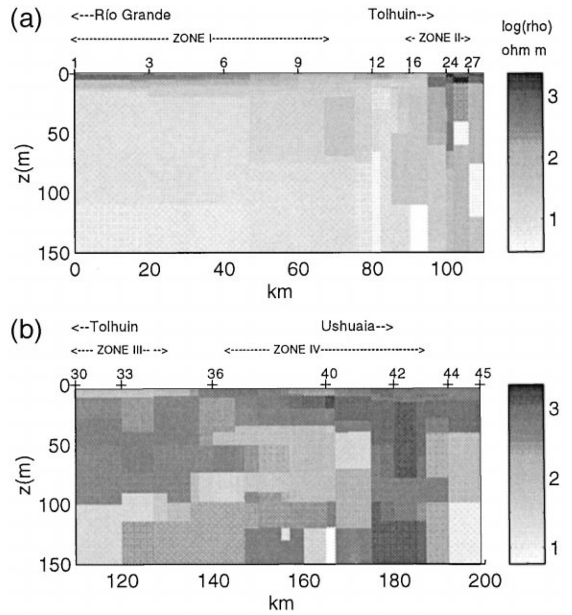

Fig. 2. Electrical resistivity map obtained by inversion of the geoelectrical data. (a) North–south cross section, from Río Grande to Tolhuin. (b) East–west cross-section, from Tolhuin to Ushuaia.

effects. The field curves were first analyzed using a 1D inversion code (Jupp and Vozoff, 1975). With the resistivity profiles obtained at each site, two resistivity cross-section were built up, one including sites between Río Grande and Tolhuin, in an approximately north–south direction, and the other from Tolhuin to Ushuaia, along the east–west direction (see Fig. 1). Then, a 2D Rayleigh–Fourier method (RF-2D code) (Osella et al., 1999, 2000) was applied to calculate the electrical response of both structures. These cross-sections were used as starting models and the parameters were varied in order to obtain the best fit to the data. The resulting cross-sections and fitting between the theoretical responses and apparent resistivity curves obtained at several representative sites are displayed in Figs. 2 and 3, respectively. The close fit of the model results to the experimental data, about 1%, suggests that the proposed 2D models provides an accurate representation of the actual conductivity structure.

The interpretation of the curves indicates the presence of four different environments. A first environment, from VES 1 to VES 16, is conductive, with mean electrical resistivities less than 200 Ωm. A second zone, more resistive, beginning at VES 17 and increasing to VES 21 to 27. Here, the resistivity of the shallower layers rises as high as 2000 to 4000 Ωm. From VES 30, this resistive effect disappears, becoming a different environment, with alternative conductive and resistive layers. In VES 36, the beginning of another change is detected. From here to Ushuaia (VES 45), once more a resistive con-

