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Province of British Columbia — Ministry of Energy, Mines and Petroleum Resources

Energy, Mines and Resources Canada — Énergie, Mines et Ressources Canada

STUDY OF MINING SHOCK HAZARDS

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STUDY OF MINING SHOCK HAZARDS

Prepared for:

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Appendices

1. SUMMARY AND ACKNOWLEDGEMENTS

1.1 SUMMARY

This report describes a program of site visits that were made to five open pit mines in British Columbia, measurements carried out, information gathered and the subsequent analysis of this material.

The report describes the following:

a) Measurement of soil resistivity for the Mines.

b) Measurement of ground resistances and impedances.

c) Primary ground fault analyses.

d) Assessment of ground potential rise.

e) Assessment of safety of the various different pit distribution systems used.

The project was funded by Energy, Mines and Resources Canada and the British columbia Ministry of Energy, Mines and Petroleum Resources under the Canada/British columbia Mineral Development Agreement.

Note: Throughout the report, numbers in square brackets [ ] indicate references which are listed in Appendix V.

1.2 ACKNOWLEDGEMENT

The study could not have been brought to a successful conclusion without the help of the Electrical Inspector for Mines and cooperation of personnel from the mines visited. Bensted, Simpson & Associates Ltd. are indebted to all these people who assisted with guidance around the mines, help with the field measurements and ready supply of drawings and information. As well, the release of information available from previous studies carried out for two of the mines, is greatly appreciated.

2. INTRODUCTION

2.1 BACKGROUND AND SCOPE OF WORK

This study arose out of concern at present practices employed at open pit mines which use electrically powered mobile equipment. As equipment size has increased in response to a desire for more efficient mining, power requirements have increased. This has resulted in the use of higher voltages in the Pit, with consequently greater fault levels. While the utilization voltage may be 4.16 kV or 7.2 kV, distribution voltages as high as 69 kV are now taken into the Pit to power mobile equipment, usually through moveable step-down substations that are frequently relocated as the mining activities proceed.

There is concern as to the safety of mining personnel working in the Pit, in and around the electrical equipment during faults. The Canadian Electrical Code for Mines [1] requires that high voltage circuits supplying portable or mobile equipment be supplied from a circuit which is resistor grounded at the source transformer so as to limit the voltage rise during a ground fault, to less than 100 volts.

Protection to this level can easily be met by trailing cable feeders derived from moveable substations. The transformer in the Moveable Substation can be provided with a neutral grounding resistor and high voltage trailing cable with shielded phase conductors and monitored internal ground wires can be used. With this arrangement and, typically, a 25 amp neutral grounding resistor, the voltage rise for ground faults at mobile eqnipment can be held to less than 100 volts, even for cable lengths of several km.

The study was not aimed at investigating this portion of the open pit mining power system. What causes concern, is the effect of faults on the primary circuit of the Moveable Substation. The Code [1] does not specifically cover these faults. In most instances, the primary power is provided by means of an overhead line which may or may not have a ground wire. Ground faults on the primary of the Moveable Substation must therefore return to source through the soil or a combination of soil and ground wire. When an overhead ground wire is used, the impedance is significant and must be taken into account. The voltage rise at a Moveable Substation due to a primary fault is therefore determined by the greund fault current and return path impedance. Depending on the Moveable Substation configuration, the voltage rise can be transferred through the trailing cable ground conductors to all the mobile equipment connected to the Substation.

To assess the extent of this problem the following scope of work was drawn up:

2.1.1 Undertake a program of visits to, and conduct soil resistivity and ground impedance measurements at four mines.

2.1.2 Obtain information on the electrical distribution systems used to supply power to portable and mobile electrical equipment at these mines and the grounding methods used.

2.1.3 Process the data gathered during these visits to determine the actual touch and step potentials in the area of portable and mobile electrical equipment.

2.1.4 Determine the appropriate soil resistivity models.

2.1.5 Review all field measurements and observations and the results of similar studies that are available in conjunction with available literature and codes including human tolerance of shock hazard levels.

2.1.6 Prepare a comprehensive report that will include all data derived by the study and interpretations of those data, and all other available data, that may lead to recommendations for a code of practice for the use of Moveable Substations in open pit mines. The report must be in a format suitable for eventual public release.

2.2 SUMMARY OF WORK CARRIED OUT

Six mines, numbered #1 through #6, were evaluated in the study. Field trips were made with the Electrical Inspector for Mines, to Mine #1, #2, #3, #4 and #6.

A series of soil resistivity and ground system impedance measurements were carried out at each mine visited. Drawings and other information related to the power system was also gathered. Mine #4 had experienced a minor shock incident prior to the site visit. Data relating to that incident was recorded and evaluated. Mine #6 were in the process of developing a new Pit and, as part of the study, soil resistivity measurements were taken for a new Moveable Substation location and a suitable grounding system was designed.

Bensted, Simpson & Associates Ltd. (BSA) have previously carried out a grounding study for Mine #3 and several studies for Mine #5. The information and measurement results from these studies were also made available.

The field measurement data was processed and the power system information reviewed in meetings with the Electrical Inspector for Mines. Fault level calculations were carried out. Diagrams of the different power systems used and possible fault situations were developed. The minor shock incident was evaluated with a grounding model.

The project concluded with this report.

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

Open pit mines in B.C. are characterized by having relatively high soil resistivity. Soil resistivity measurements showed resistivity in the range of 100 to 1000 ohm-metres. In the pit areas, the soil resistivity was generally found to be several hundred ohm-metres. This makes for difficult grounding conditions for electrical equipment in the pits.

Ground resistance and impedance measurements showed that individual ground beds used by most mines have impedances of between 7 and 32 ohms. Connection of mobile equipment and/or the use of an overhead ground wire network or bonds to remote ground beds reduces the effective impedance to as low as 1.5 ohms in some instances.

Each mine analyzed for this study uses a different pit distribution system. The potential for shock hazard at each mine can be summarized as follows:

<u>Mine #1</u> A 69 kV ground fault at a moveable substation can cause a ground potential rise of about 16500 volts. This will result in lethal step and touch potentials around the moveable substation and any other equipment such as a skid breaker, shovel or drill, bonded to it. This is because:

a) The 69 kV supply is taken direct from the B.C. Hydro source which does not have a ground fault current limiting neutral resistor.

b) The soil resistivity in the pit areas is relatively high.

c) There is no overhead ground wire on the pit distribution system.

d) Because of b) and c), the resistance of the ground bed used at each moveable substation cannot be made low enough to reduce the ground potential rise to tolerable levels.

In considering the use of an overhead ground wire, it is unlikely that this will alleviate the problem because of the high fault level and the significant impedance of the length of ground wire that would have to be used. The mine has a voltage regulating transformer in the main 69 kV feeder. This will not reduce the ground fault level at the pit as it only inserts a relatively small impedance in series with the line when the tap setting is off normal.

Mine #2 Ground faults on the 13.2 kV side of the Moveable Substation produce a relatively high and possibly lethal ground potential rise. This is due to:

a) The use of an 800 amp neutral grounding resistor on the 13.2 kV system.

b) No overhead ground conductor to reduce the impedance of the ground fault return path.

A potentially lethal 657 volts could appear on the mobile equipment during a 13.2 kV ground fault because:

a) Although the mine uses an effective method of isolation between the 13.2 kV pit distribution system and the 4160 volt mobile equipment feeders and provides separate ground beds for each, the ground bed separation of 24 metres indicated on the mine drawings is not adequate. (It should be noted that the actual separation observed at the mine was much greater than 24 metres)

There is also the possibility of a 13.2 kV primary to 4160 volt secondary fault within the transformer. If this fault causes an insulation breakdown in the secondary wiring, the same 4600 volt potential rise could occur at the mobile equipment. In any event, the secondary neutral grounding resistor will allow about 80 amps to flow to the mobile equipment ground bed with a possible 1270 volts ground potential rise.

As overhead ground wires are not installed along the 13.2 kV distribution system, the mobile equipment is well isolated from transfer of ground potential rise due to faults on the incoming 132 kV B.C. Hydro supply at the Main Substation.

Mine #3 Ground potential rise due to 13.8 kV ground faults exceeds 100 volts at many locations at this mine, with the worst GPR being 472 volts. This is because:

a) A 400 amp 13.8 kV neutral grounding resistor was installed at the time a grounding study was carried out for this mine.

b) Although an overhead ground wire network with many grounded points is used on the secondary distribution system and a common ground is provided at each moveable substation for both the 13.8 kV primary and 4160 volt secondary, the ground network performance is such that ground potential rise is not adequately controlled for a 400 amp neutral resistor.

It is understood that the Mine is implementing a change in the neutral grounding resistor to reduce the ground fault current and consequently, the ground potential rise.

Potential rise due to ground faults on the 138 kV supply at the Main Substation will be transferred to the mobile equipment because overhead ground wires are installed on the 13.8 kV distribution system. However, there is appreciable attenuation of the GPR between the Main Substation and the pit so that only about 228 volts will appear on the mobile equipment nearest the pit feed point.

Mine #4 13.8 kV ground faults at a Moveable Substation can cause dangerous GPR which exceeds the 100 volt Mining Code limit because:

a) Except for a 13.8 kV dragline that is grounded to a separate ground bed near the Main Substation by an overhead ground wire, the Moveable Substations are not provided with overhead ground wires.

b) Each Moveable Substation is provided with two ground beds with a ground resistance of typically 20 to 30 ohms. The Mine used to use one ground bed for the Moveable Substation transformer ground and the other for the 4160 volt secondary neutral resistor ground. (Since the shock incident described later, the mine has been bonding the two ground beds.)

c) The 13.8 kV system has a 25 amp neutral grounding resistor limiting the GPR to about 470 volts (assuming a 20 ohm ground bed).

d) The transformer and secondary switchgear are separate assemblies, connected by trailing cable.