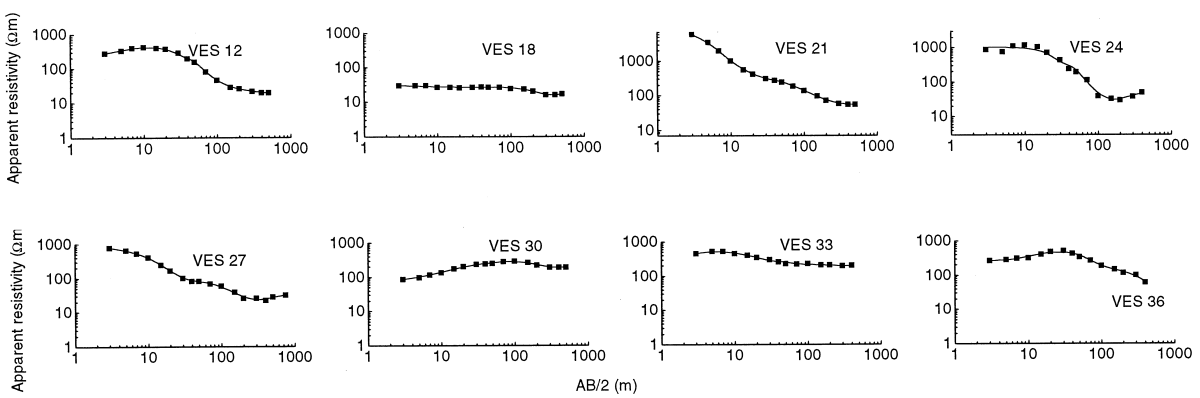

Fig. 3. Fitting of the apparent resistivity curves obtained from the cross-sections shown in Fig. 2 (full line) to data (squares) for some representative sites. The locations of these sites are also shown in Fig. 2.

trast appears, with $\rho \sim 1000\ \Omega$m. This interpretation can be tested with the geological data.

2.3. Geological setting

The main geological features of the area are shown in Fig. 1 (Caminos, 1980). The stratigraphy is represented by Alvear and Yaghan Formations, the principal features of the Andes Patagónicos; Río Bueno and Río Claro Formations and the Quaternary covers, which include glacial deposits and peats in the intermontane valleys.

The first part of the pipeline route, from Río Grande to VES 18, crosses Río Bueno and Río Claro Formations, which are formed by Tertiary sediments from the Paleocene and Eocene. The presence of these sediments, together with the infiltration of saline water (this sector runs parallel and very close to the seashore), are the causes of the low resistivities found in the shallow layers.

Then the route runs across a peat deposit and, in the neighborhood of Tolhuin, a resistive intrusive appears, which outcrops at Huehuepen Mountain. The exposed outcrops indicate that the main constituents are quartz, feldspars and biotites. These rocks, as well as peats, are highly resistive, which explains the large electrical contrast found in this zone (Fig. 2).

From here (VES 30) to VES 33, the route follows the Fagnano lake border, crossing peat deposits with an increase of water content due to the proximity of the lake.

To the south, the route crosses the Alvear Formation, which is formed by Jurassic sediments, its main constituents being lutites and dark slates. The most accessible outcrops appear along the route, where wide packs of slates injected by quartz are observed; also, in some places the statigraphy is denoted by dark and bright bands. Finally, the last soundings were located over the Yaghan Formation, which outcrops in the Olivia and Martial mountains. The constitution is quite similar to the Alvear Formation, and is characterized by dark slates. The intermontane valleys, in particular the Olivia River valley where VES 45 is located, are covered by peats, which make the electrical resistivity increase.

2.4. Correlation between the electrical resistivity profiles and geological features

The main objective of the geoelectrical survey was the detection of zones of contrast in the electrical resistivity of the shallow layers in the host media. From the interpretation of the apparent resistivity curves, two zones of contrast have been detected, which was confirmed by the geological data.

A resistive jump was found in the neighborhood of Tolhuin, caused by the presence of a resistive intrusion, which outcrops in Huehuepen Mountain. This discontinuity shows the border between two zones: zone I (from VES 1 to VES 18), with mean resistivities of 100 Ωm, and zone II, very resistive, with $\rho \sim 2500\ \Omega$m.

Another zone of resistive contrast has been detected between VES 30 to 33 (named zone III) and VES36 to the south (zone IV). Zone III exhibits vertical profiles where alternation appears between resistive and conductive layers, with a mean value of 200 to 300 Ωm, increasing to the south, where resistivities reach values of about 800 to 1000 Ωm.

3. Current measurements and theoretical predictions

3.1. Current measurements

To test the validity of the model prediction, the current drainage was measured along the pipeline. These measurements were made in sites where permanent recording stations were located, i.e., the only sites where connections to the pipe were possible. Because these stations were located at least every 2 km, measuring the voltage drop along this length (necessarily to determine the current flowing along the pipe) was extremely inaccurate. Then, the potential of the pipe relative to a $Cu/CuSO_4$ half-electrode was recorded. Data Acquisition Systems (with a resolution of 0.33 μV) were used and voltage was converted into current through a shunt. This current was forced to drain to the soil through the half-electrode so it is expected that only a small percentage of the total flow would be recorded. This measurement does not provide an absolute value, but it is adequate for showing relative variations.