A shock incident described later in the report reveals one of the problems of operating separate ground beds with a Moveable Substation which has separate transformer and secondary switchgear. A line-to-ground fault at the transformer is undetected by the ground fault detection system and allows current to flow through the transformer ground bed to the neutral ground bed, resulting in a hazardous ground potential rise on the transformer.

Mine #5 The distribution system configuration for this mine is such that ground potential rise at moveable substations and mobile equipment is held to less than 100 volts. This is achieved for the following reasons:

a) The Mine receives utility power at 230 kV which is transformed to 67 kV.

b) The 67 kV supply has a neutral grounding resistor with 25 amp current limit.

c) There is several km distance between the 230 kV Substation and the pits and no overhead ground wire is provided, so that transfer of 230 kV ground fault potential rise is prevented.

d) The lack of a low impedance return path is compensated for by the installation of a pit overhead ground wire system which is provided with ground beds so that the ground impedance at any Moveable Substation is less than 4 ohms.

Mine #6 Ground faults on the older part of this mine's 4160 volt distribution system do not cause a ground potential rise that exceeds 100 volts because:

a) The 4160 volt source neutral is grounded through a 25 amp resistor.

b) An overhead ground wire is used. Fault currents are therefore limited and provided with a low impedance return path.

However, faults on the 138 kV Utility supply will propagate to the old pits through the overhead ground wire because the 4160 volt neutral is grounded to a separate ground bed that is fairly close to the Main Substation ground grid. The Main Substation ground grid resistance is such that the ground potential rise at the Main Substation will be about 2070 volts. This will result in 635 volts ground potential rise on the separate ground bed.

For the new pit, ground potential rise is held to within 100 volts for the following reasons:

a) The 4160 volt power is transformed up to 25 kV and transmitted several km to the new pit site with no overhead ground wire so that 138 kV ground fault potential rise cannot be transferred to the new pit.

b) The 25 kV system has a 25 amp neutral grounding resistor.

c) A ground bed with resistance less than 4 ohms is provided at the new pit.

General Comments

In reviewing the different moveable substation configurations, some require that the equipment operator stand on the ground while operating switchgear while others, specifically moveable substations that consist of a single structure containing switchgear and transformer, ensure that the operator is standing on the grounded metal structure while operating the switchgear.

There is also a possibility of a ground fault while a person is stepping on or off the Moveable Substation.

Another potentially hazardous area where there is no clear conclusion as to the worst situation, is in the connection of trailing cables to the moveable substation. If the operator stands on the ground while plugging in the cable, he may receive a shock from the substation. If he stands on the substation while there is a fault, he may be holding the trailing cable coupler which is remotely grounded through a machine and receive a shock that way.

If the power distribution system is adequately designed to limit potential rise to less than 100 volts and the fault duration is less than 1 second, then the shock hazard is minimized.

3.2 RECOMMENDATIONS

All mine electrical systems should be reviewed periodically. Because of ongoing changes in the power distribution configuration as mining proceeds:

a) Power systems should be analyzed.

b) Resistance of ground mats should be measured periodically and compared with minimum requirements.

c) Integrity of overhead ground wires should be measured periodically.

System analysis must consider the possibility of transferring ground potential rise from the Main substation to moveable substations and mobile equipment.

The design of moveable substations should be examined to ensure that personnel are not subjected to unnecessary risk whilst in contact with the grounding system when:

a) Changing cables. In this regard, it is suggested that a jumper cable with alligator clips be used to bond cable couplers before handling so that the operator is not placed between two different potentials.

b) Operating switchgear.

c) Maintaining equipment.

d) Mounting and dismounting from platforms.

The positioning of equipment and cable outlets on the platform and the use of gradient control mats where personnel operate switchgear or step on or off equipment, must be designed to maintain personnel at the same potential as the grounding system.

Ground fault current on pit distribution systems should be reduced to a practical minimum. Even when ground fault current is limited to 25 amps, an unacceptable ground fault potential rise can result from faults on systems with high impedance ground return paths.

The following are recommendations to improve the power systems at each mine to within Electrical Code [1] requirements. Where reference is made to "unit construction moveable substations", these are is defined as single moveable substation structures with all equipment mounted on skids or a trailer, containing a high voltage circuit breaker that can be tripped by a secondary ground fault, transformer, secondary neutral grounding resistor and secondary switchgear enclosure. The secondary enclosure should be throat coupled to the transformer and contain zero sequence ground fault detection and trailing cable ground integrity monitoring systems. Some method of monitoring the neutral resistor integrity should also be provided:

<u>Mine #1</u>

a) A ground fault current limited distribution system should be installed.

b) Overhead ground wires, not interconnected with the Main Substation ground system, should be installed because even with ground fault current limited to say 25 amps, it will be difficult to create local ground beds with low enough resistance at each moveable substation. Low resistance remote ground beds should be created or a grounding network formed by interconnection of overhead ground wires should be implemented.

c) Unit construction moveable substations should be used.

<u>Mine #2</u>

a) The neutral resistor for the 13.2 kV distribution system should be changed from 800 to say 25 amp rating.

b) A low resistance remote ground bed should be installed with a system of overhead ground wires for the pit only.

c) Moveable substations should be bonded to the overhead ground wire system and have one common ground bed similar to those already in use.

Mine #3 a) The pit distribution neutral ground resistor should be reduced from 400 amp to 75 amp.

Mine #4 a) One or more remote ground beds and a separate pit overhead ground wire system, not interconnected with the Main Substation ground, should be installed so that a low enough ground impedance is available at each moveable substation. This is required because it is impractical to create a sufficiently low resistance ground bed for each moveable substation whenever it is relocated.

b) Unit construction moveable substations should be used.

Mine #5 a) No changes are required although it would be beneficial if trippable high voltage circuit breakers were provided in the unit construction moveable substations.

Mine #6 a) For the old pits, a new remote ground bed should be provided for the mobile equipment ground system. This ground bed should be located further away from the Main 138 kV Substation than the present ground bed.

3.3 EXCLUSIONS

The study is limited to 60 Hz power frequency effects and does not consider impulse hazards such as those produced by lightning, SF_6 switchgear and similar high speed fault interruptions.

4. METHODOLOGY AND RESULTS

4.1 SOIL RESISTIVITY MEASUREMENT AND INTERPRETATION

Soil resistivity was measured at all the mines visited except Mine #3. Soil resistivity data for Mine #3 was available from the previous BSA study. The figures and tables for the soil resistivity measurement results are contained in Appendix I.

Soil resistivity measurements were carried out using the "Wenner" method described in Appendix III. Measurements were made with an Evershed Vignoles DET-2 electronic Direct Earth Tester, some check readings being taken with an Evershed Vignoles ET3 hand-cranked meter. Due to the influence of deeper soil layers on the ground resistance, the soil resistivity measurements were taken to as wide a probe spacing as practicable for each measurement.

Soil resistivity measurements taken using the "Wenner" method can be interpreted, to a first approximation, as being indicative of the average soil resistivity to a depth equal to the probe spacing for each reading. The apparent measured soil resistivity usually varies with probe spacing and it can become difficult to interpret the measurement results correctly. Interpretation methods are discussed in Appendix III. To obtain a better interpretation of the results, the curve fitting procedure described in Appendix III was applied to derive an equivalent two-layered soil model from the measurement data.

4.1.1 Mine #1

Soil resistivity Traverses #3 and 4 were carried out at in a coal bearing area at Mine #1 at right angles to each other. The measurement results are plotted in Figures I.4 and I.5 in Appendix I. The average of Traverses #4 and #5 is plotted in Figure I.6. There are some irregularities in the curve but it shows a soil resistivity that increases with increasing probe spacing. The curve fitting process was applied and resulted in an equivalent two-layer soil model:

Upper layer resistivity	271.0 ohm-metres
Height of upper layer	10.7 metres
Deep layer resistivity	590.4 ohm-metres

Traverse #5 was carried out in an area of loose dump rock. The measurement results are plotted in Figure I.7 in Appendix I. They show a higher soil resistivity than Traverses #3 and #4, but decreasing with wider probe spacing. In deriving an equivalent two layer soil model, the first 4 probe spacing readings were deleted from the measurement data. This produced an equivalent soil model:

Upper layer resistivity	798.1 ohm-metres
Height of upper layer	19.3 metres
Deep layer resistivity	282.0 ohm-metres

4.1.2 Mine #2

Soil resistivity Traverses #6 and #7 were taken at the same location at right angles to each other, at the bottom of the Pit at Mine #2. The results are plotted in Figures I.8 and I.9 in Appendix I. The area was substantially undisturbed bedrock and copper ore. These two traverses indicate a soil resistivity that is low near the surface, probably due to water and crushed fines on top of the bedrock, which increases with depth to a fairly constant value. The average of the two traverses is plotted in Figure I.10 and the data was used to develop an equivalent two layer soil model:

Upper layer resistivity	151.4 ohm-metres
Height of upper layer	2.7 metres
Deep layer resistivity	352.1 ohm-metres

Soil resistivity Traverse #8 was also taken at Mine #2, outside the Pit in apparently native soil. The results are plotted in Figure I.11 in Appendix I. A two-layer curve fit resulted in the soil model:

Upper layer resistivity	156.3 ohm-metres
Height of upper layer	13.3 metres
Deep layer resistivity	114.6 ohm-metres

4.1.3 Mine #3

No soil resistivity measurements were carried out at Mine #3 in conjunction with this study. However, soil resistivity measurements were done by BSA as part of a previous study for Mine #3. The following equivalent soil models were obtained:

- Near Mobile Crusher location. This area is approximately 200 metres for the edge of the Pit and appears to be native top soil over copper bearing rock:

Upper layer resistivity	1952.8 ohm-metres
Height of upper layer	10.3 metres
Deep layer resistivity	188.7 ohm-metres

- Grassed area in front of Mine Offices:

Upper layer resistivity	261.4 ohm-metres
Height of upper layer	1.6 metres
Deep layer resistivity	108.8 ohm-metres

- Near Settling Pond Recovery Substation. This area is 15 to 20 km from the Pit, further down the valley and is thought to be similar in soil structure. The readings were taken in order to study the Substation grounding safety, but are representative for the area. The soil appeared to be original native soil:

Upper layer resistivity	208.5 ohm-metres
Height of upper layer	1.8 metres
Deep layer resistivity	99.6 ohm-metres

The soil resistivity measurements showed that, apart from upper layer variations, the deep layer resistivity is fairly consistent and in the range of 100 to 190 ohm-metres. The relatively high upper layer resistivity measured near the Mobile Crushers is probably due to de-watering of the area resulting in drying of the upper 10 metres.