For this pipeline system, CP was carried out through batteries, which try to maintain the pipe at a constant potential. To avoid battery effects, they were disconnected during the survey. Then, tests were made when the protection was again activated. The records obtained in each situation showed an attenuation of the signals, but the main features and relative variations were maintained.

Simultaneously with the current recordings, a three-component Flux-Gate magnetometer was used to get the components of the external magnetic field, the source of these induced currents. This data was obtained with a sampling rate of 10 s.

Measurements at 15 stations were acquired, these sites being located close to some of the VES's soundings. Data was recorded within the same day for all the stations (to guarantee the correlation with the same external field), and then the measurements were repeated during four more days in order to confirm the relative behavior. As an example, a simultaneous record of the drainage current, obtained close to VES 18 (~ 110 km from Río Grande, Fig. 1) with the external magnetic field, is shown in Fig. 4. The measured current shows the induction effects of the external field, which results in a varying contribution superposed to the direct current originated by the pipe-to-soil potential difference.

Mean-time values of the drainage currents were obtained from the records corresponding to the different stations. The results are shown in Fig. 5a. To test the correlation with the electrical characteristics of the soil, the resistivity profiles for the different sites, obtained from the analysis of the VESs, were averaged by the integration of the profiles considering the first tenths of meters. The results are shown in Fig. 5b.

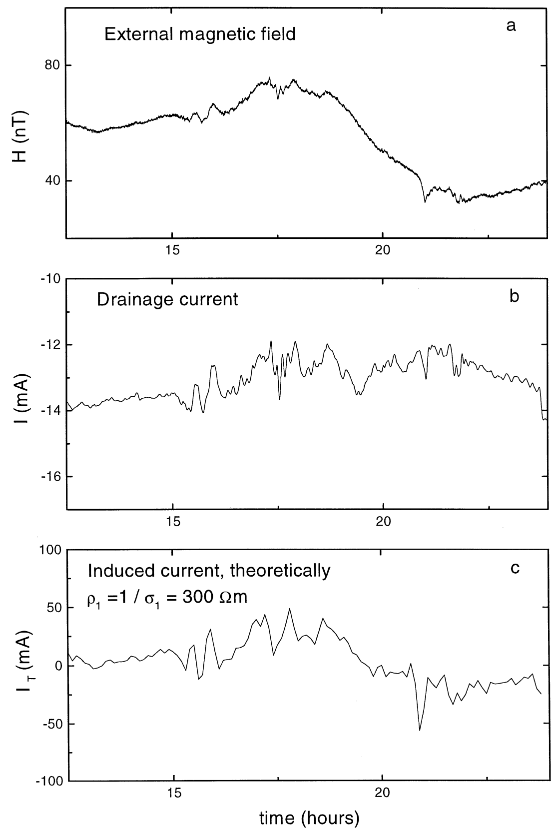

Fig. 4. (a) Records of the horizontal magnetic field, (b) measurement of the current flowing through the pipeline in a site close to VES 18, and (c) the corresponding current simulated numerically.

The comparison between both figures gives interesting results. Along the first section, between VES 1 and VES 18, characterized by a conductive host medium, the drainage of currents remains low, no more than 10 mA. Near VES 21, where the resistivity abruptly increases due to the presence of intrusive rocks, currents also increase, up to 60 mA. A similar behavior