4.1.4 Mine #4

Soil resistivity Traverses #1 and #2 were carried out at Mine #4. Traverse #2 was taken at right angles to #1 with the same centre location. The results are plotted in Figures I.1 and I.2 in Appendix I. Similar results were obtained in the two directions. The average of the Traverse #1 and #2 measurement results was calculated and is plotted in Figure I.3. The plotted results indicate a soil resistivity that first increases slightly and then decreases with increasing probe spacing. To a first approximation, this indicates an underlying soil structure with resistivity that first increases slightly with depth and then decreases.

To obtain a better understanding of the soil resistivity for the area, the curve fitting process described in Appendix III was used to analyze the average soil resistivity measurement results. The curve fitting process develops an equivalent two layer soil model that would produce a series of field measurement results the same as were actually measured. The curve fit obtained is shown as an example, in Figure III.8 in Appendix III.

The curve fit was obtained with a soil model with:

Upper layer resistivity	893.5 ohm-metres
Height of upper layer	11.3 metres
Deep layer resistivity	368.9 ohm-metres

It is interesting to note that the curve fit results in a deep layer resistivity that is appreciably lower than the value measured at the widest probe spacing. The plotted measurement results indicate that the soil really has three layers. There is a thin upper layer with lower resistivity which is probably due to mud and soil mixed into the top layer. A better curve fit can be obtained if the first two measurement data points are deleted from the curve fit input. A slightly different soil model is then obtained:

Upper layer resistivity	938.9 ohm-metres
Height of upper layer	10.5 metres
Deep layer resistivity	372.1 ohm-metres

4.1.5 Mine #5

No soil resistivity measurements were carried out at Mine #5 in conjunction with this study. However, soil resistivity measurements were done by BSA and others as part of previous studies for Mine #5. The following equivalent soil models were obtained:

- 230 kV Substation and Plant Site. Measured by others. 140 to 285 ohm-metres.

- Pit Area. Measured by others. 600 to 800 ohm-metres.

- Geological Well-Log at an area with similar geological formation. Measured by others. Approximately 360 ohm-metres.

- Electrified Railway (Valley area). 160 ohm-metres.

- Native mountain top (saddle area) outside Pit:

Upper layer resistivity	248.4 ohm-metres
Height of upper layer	10.3 metres
Deep layer resistivity	342.9 ohm-metres

- Conveyor Access Road near top of Conveyor. Measured during construction of the conveyor:

Upper layer resistivity	158.2 ohm-metres
Height of upper layer	1.83 metres
Deep layer resistivity	431.0 ohm-metres

- Top of Mountain. Measured on a dump rock area during early mine development:

Upper layer resistivity	202.1 ohm-metres
Height of upper layer	7.1 metres
Deep layer resistivity	1569.6 ohm-metres

- Moveable Substation hill-top location near Pit Office Building:

Upper layer resistivity	299.6 ohm-metres
Height of upper layer	2.5 metres
Deep layer resistivity	664.8 ohm-metres

- Along Conveyor ROW:

Upper layer resistivity	1298.4 ohm-metres
Height of upper layer	2.6 metres
Deep layer resistivity	244.8 ohm-metres

4.1.6 Mine #6

Soil resistivity Traverses #9 and #10 were taken at the location for a new Pit Substation at Mine #6. The traverse centre is at the top of a small hill and was undisturbed at the time of the measurements. Traverse #10 extended down the sides of the hill so that the outer probes at the widest spacing were appreciably lower than the centre. This is though to be the reason for the decrease in apparent resistivity at the widest probe spacing as the assumed water table is nearer the surface. The measurement results are plotted in Figure I.12 and I.13 in Appendix I. The average of Traverse #9 and #10 is plotted in Figure I.14

From the change in apparent resistivity which first increases and then decreases, a three layer soil model is more appropriate. Two curve fit calculations were therefore done. In the first, the data for probe spacings 1 to 20 metres was used to produce an equivalent two layer soil model. This approach is valid because most of the test current would be confined to the upper layers:

Upper layer resistivity	235.0 ohm-metres
Height of upper layer	2.7 metres
Deep layer resistivity	598.6 ohm-metres

In the second curve fit, the readings for probe spacings 20 to 36 meters were used. These few readings, when plotted, are almost a straight line. The analysis of measurement results like this is subject to large errors if there is any error in the measurement results because a small measurement error changes the average slope of the plotted results. Also, one is trying to obtain information about a much deeper layer. Initially quite a good curve fit was obtained for the soil model:

Upper layer resistivity	671.5 ohm-metres
Height of upper layer	14.1 metres
Deep layer resistivity	345.3 ohm-metres

Comparing this with the two layer curve fit obtained for probe spacings 1 to 20 metres, the deep layer of the 1 to 20 metre fit (598.6 ohm-m) is similar to the upper layer of the 20 to 36 metre fit (671.5 ohm-m). The conclusion therefore was to use a two layer model with upper layer as indicated by the 1 to 20 metres probe spacing measurement results an a deep layer of approximately the average of the deep layer resistivity for 1 to 20 metre readings and both layers of the 20 to 36 metre readings. This results in the soil model which was used to design a suitable ground bed for the Moveable Substation at the new Pit:

Upper layer resistivity	235 ohm-metres
Height of upper layer	2.7 metres
Deep layer resistivity	500 ohm-metres

A later more detailed analysis of the soil resistivity measurements shows that for the 20 to 36 metre readings, a better curve fit is obtained using different starting values. It should be understood that the curve fit process is given a set of starting soil model values (Upper and deep layer soil resistivity and height of upper layer). It then adjusts these values progressively to obtain the best fit. Different starting values can produce different results, particularly with the type of data for the 20 to 36 metre probe spacing readings. A better fit was obtained for a soil model:

Upper layer resistivity	587.5 ohm-metres
Height of upper layer	44.1 metres
Deep layer resistivity	61.4 ohm-metres

However, this soil model gives similar ground resistance for an electrode located in it because the low resistivity layer is very deep.

Traverse #11 was taken near the Main Substation for the mine. Relatively low resistivity readings were obtained. This is thought to be due to the area being low lying compared with the other area measured. With the arid climate, salts collect in the soil in low lying areas. In areas where the terrain slopes or where the rainfall is higher, salts tend to be leached out with time and the soil has a higher resistivity. The measurement results are plotted in Figure I.15 in Appendix I. A good approximate interpretation for the measurement data would be a uniform soil with resistivity 25 ohm-metres. A two layer equivalent soil model was derived from the data, omitting the first point (1 metre probe spacing):

Upper layer resistivity	16.3 ohm-metres
Height of upper layer	7.0 metres
Deep layer resistivity	34.1 ohm-metres

4.1.7 Summary of Soil Resistivity Measurement Results

Mine #	Upper Layer ohm-m	Height of Upper Layer metres	Deep Layer ohm-m
1	271.0	10.7	590.4
1	798.1	19.3	282.0
2	151.4	2.7	352.1
2	156.3	13.3	114.6
3	1952.8	10.3	188.7
3	261.4	1.6	108.8
3	208.5	1.8	99.6
4	938.9	10.5	372.1
5	248.4	10.3	342.9
5	158.2	1.8	431.0
5	202.1	7.1	1569.6
5	299.6	2.5	664.8
5	1298.4	2.6	244.8

Note: For Mine #5, a soil resistivity of 140 to 285 ohm-metres was measured by others for the Main Substation area and 600 to 800 ohm-metres for the pit area.

4.2 GROUND SYSTEM IMPEDANCE MEASUREMENT

Ground system impedance measurements were carried out at all the mines visited except Mine #3. The figures and tables for ground system impedance measurement results are contained in Appendix I.

Ground impedance measurements were carried out using the fall-of-potential method described in Appendix III. The test current was provided by a Honda portable generator and interface unit. The interface unit contains a Variac and step-up transformer for adjusting the test current and a rectifier which can be used for dc measurements. Test currents were measured with a Beckman DM25L digital multimeter.

The ac measurements were carried out at a frequency of about 50 Hz and about 70 Hz by changing the portable generator speed. The ac potential was measured with a Hewlett Packard 3581C frequency selective voltmeter. This meter has a 3 Hz bandwidth and effectively screens the test signal from interference due to spurious 60 Hz signals that are present on the ground system. The test current was sufficient to produce a potential rise that could be reliably detected and measured with this voltmeter.

The dc measurements were carried out using a Fluke 8050A digital voltmeter which has a relative feature. This enables off-setting the soil/metal electrolytic component of the potential. The dc test current was reversed about once per second to prevent build up of the polarizing potential.

Some measurements were also taken with the Evershed Vignoles DET-2 direct earth tester. This meter is an electronic four terminal resistance meter which uses a rapidly reversing (128 Hz) dc test current. In theory, it measures dc resistance, however, for very low resistances typically less than 0.5 ohm, the time constant of the measuring circuit can introduce some errors.

Most of the measurements of small ground beds or Moveable Substations were taken with the C2 current return electrode located 100 to 200 metres from the ground and a series of P2 potential electrode locations starting at the ground bed and moving towards the C2 electrode. In most cases, the measurement results were interpreted by taking the apparent impedance at 62% of the distance to the C2 electrode [5].

The ground impedance measurement results have not been summarized as they are dependent on whether the measurement was taken with overhead ground wire connected, or not.

4.2.1 Mine #1

This mine does not use overhead ground wires on the distribution to the Moveable Substations. One common ground bed is used for each Moveable Substation. Fall-of-potential Traverse #4 was taken on the ground bed at one of the Moveable Substations. The measured resistance was about 6.8 ohms.

Fall-of-potential Traverse #5 was taken on the ground bed at another Moveable Substation. The conventional fall-of-potential measurement had to be abandoned because of excessive noise. The Substation and equipment supplied by it were shut down and a single measurement was taken using the 62% P2 location. The measured resistance was 7.2 ohms.

The reason for the noise on this ground appears to be due to several 100 metres of 6.9 kV secondary overhead line with ground wire between the Moveable Substation and the Mobile Equipment. At least two skid breakers feeding Mobile Equipment were attached to the 6.9 kV line. It is understood that some ground rods were installed at the skid breakers. The machines also make ground contact. When the machines are operating, noise is induced in the secondary overhead ground wire due to inductive coupling between the phase conductors and ground wire. The measured resistance is therefore the combination of the Moveable Substation ground bed resistance and all the other grounds provided by machines and ground rods along the secondary overhead line. The Substation ground bed resistance is therefore higher than 7.2 ohms.

4.2.2 Mine #2

Mine #2 uses separate ground beds for the Moveable Substation transformer and the Mobile Equipment supplied by it. An effective means for ensuring that the separation between the ground systems is maintained with time, is used.

Fall-of-potential Traverse #9 was taken near the bottom of the Pit on an old Mobile Equipment ground bed. The measured resistance was about 9.5 ohms. The transformer ground bed that had been associated with this Substation location measured about 19.0 ohms. A transferred potential measurement was also made by injecting the test current into transformer ground bed and measuring the potential transferred to the equipment ground. About 2.1% of the transformer ground potential rise was transferred to the equipment ground.

Fall-of-potential Traverse #10 was taken at a working Moveable Substation. The Substation supplied power to two shovels. The following resistances were obtained for the equipment ground bed:

With both shovels disconnected	21.2 ohms
With shovel #136 connected	6.21 ohms
With shovel #137 connected	7.35 ohms
With both shovels connected	3.96 ohms

These readings illustrate how the contact between the shovel and ground can improve the effective ground resistance of the Moveable Substation. If one makes the reasonable assumption that the equipment ground bed and each shovel were far enough apart that the ground resistance of each was unaffected by the others, the shovel resistances can be calculated to be:

Shovel #136	8.78 ohms
Shovel #137	11.25 ohms

The transformer ground bed was measured at 27.4 ohms.

The resistance between the transformer ground bed and the equipment ground bed was measured at 32.2 ohms with both shovels connected. This agrees fairly well with the sum of the transformer and equipment ground bed resistances:

27.4 + 3.96 = 31.6 ohms (vs 32.2 ohms measured)

An examination of the methodology used by this mine to achieve separation between the ground systems illustrates how carefully this must be done.

4.2.3 Mine #3

This mine uses a network of overhead ground wires with ground rods installed at intervals and many bonds to equipment that has ground contact.

Due to wind and snow conditions, fall-of-potential measurements at Mine #3 were limited to single measurements where the C2 current return electrode was placed 100 metres from the unknown ground bed and the P2 reference at 62 metres in the same direction. Three Moveable Substation grounds were measured. The results are summarized below:

Sub #	Frequency Hz	Measured Impedance ohms
7	dc	2.12
7	49	2.65
7	73	2.89
6	dc	4.48
6	49	4.15
6	71	4.07
1	50	8.81
1	71	10.39
1	51	32.85 O/H ground disconnected
1	71	30.79 O/H ground disconnected

The measurements at Sub #7 and #1, with the overhead ground wire connected, follow an expected trend of increasing impedance with frequency. At Sub #6, the impedance follows a reversed trend. As mining was in progress during the measurements, it is possible that the impedance was changing with machine movement. This seems to be the only reasonable explanation. Sub #1 supplied well pumps and the reason for the difference in ground impedance at 51 and 71 Hz is unknown.

4.2.4 Mine #4

This mine used two separate ground beds for each Moveable Substation. Traverses #1 and #2 were taken at a Moveable Substation. The first fall-of-potential measurements were done with single point C2 and P2 references:

Secondary neutral ground bed	13.83 ohms
Transformer ground bed	18.84 ohms

The second measurement, Traverse #2, was a conventional fall-of-potential measurement from the ground beds towards the C2 electrode 175 metres away. This gave a transformer ground bed resistance of about 21 ohms. Mine personnel had previously measured 2 ohms ground resistance at this Substation. The difference between the measurement done by the mine personnel and Bensted, Simpson & Associates is thought to be due to use of reference electrodes that were too close to the ground electrode

Fall-of-potential Traverse #3 was a measurement of a disused ground bed that had been used to ground a 15 kV dragline switch house. The dragline was normally supplied by an overhead line with a ground wire back to a separate neutral ground bed at the Main Substation for the mine, however, the ground bed under test was completely isolated from any other ground systems during the measurement. Measured resistance was about 130 ohms. The measured resistance of the overhead ground wire using the digital earth tester was 6.1 ohms. The length of the ground wire back to the Main Substation was estimated at 1.5 km. The ground resistance of the separate ground bed at the Main Substation was later measured in Traverse #7, to be about 3 ohms with various ground wires connected. The resistance of the overhead ground wire for the distance in question, should be less than 1 ohm.

The measurement was repeated later in fall-of-potential Traverse #8 using the ac measurement methodology with a portable generator. An ac impedance of about 6.6 ohms was measured.

It is unclear why the measurement taken at the dragline is as high as 6.6 ohms. It may be due to poor splices in the overhead ground wire.

Fall-of-potential Traverse #6 was taken at another Pit area. A minor shock incident had occurred at equipment powered by this Substation a few days before the measurements. Separate 4160 volt secondary neutral and transformer ground beds were used. The neutral ground bed resistance was 19.8 ohms. The secondary of this Substation supplied a shovel partially by overhead line. The measured resistance includes the contribution of the overhead ground wire from the Substation to the shovel. The transformer ground bed resistance was 33 ohms.

Fall-of-potential Traverse #7 was taken at the Main Substation for the Mine. The Main Substation has a conventional ground grid for the Substation Equipment as well as a separate ground bed for the secondary neutral grounding. Details of the separate ground bed are unknown. Measurements show that the impedance of the Main Substation ground grid is about 3.7 ohms. The separate ground bed resistance is about 3.0 ohms. A measurement was also taken between the Substation ground grid and the separate ground bed with a reading of 3.0 ohms. This indicates that the two ground systems are separated, however, the effective isolation between the two grounds cannot be assessed without knowing the physical location and configuration of the separate ground bed.

4.2.5 Mine #5

This mine uses a network of overhead ground wires to bond the Moveable Substations to remote ground beds and a large conveyor structure.

No fall-of-potential measurements were carried out at Mine #5 as part of this study. During a previous study when the mine was shut down, a number of impedance measurements were carried out. The following are the results of measurements taken at individual machines, connected to the grounding network:

Equipment	Ground Impedance - ohms
Excavator 1	3.46
Excavator 2	3.88
Drill 1	3.20
Drill 2	3.22
Drill 3	3.42
Excavator 3	3.30
Excavator 4	2.85
Drill 4	3.85
Excavator 5	2.20
Excavator 6	1.80
Excavator 7	2.20
Excavator 8	2.65
Drill 5	2.85

The following measurements were taken at Moveable Substations connected to the grounding system and machines.

Substation	Ground Impedance - ohms
#1	2.60
#2	1.57
#3	1.92
#4	1.85
#5	1.90

The following measurements were taken at remote ground beds. The ground beds were isolated from the rest of the grounding network during the measurements.

Ground Bed	Ground Impedance - ohms
#1	1.60
#2	3.05
#3	1.65

Each of the ground beds consists of a horizontal length of copper wire about 100 metres long, buried about 2 or 3 metres deep in an area with relatively low resistivity soil.

4.2.6 Mine #6

Fall-of-potential Traverse #11 was taken at the Main 138 kV Substation for the mine. Mine personnel had previously measured the Substation resistance and had established some reference electrodes. One of these was used as the C2 current return electrode. The potential reference was moved out towards the C2 electrode up another reference which had be established by the Mine at 60% of the distance towards the C2. This configuration of references was then used for the measurements.