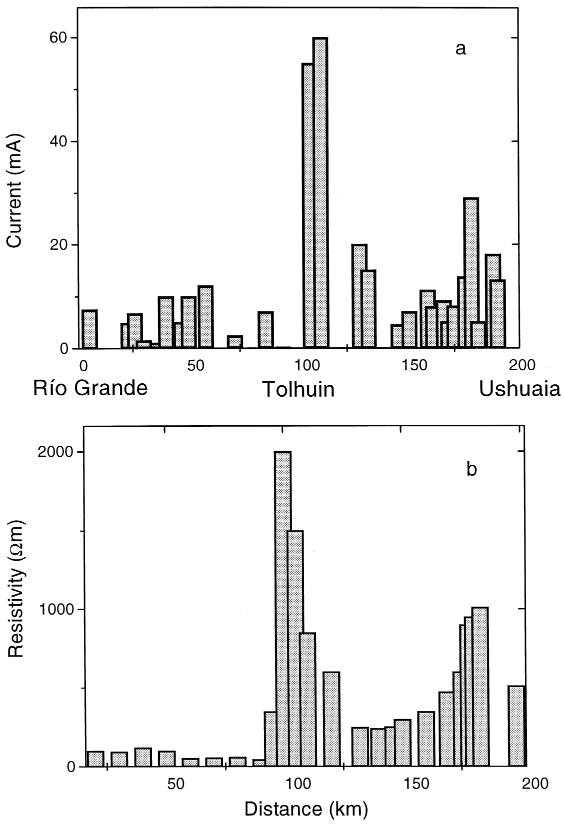

Fig. 5. (a) Mean time values of the electric current flowing from the pipeline to the soil through $Cu/CuSO_4$ electrodes. (b) Mean values of the electrical resistivity of the soil, averaged from the surface down to 50 m.

is observed to the south, where values of 10 to 15 mA quickly increased to 30 mA as the more resistive area was approached.

3.2. Numerical simulation

According to the geoelectrical prospecting results, shown in the previous sections, the pipeline route crosses different kind of soils, and variations in the current flowing along the pipe should be obtained. Then, we calculated the theoretical current that would flow through the pipeline for the different soil characteristics.

The induction effect produced by embedded cylinders has been widely discussed, assuming a circular section to model the body and usually applied to represent the response of subsurface electrical inhomogeneities (see, e.g., Wait, 1952; D'Yakonov, 1959; Howard, 1972). In a previous paper (Osella et al.,1998), we implemented a method for calculating the currents induced in a pipeline, modeled as an embedded cylinder with a ring section inside where the non-conducting fluid flows. The proposed model was defined by four regions: the free space (0), the medium in which the body was embedded (1), the cylinder with a width given by $a_2 - a_3$ (2) and, finally, its interior, occupied by the gas (3). The electrical and magnetic properties of each region were identified through the corresponding electrical conductivity, σ_j, magnetic permeability, μ_j, and dielectric constant, ε_j, with $j = 0 \ldots 3$. The external field was created by a current line parallel to the cylinder, given by $Ie^{i\omega t}$, located at (r_o, φ_o) measured from the center of the cylinder. For simplicity, we considered only the TE mode, but it is well-known that this mode gives the main contribution in the presence of long conductors, producing a channelling effect (see, e.g., Duhau and Osella, 1984) (see Fig. 6). With these assumptions, the electric field along the cylinder, $E_x^1(r, \varphi)$, was obtained by applying Maxwell equations with the corresponding boundary conditions at each interface and from it the induced current was determined (Osella et al., 1998).

The numerical simulation was performed using the horizontal-component recording shown in Fig. 4a as the inducting field. A Fourier analysis of the field was performed and each component was modeled as produced by an induction line of current of intensity $I(\omega)$, flowing at a height $h' = 100$ km; this height was required to reproduce the field measured at the ground.