The measured impedance is about 0.40 ohms. It is understood, and it was evident, that there is no effective bonding between the Substation and Mine pit equipment or buildings. A separate ground bed is provided for pit equipment grounding and the Concentrator and other plant is supplied by overhead line without any ground conductor to isolate these buildings from Substation primary faults. The ground resistance appears to be quite low for the size of ground grid. Soil resistivity Traverse #11, which was taken near the Substation, shows that the soil resistivity is relatively low in that area.

The P1 test lead was relocated to the separate equipment ground bed to measure the transfer of ground potential rise between the Substation and separate ground bed. It was found that about 30% of the potential rise appearing on the Substation ground grid would be transferred to the separate bed. This fairly high percentage is due to the proximity of the separate bed to the Substation. The exact configuration of the separate ground bed is unknown.

The resistance of the separate ground bed was also measured to be:

0.25 ohms at dc
0.35 ohms at 51 Hz
0.43 ohms at 70 Hz

The reason for the marked difference in impedance at different frequencies is probably due to the reactance of several 100 metres of overhead ground wires bonding the ground bed to other ground electrodes in the pits. This suggests that the remote ground bed, if isolated from the overhead ground wire bonds, may have quite a high ground resistance.

Fall-of-potential Traverse #12 was taken at a group of skid breakers in the active Pit area. Two drills and a shovel were connected to these breakers. The breakers were provided with local ground rods and bonded back to the separate ground bed by an overhead ground wire. The measured impedances were:

1.89 ohms at dc
2.42 ohms at 50 Hz
2.88 ohms at 69 Hz

Again, there is a marked frequency dependence in the impedances indicating that much of the grounding is provided through the overhead ground wire.

4.3 GROUND ELECTRODE MODELLING AND ANALYSIS

Computer models of several ground systems were used to obtain additional information about the mine grounds. The grounding analysis computer program KWIKGRID, developed by BSA was used to analyze the models. The computer program is described in Appendix IV which also contains input and results data files for the first model discussed.

4.3.1 Modelling of Ground Bed Measurements - Use of C2 100 and P2 62 metre References

This model was developed to simulate the field measurements of Fall-of-Potential Traverse #9. The input data file for a model representing the group of ground rods used for these beds, a C2 return electrode 100 metres away and P2 electrode 62 metres away is listed on page IV-5 in Appendix IV. The analysis was done using a two-layered soil model with:

Upper layer resistivity	151.36 ohm-metres
Upper layer height	2.67 metres
Deep layer resistivity	352.08 ohm-metres

This corresponds with the equivalent two layer soil model derived from soil resistivity Traverses #6 and #7 taken at the bottom of the Pit for this mine.

The following is a description of the input data file layout:

The lines up to the word 'END' are run description. These are followed (next four lines) by codes specifying that separate buried structures are involved, soil potentials are required and the calculation accuracy of the infinite series for the two-layer soil should be 0.001 p.u. The next line has the soil model '151.36352.082.67' in the format upper layer resistivity, deep layer resistivity, depth of upper layer. The next line '1000.0' is the fault current (1000 amps) injected into the main electrode of the model. The next line specifies 6 conductors in the main electrode. This is followed by 6 lines, each of which specifies the x, y and z coordinates of the origin and extremity, the radius, number of subdivisions and conductor number for each conductor. Dimensions, including the conductor radius, are in metres. x and y are in the east-west and north-south direction respectively while z is downward relative to the soil surface. The number of subdivisions is the number of smaller pieces the program subdivides each conductor into. Current flow from a conductor to the soil is not uniform and subdivision makes some allowance for this by splitting the conductor into smaller pieces, each of which can have a uniform current flow. As the soil is two layered and the rods penetrate both layers, one subdivision point will be on the boundary between the upper and deep layers. The line '888999' is a separator indicating specifications for separate structures follow. This is followed by an inactive flag and then the line '1 1' which indicates one separate structure with injected current and one without any connection, i.e. just picking up the potential of the surrounding soil. The next line '-1000.0' indicates that the separate structure with current injection receives a negative or return current. This is the C2 electrode whose x, y and z coordinates, radius and subdivision are specified on the next line. This is followed by the P2 electrode information. A series of surface soil potential calculations is specified after another separator '888888'. The specification is for 51 soil potentials to be calculated, starting at x = 0.0, y = 0.0, z = 0.0 and moving incrementally by y = -2.0 for each calculation. This effectively calculates the soil potential at all locations along the fall-of-potential traverse.

The results of the calculation are on pages IV-6 through IV-8. Page IV-6 repeats the input data, but after the subdivision process has been made. The original conductor #1 is now broken into #1, #13, #14 and #7 and similarly for the other conductors. Page IV-7 has the ground potential rise of 15425.54 volts for the ground bed with 1000 amps fault current, which translates into a resistance of 15.43 ohms. The buried structure No. 3 is the P2 electrode which has a potential rise of -573.70 volts. The difference between the P2 and the ground bed is 15999.24 volts. Divided by 1000 amps, this gives the apparent measured resistance of 15.999 ohms.

The calculation was repeated without the C2 and P2 electrodes, which have a small effect on the ground resistance of the ground bed. This is the more commonly used modelling technique which represents the fault current returning through the soil to a far-away remote source. The calculated resistance is then 15.975 ohms, about 0.15% different. Use of the 100 metre C2 and 62 metre P2 configuration for this type of ground bed results in a fairly accurate measurement result.

The measurement results for Mine #2 can be compared with the calculation of about 16 ohms. The disused ground beds measured 9.5 and 19 ohms. Ground beds currently in use, but with equipment disconnected, measured 21.2 and 27.4 ohms. This indicates the wide variations that can be experienced when theoretical calculations based on perfect layered soil models are assumed to apply in general.

4.3.2 Modelling of Ground Bed Measurements - Use of References that are Too Close to the Grid

The computer models are useful, however, in comparing alternative ground bed configurations and measurement methods. A Moveable Substation ground bed at Mine #4 was measured to have a resistance of 19.81 ohms using the 100 metre C2 and 62 metre P2 reference locations. The practice at this mine was to use a C2 reference 16 metres away and P2 8 metres. Using these references, which were still in place, an incorrect, lower resistance of 17.09 ohms was obtained. This is only 86.3% of the true value. Moving the P2 to three metres, only 10.89 ohms was obtained, which is 55% of the true value.

The computer model used above for Mine #2 was modified, relocating the C2 and P2 reference electrodes to 16 and 8 metres. The calculated resistance is then 89.3% of the true value. This compares with the 86.3% difference actually measured at Mine #4 using the closer spaced reference electrodes. The difference in results is probably due to the different soil structure at Mine #4, but, it is clear that using references as close as 16 and 8 metres introduces significant error into measurement of typical ground beds currently in use. Such close references should only be used for measuring electrodes a small as single rods.

Mine #3 regularly tests ground bed resistance using reference electrodes at 100 ft. and 62 ft. The ground bed used by this mine consists of 6 - 20 ft. deep rods in a rectangular configuration with 20 ft. spacing between the rods. Field measurements of an isolated ground bed using 100 metre and 62 metre references gave a resistance of 31 to 36 ohms for one of these beds. A computer model of such a bed using a uniform soil resistivity of 800 ohm-metres gives a calculated resistance of 32.7 ohms if the rods only are modeled. If interconnecting conductors buried 2 ft. deep are added to the model, the resistance is reduced to 28.6 ohms. Computer modelling of the measurement using references at 100 and 62 ft. results in a measurement that is 5.2% low.

4.3.3 Modelling of Ground Bed Measurements - Transfer Between Separate Ground Beds

The isolation between ground beds that are intended to be separate, can be modeled and analyzed with the computer program. Mine #2 uses two similar ground beds as shown in Figure 4.1 for the Moveable Substations. One bed is used to ground the transformer tank and the other is effectively maintained separate as a ground for the Mobile Equipment.

Two disused ground beds were available for measurement. The configuration of these beds was different in that they were rotated 90 degrees compared with Figure 4.1 and the clear space between them was about 37 metres rather than