Values of the remaining parameters (described in Fig. 6), for the particular pipeline system studied here, were:

$$a_2 = 0.20\text{m}; \quad a_3 = 0.29\text{m};$$

section $s = 0.0185\text{m}^2$

$$\sigma_2 = 10^7 \text{S/m}; \quad \mu_2 = 2000\mu_0$$

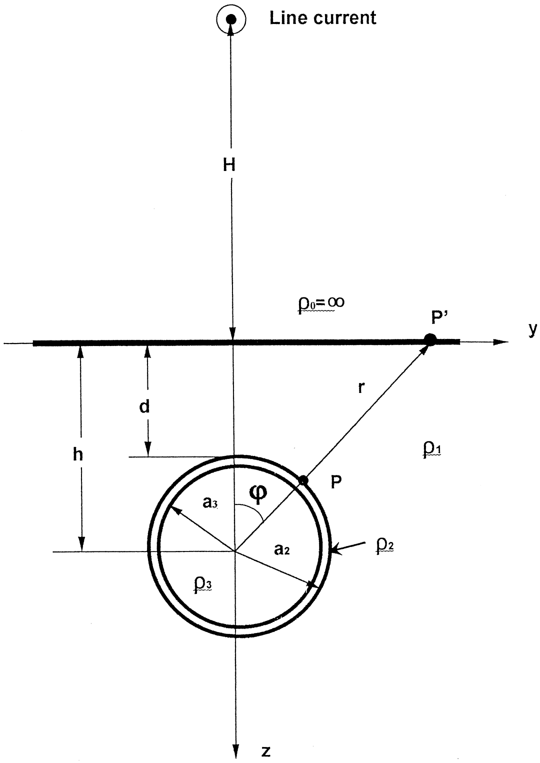

Fig. 6. Model geometry of the embedded pipeline.

This pipeline was located at a depth $h_1 = 0.5$ m in a half-space of conductivity σ_1.

The theoretical induced current, calculated using $\rho_1 = 300\ \Omega$m, which corresponds to the average value of the resistivity at this site (see Fig. 2) is shown in Fig. 4c. A close correlation is observed, the differences in the intensities can be explained if we take into account that, while the numerical simulation gives the current flowing along the pipeline, the experimental possibilities make it possible to determinate only the current draining through a reference electrode (a small fraction of the total flowing current).

Then, calculations of the induced current were performed for four different values of the resistivity $\rho_1 = 1/\sigma_1$ of the host medium, related with the averaged values obtained for the different zones: 100,300,800 and 2500 Ωm, (zones I, III, IV and II) respectively. A section of the horizontal component recording, assumed as the inducting field, is shown in Fig. 7a.

The results for the different cases are shown in Fig. 7b. The intensity of the induced current clearly varies with the resistivity of the host medium. Moreover, if mean-time values are calculated (averaging over, for example, half an hour), it is found that an excess of about 80 mA