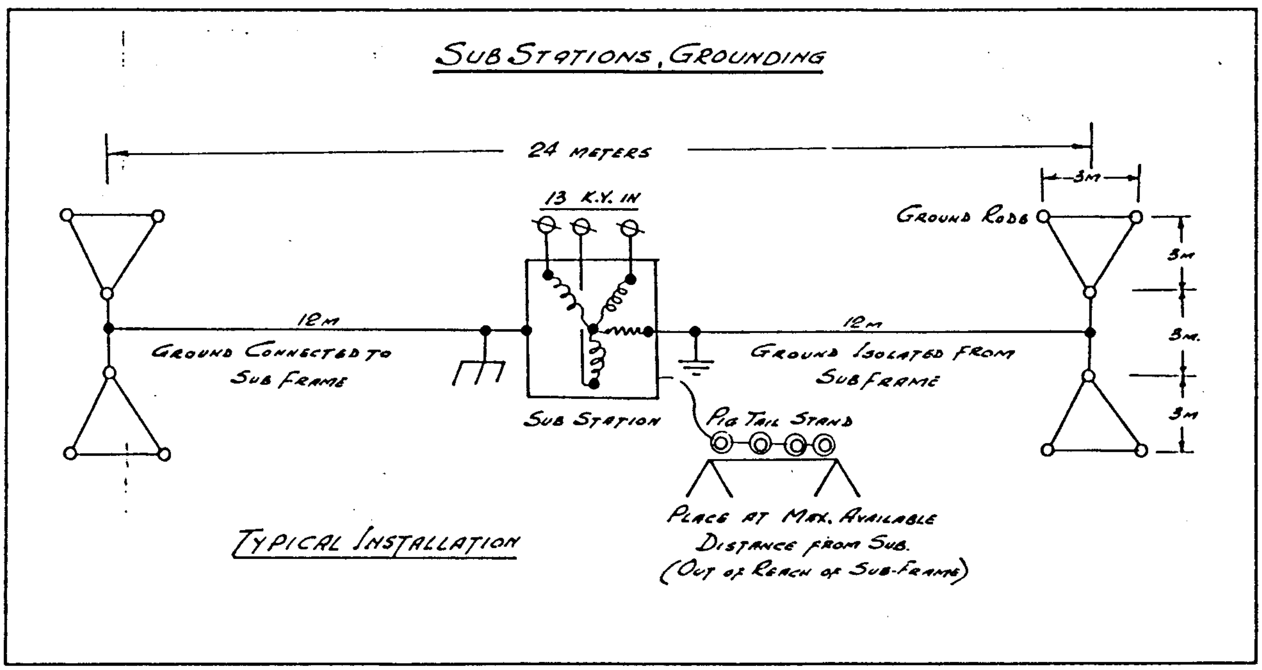

Figure 4.1 Isolated Ground Bed Arrangement Used at Mine #2

24 metres between the centres as indicated in Figure 4.1. The measured transfer of ground potential rise appearing on one bed, to the other, was 2.1%. The beds were computer modeled as found. The calculated transfer was 4.9% if a uniform soil model was used. The two ground beds were installed against the almost vertical side of the Pit which cannot be computer modeled. This is thought to be the reason for the smaller measured transfer, combined with increased error in this type of measurement.

It is clear, however, that the transfer is quite small when this order of separation is used. If the ground beds are modeled as shown in Figure 4.1 with a separation of 24 metres and the two-layered soil model measured for the bottom of the Pit is used, the calculated ground resistance is 15.5 ohms and transfer of potential rise is 14.2%.

Mine #2 uses a resistor grounded 13.2 kV Pit distribution system. A ground fault at a transformer grounded to such a ground bed would result in a ground fault current of 299 amps (limited by the ground resistance and the neutral resistor). This would produce 4629 volts GPR at the transformer ground and 657 volts on the Mobile Equipment. Of course, the amount transferred to the Mobile Equipment would be reduced by the grounding afforded by the contact between the Mobile Equipment and the soil. However, in the worst case, a mine worker could be attempting to connect two cable couplers on a trailing cable to a mobile machine at the time of the fault. The full 657 volts could then appear between the two couplers.

4.4 DESIGN OF MINE GROUND BEDS

4.4.1 Ground Bed Design Methodology

Once soil resistivity is known for a particular area, mine ground beds can be designed to achieve a required resistance. If the soil resistivity is approximately uniform, simple equations can be used to calculate the resistance of ground beds with fair accuracy. If the soil is layered, approximations can be used to derive an equivalent uniform soil from the layered model.

For example, if the upper layer is quite thick so that the whole ground bed is located in the upper layer only and the ground bed is quite small, the calculations could be done assuming the soil is uniform with a resistivity equal to the upper layer resistivity. As a second example, if the upper layer is quite thin, has a higher resistivity and most of the ground bed is located in the deep layer, as in the case of a group of deep rods, the upper layer could be ignored in the resistance calculation. As a third example, if the grid is located equally in both layers and there is not much difference in resistivity between the layers, the calculation could be done using the average resistivity of the two layers.

These approximations allow simplified equations to be used to obtain an

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} \quad \text{(Eq 38)}$$

where

R = station ground resistance in Ω
ρ = average earth resistivity in Ω-m
A = the area occupied by the ground grid in m^2

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L} \quad \text{(Eq 39)}$$

$$R_g = \rho\left[\frac{1}{L} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \quad \text{(Eq 40)}$$

Figure 4.2. Simple Equations for Ground Bed Resistance Calculation

indication of the extent of ground bed that may be required, but it must be accepted that the resulting ground bed resistance, proved by measurement, may differ from the desired value. A full understanding of the effects of layered soil structures on ground beds is required to apply approximations appropriately. However, a ground bed can be constructed on the basis of simple equations using approximate uniform soil models, measured and if deficient, can be adjusted by the addition of more buried metal.

Accurate calculation of ground bed resistance in layered soils cannot be done with simple equations and more complex procedures such as the grounding analysis computer program KWIKGRID already described must be used. While the simple equations rely on regular ground bed configurations, KWIKGRID and other similar computer programs allow irregular combinations of conductors to be modeled, located in uniform or layered soil.

Correct application of grounding analysis programs is complex and usually requires a specialist who understands how the input data should be formatted. Some of the programs also require mini or main frame computers and are relatively expensive to buy. Therefore, for ground bed design, as applicable to the typical 4 ohm mine ground bed, the simple equation techniques are to be preferred where possible.

The IEEE Guide for Safety in AC Substation Grounding [16] is an excellent reference for ground bed design. Chapter 12 contains a number of simple equations that can be effectively applied. Figure 4.2 contains three of the simplest equations from the IEEE Guide. Equation (38) calculates the resistance of a circular metal plate at zero depth, with area equal to that of the ground bed. Assuming the ground bed is a rectangular mat of conductors near the surface, the resistance will not be less than this. Equation (39) includes the total length of buried conductor L (metres) giving an upper limit to the resistance. This equation can be used for grid-rod combinations, but will give slightly conservative results as the rods are usually more effective than the grid conductors, on a per unit length basis. Equation (40) includes another parameter h (metres), the depth of the ground bed below the soil surface. This should be used for beds that are between 0.25 and 2.5 metres deep.

$$R_g = \frac{R_1 R_2 - R_{12}^2}{R_1 + R_2 - 2R_{12}} \qquad \text{(Eq 41)}$$

where

- R_1 = resistance of grid conductors
- R_2 = resistance of all ground rods (rodbed)
- R_{12} = mutual resistance between the group of grid conductors and group of ground rods

$$R_1 = (\rho_1/\pi l_1)(\ln(2l_1/h') + K_1(l_1/\sqrt{A}) - K_2) \qquad \text{(Eq 42)}$$

$$R_2 = (\rho_a/2n\pi l_2)[\ln(8l_2/d_2) - 1 + 2K_1(l_2/\sqrt{A})(\sqrt{n} - 1)^2] \qquad \text{(Eq 43)}$$

$$R_{12} = (\rho_a/\pi l_1)[\ln(2l_1/l_2) + K_1(l_1/\sqrt{A}) - K_2 + 1] \qquad \text{(Eq 44)}$$

where

- ρ_1 = soil resistivity encountered by grid conductors buried at depth h in Ω-m
- ρ_a = apparent soil resistivity as seen by a ground rod in Ω-m,
- H = thickness of the upper layer soil in m
- ρ_2 = soil resistivity from depth H downward in Ω-m
- l_1 = total length of grid conductors in m
- l_2 = average length of a ground rod in m
- h = depth of grid burial in m
- h' = $\sqrt{d_1 h}$ for conductors buried at depth h, or 0.5 d_1 for conductors at $h = 0$ (on earth's surface)
- A = area covered by a grid of dimensions $a \cdot b$ in m^2
- n = number of ground rods placed in area A
- K_1, K_2 = constants related to the geometry of the system
- d_1 = diameter of grid conductor in m
- d_2 = diameter of ground rods in m
- a = short-side grid length in m
- b = long-side length in m

$$\rho_a = l_2(\rho_1 \rho_2) / (\rho_2 H + \rho_1(l_2 - H)) \qquad \text{(Eq 45)}$$

$$\rho_a = l_2(\rho_1 \rho_2) / (\rho_2(H-h) + \rho_1(l_2 + h - H)) \qquad \text{(Eq 46)}$$

Figure 4.3 Schwarz's Equations for Grid/Rod Bed Resistance Calculations

These relatively simple equations can be hand calculated or stored in a programmable calculator for quick estimation of the resistance of a small ground bed. To be preferred, however, are the equations in Figure 4.3, which are from the same source [16]. These are known as Schwarz's Formula and enable the calculation of grid-rod combinations with good accuracy and some layered soil capability. The grid and rod layout must be regular. The rods must be evenly spaced throughout the ground bed area and the grid conductors must be evenly spaced in both directions. The layered soil model must fit the following limitations:

- The upper layer resistivity must be greater than or equal to the deep layer resistivity
- The grid must be in the upper layer
- The height of the upper layer must be at least 0.1 times the longest dimension of the ground bed.