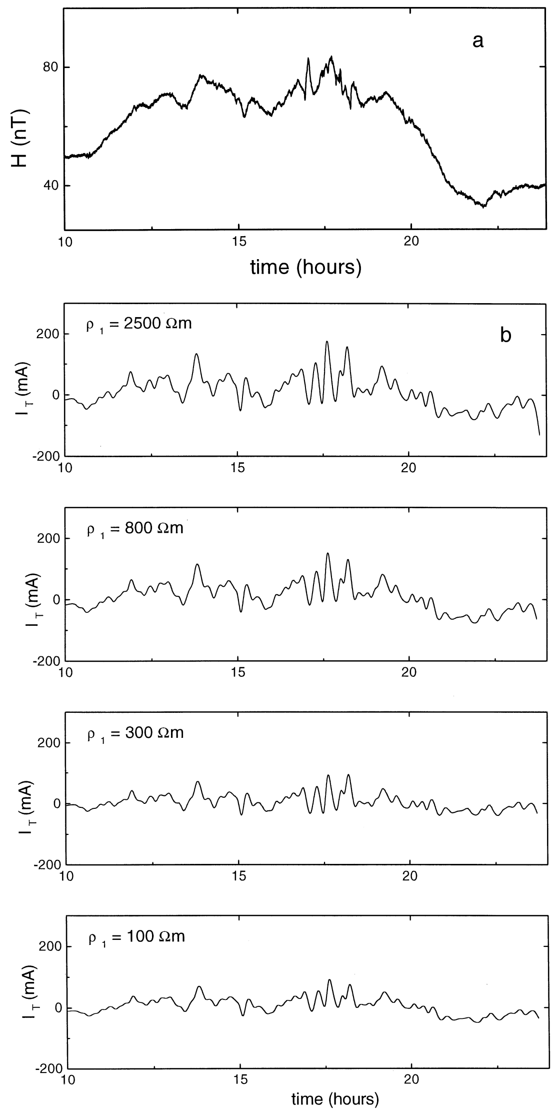

Fig. 7. (a) Horizontal magnetic field recorded with a sample rate of 10 s. (b) Theoretical calculations of the current flowing along the pipeline (I_T) induced by the field shown in Fig. 4a, for different values of the resistivity of the host medium.

would appear when crossing from zone II to zone I and about 40 mA from zone IV to III.

4. Discussion and conclusions

The theoretical modeling of the pipelines embedded in a conducting soil has allowed to estimate the induced current due to an external magnetic field predicting an enhancement of this current when the pipe is embedded in a more resistive soil. The experimental tests seem to support this hypothesis.

The resistive imaging of the soil along the Tierra del Fuego-pipeline trend showed the presence of two zones characterized by strong electrical resistivity contrasts. Close to Tolhuin village, the presence of a highly resistive intrusion, which outcrops in the Huahuapen mountain, is detected. To the south, the electrical resistivity of the soil increases when crossing the Yaghan Formation, in the Cordillera Fueguina, due to the presence of outcropping slates and peats in the intermontane valleys. Analyzing the measurements of drainage currents, low values were detected in zones with tertiary sediments while a clear increase was found along more resistive host media.

The theoretical model also shows a linear relation with the intensity of the external field. That is to say that when the intensity of the field increases, the induced current also increases. This result is specially important when dealing with geomagnetic storms. When these events take place, the intensity of the external field increases in one or two orders of magnitude with respect to the non-disturbed days (as the ones when measurements were performed). This implies that, in zones of resistive contrasts, the flowing currents would proportionally increase reaching, according to the theoretical predictions, up to some tens of amperes. Moreover, if it is taken into account that the diameter of the pipeline network studied here (40 cm) is smaller than the values usual for distribution network systems (60–80 cm), it may be asserted that in this case the effect would be even stronger. Considering that geomagnetic storms occur several times a year, there would be many days when currents of about 10 A would be flowing along the pipes. This fact implies two main risks. The first one is directly correlated with the enhancement of the induced current when the pipe is embedded in more resistive media; a sector of the pipe would be anodic with respect to the other, with the consequent risk that the excess of the currents could drain through the pipe to the soil. Moreover, as the common practice is to increase the current if the medium is conductive the final result would lead to an actually improper setting of the CP voltages. The other risk is related to the intensity of the currents, since values of some amperes could contribute to the degradation of the coating.

We can conclude that an improvement to the CP should be made in order to take into account the effects produced by the external natural fields, specially during disturbed days. This method includes a prospecting sounding of the host medium to determine the electrical characteristics of the soil; since inductive process is involved, it is not enough to know the composition of the ground-bed but to determine the electrical properties even down to some meters. In this way, the regions of resistivity contrasts should be determined and, once those that present higher risks have been identified, a theoretical prediction of the currents that could flow during high magnetic activity can be evaluated. The simple model applied in the paper gives a first insight into the intensities of the induced currents and the behavior with the resistivity. The results obtained here encourage the development of a more realistic model, which includes the presence of lateral inhomogeneities, the effect of deeper layers and spatial-varying external fields. These would provide the necessary information to improve and reinforce the actual protection systems in these regions, which in turn should lead to an extension of the mean life of the pipelines.

Acknowledgements

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