As indicated, Equation (42) calculates the resistance of the grid (horizontal) conductors, (43) calculates the resistance of the rods and (44), the mutual

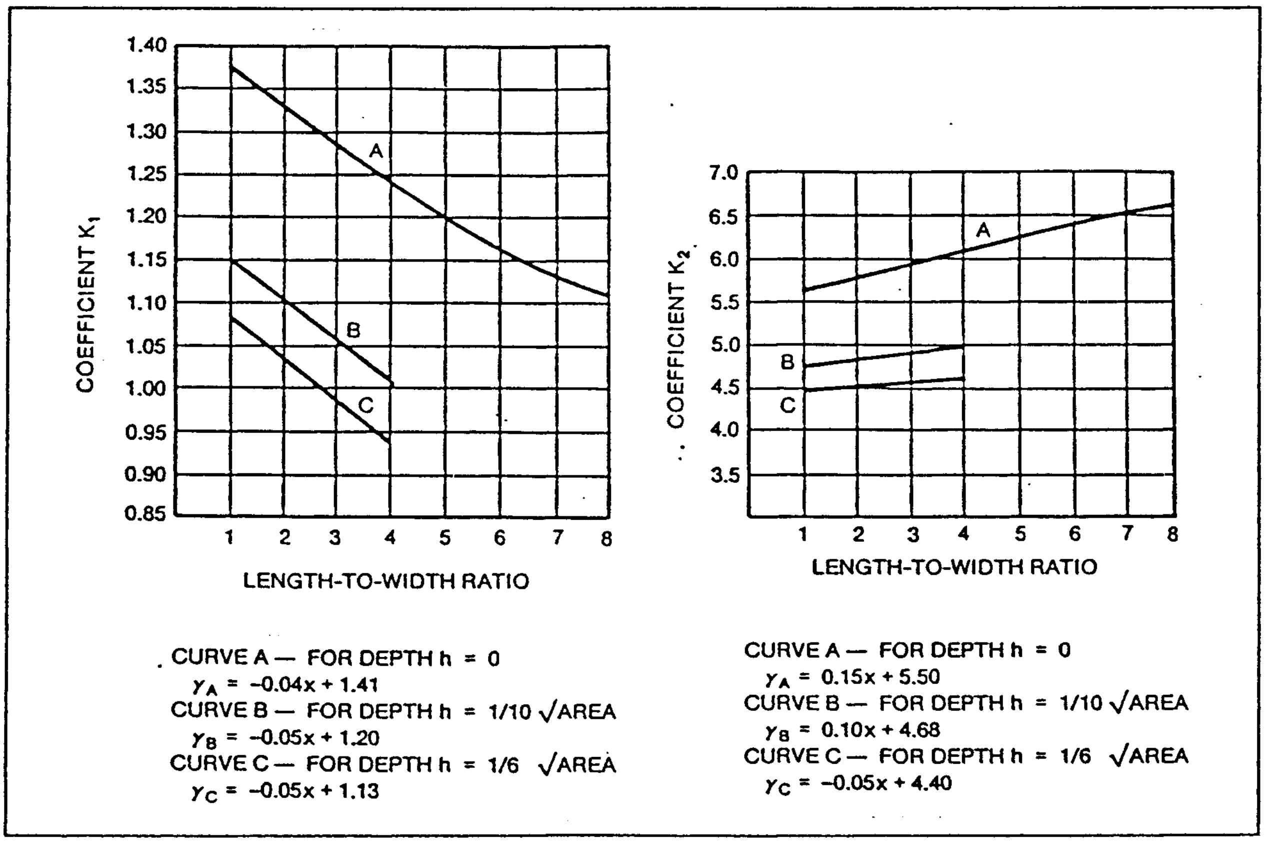

Figure 4.4 Graphs and Equations for Coefficients K_1 and K_2

doubled. The constant cost analysis can be repeated within this constraint and in some cases an optimum depth can be determined. This is shown in Figure 4.7 which plots the ground resistance for a constant cost, using different rod depths if the cost of installing rods is proportional to the square of the depth. The form of this curve is dependent on the grid area and total length of rods installed and no simple rule emerges other than for uniform (i.e. non-layered) soil, it is generally better to install a few long rods than many short ones.

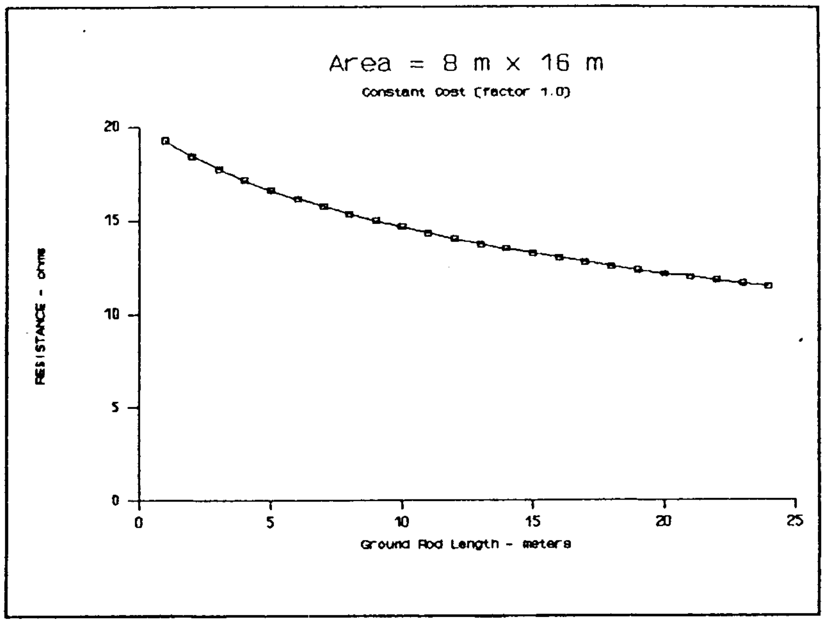

Figure 4.6 Constant Cost Installation - Effect of Rod Length on Resistance

The choice of ground bed configuration should also consider the available sites for the area. This is most applicable where an overhead ground wire can be used to bond to a ground bed somewhere outside the Pit where better soil conditions are found. Sometimes an area of low resistivity soil can be found where a horizontal conductor can be buried in a trench. Other simple equations can be found in the references in the IEEE Guide [16] to calculate the resistance of such a ground electrode.

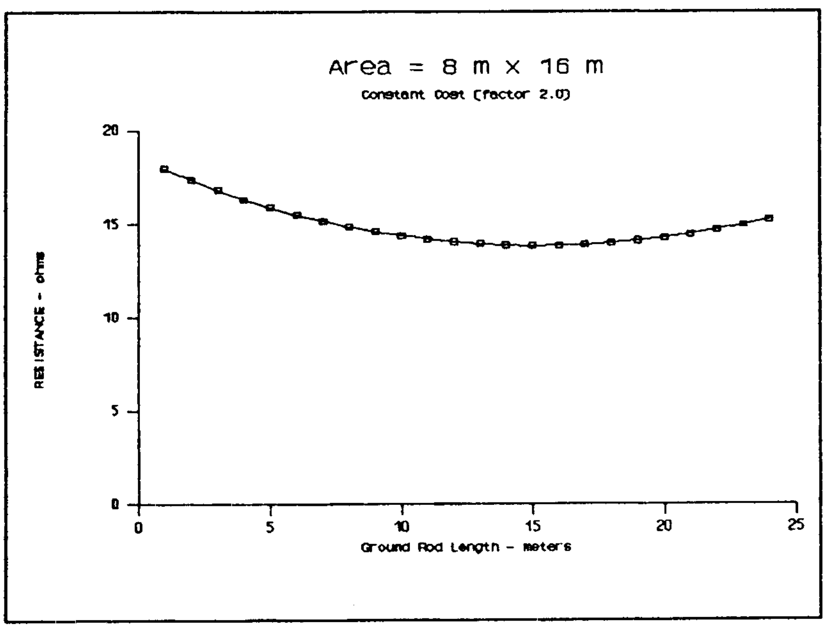

Figure 4.7 Cost Proportional to Square of Depth - Effect of Ground Rod Length on Resistance

4.4.2 A Mine Ground Bed Example

Mine #6 was in the process of developing a new Pit. The Pit is located several km from the reduction plant, Main Substation and existing pits. This presented an opportunity to install a grounding system that would fully satisfy the Electrical Code [1] requirements. Due to the distance involved and use of 4160 volt power at the existing Pit and plant, transmission to the new Pit was done at 25 kV with transformers at each end of the overhead line. The source transformer was provided with a 25 amp neutral grounding resistor. This required a 4 ohm ground bed at the new Pit to limit GPR to less than 100 volts.

Soil resistivity was measured at the site of the new Pit Substation on top of a small hill. The following equivalent soil model was interpreted from the measurements. As discussed under Section 4.1.4, a deeper review of the data showed that a different soil model fits the measurement data better, however, the resulting resistance calculation is not affected much.

Upper layer resistivity	235 ohm-metres
Height of upper layer	2.7 metres
Deep layer resistivity	500 ohm-metres

A number of different ground grid models were developed and analyzed using this soil model until the model shown in Figure 4.8 was shown to produce a ground resistance of 4.04 ohms. The final measured resistance of this ground bed was about 2.8 ohms. This lower value was expected for two reasons. First, the bed was installed by drilling holes approximately 100 mm in diameter, inserting conductors and back filling with Bentonite mud. Bentonite is a natural clay material that has a very low resistivity when wet. It is hygroscopic and swells to many times its dry volume when wet. The conductive ions do not wash out with time as

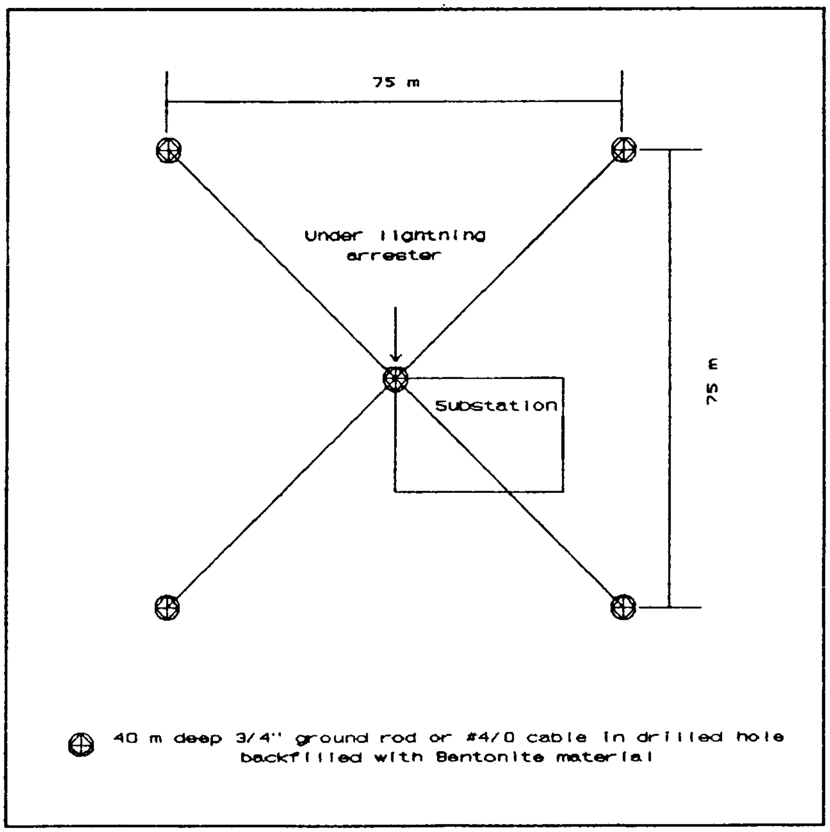

Figure 4.8 Ground Bed for Mine #2 New Pit Substation

does salt. It is therefore an excellent product for filling ground rod holes that are drilled into rock. Filling the drill hole with Bentonite results in a rod that is effectively 100 mm diameter rather than 19 mm. The calculated resistance of the whole bed is reduced to 3.46 ohms.

Second, the soil resistivity measurements suggested, but were unable to clearly resolve, a lower resistivity layer at greater depth. This was been born out during construction of the ground bed when water was encountered in the holes. The holes were only drilled 23 metres deep.

A similar temporary ground bed with 33 metre deep holes, at a lower elevation where a water table was encountered in three of the holes was measured by the mine to have a resistance of 1.4 ohms. It appears therefore, that there is a water table with a lower resistivity underlying the area.

4.4.3 Chemical Treatment

Chemical treatment can be used to reduce ground resistance to a certain extent. As mentioned in Section 4.4.2, a material such as Bentonite can improve rod to hole contact. For large ground beds, say 20 X 20 metres and bigger, further chemical treatment such as salting and watering has little effect once the ground bed makes good contact with the soil because the effective area of the ground bed must be increased to reduce the ground resistance.

For small ground beds of say one or two 3 metre long rods placed in a 3 metre wide hole and backfilled, the addition of salt or other ion rich chemical to the backfill, can reduce the ground resistance. For this reason, commercial products such as hollow rods which contain chemicals that are progressively leached into the soil, have limited efficacy.

4.5 MOVEABLE SUBSTATION CONFIGURATIONS

Moveable Substations are defined by the Electrical Code for Mines [1] as "substations consisting of an assembly of electrical equipment mounted on a self-supporting moveable structure". Each mine considered in this report, uses a different Moveable Substation configuration.

4.5.1 Mine #1

Distribution to the moveable substations is at 69 kV. Overhead open wiring is used for the primary connection. The Moveable Substation consists of two 3750 kVA transformers connected in parallel supplied by a fused disconnect. The disconnect switch handle is provided with a gradient control mat. The 6.9 kV secondary is taken to a separate skid breaker using a length of trailing cable. The secondary neutral grounding resistor, zero sequence relay and ground fault relay, is located in the skid breaker. A length of insulated cable is used to connect the transformer neutrals to the neutral ground resistor. Mining personnel stand on the native soil while operating the skid breaker switchgear and connecting or disconnecting secondary trailing cables.

4.5.2 Mine #2

Distribution to the moveable substations is at 13.2 kV. The Moveable Substation consists of a 3000 kVA transformer with primary fuses and metal-enclosed secondary switchgear mounted on a steel trailer. The transformer secondary bus is totally enclosed and makes direct connection between the transformer and secondary switchgear. The secondary ground fault relay and zero sequence C.T. are mounted in the switchgear enclosure. The 13.2 kV supply is taken overhead from a pole mounted disconnect to a terminal structure on the Moveable Substation. The secondary trailing cables are plugged into connectors mounted on a steel trestle that is placed sufficiently far from the trailer assembly that a person cannot touch both at the same time.

The trailing cable grounds which are bonded to the trestle, are taken to a separated isolated ground bus which is also the ground reference for the secondary neutral grounding resistor. A separate ground bed is provided for this ground bus. The ground system of the transformer and metal trailer assembly is therefore effectively isolated from the Mobile Equipment ground system. Mining personnel stand on the metal trailer while operating the secondary switchgear, but on the native soil while operating the 13.2 kV disconnect and connecting or disconnecting secondary trailing cables.

4.5.3 Mine #3

Distribution to the moveable substations is at 13.2 kV. The Moveable Substation consists of a transformer with metal-enclosed primary switchgear and metal-enclosed secondary switchgear all mounted on a steel trailer. The transformer primary and secondary bus is totally enclosed. Secondary switchgear is contained inside a small sheet metal building on the trailer. The secondary zero sequence C.T. and ground fault relay are contained in this building. Secondary ground faults trip the primary breaker. The 13.8 kV supply is taken from the overhead line by a length of trailing cable. Mining personnel stand on the metal trailer while operating the switchgear, but stand on the native soil while connecting or disconnecting secondary trailing cables.

4.5.4 Mine #4

Distribution to the moveable substations is at 13.8 kV. The Moveable Substation consists of one or two separate trailer-mounted transformers and a trailer-mounted secondary breaker unit containing the secondary zero sequence C.T. and ground fault relay. The 13.8 kV supply is taken overhead from a disconnect on the overhead line, to an open wire bus over the transformer. The transformer is connected to the overhead bus through drop-out fuses. The neutral grounding resistor is mounted on the transformer trailer. Mining personnel stand on the trailer while operating the secondary breaker, but stand on the native soil while operating the primary disconnect or connecting or disconnecting secondary trailing cables.

4.5.5 Mine #5

Distribution to the moveable substations is at 69 kV. The Moveable Substation consists of a trailer-mounted transformer, secondary neutral grounding resistor and secondary switchgear enclosure containing the secondary zero sequence C.T. and ground fault relay. The 69 kV supply is taken overhead from the overhead line to a fused disconnect on a steel structure on the trailer. Mining personnel stand on the trailer while operating the primary disconnect or secondary switchgear, but stand on the native soil while connecting or disconnecting secondary trailing cables.

4.5.6 Mine #6

The existing pits of Mine #6 do not use moveable substations. 4160 volt power is provided direct from the mine's Main Substation by overhead line to skid breaker units which contain the secondary switchgear, zero sequence C.T. and ground fault relay. Mining personnel stand on an extended frame of the skid breaker while operating the secondary switchgear and stand on the ground while connecting or disconnecting secondary trailing cables.

A moveable substation is used at the new pit. Primary distribution is at 25 kV. The Moveable Substation consists of a skid-mounted unit containing primary switch, transformer, secondary neutral grounding resistor and secondary switchgear enclosure containing the secondary zero sequence C.T. and ground fault relay. The 25 kV supply is taken from the overhead line through dropout fuses and a length of cable to the Moveable Substation. Mining personnel stand on the Substation while operating the primary or secondary switchgear. The Substation feeds a 4160 volt overhead pit distribution system. Skid breakers are used to tap off the 4160 volt distribution system to the mobile machinery trailing cables. Mining personnel stand on an extended frame of the skid breaker while operating the skid breaker switchgear and stand on the ground while connecting or disconnecting secondary trailing cables.

4.6 REVIEW OF MINE DISTRIBUTION SYSTEMS

Figures II.1 through II.8 in Appendix II show the different distribution configurations used at each mine.

The only common feature between all the mines is the way in which the Mobile Equipment trailing cable is protected. Invariably, the trailing cable used is type SHD-GC cable, a high voltage trailing cable that incorporates ground wires and pilot wire to monitor the integrity of the ground conductors. The monitoring systems used appears to be adequate. The final circuit to the Mobile Equipment is always protected by a current limiting resistor grounded neutral so that ground fault currents are less than 25 amps.

The configuration is such that, with the lengths of trailing cable typically used, ground faults at the Mobile Equipment cannot cause a ground potential rise in excess of 100 volts. This portion of the distribution system is therefore not considered further except in one context where there can be a short portion of the circuit at the Moveable Substation, that does not have adequate protection.

The ground fault potential rise situation that is possible at all mines is for a ground fault to occur at the Moveable Substation. At mines that use an overhead ground wire on the distribution system, there is the additional possibility of a ground fault at the Utility Primary causing a transferred potential rise at the Moveable Substation.

It must also be appreciated that when overhead ground wires are used in pit distribution systems, with the distances involved, typically several km, the series impedance of the ground wire is significant and cannot be reduce much by using larger or bundled conductors. This is an accepted fact in transmission line theory.

4.6.1 Mine #1 (Figure II.1)

Mine #1 takes a 67 kV supply direct from B.C. Hydro into the Pit. There are no overhead ground wires taken into the Pit to provide a partial return path for ground fault currents. All ground fault current must therefore return to the B.C. Hydro source through the soil.

There is a regulating transformer in the circuit that is intended to control the voltage drop in the feeder to the Mine which is several km long. This transformer is effectively an auto-transformer and as such, only inserts a small impedance in the line when the ratio is not 1:1. Its effect on reducing fault levels in the Pit is negligible.

At each Moveable Substation, a common ground bed is used for transformer and Mobile Equipment grounding. The ground bed resistance is relatively high due to the soil resistivity of 250 to 800 ohm-metres and the small size of the ground bed which consists of 2 or three ground rods. The measured resistance of a ground bed (R2 in parallel with the Mobile Equipment ground resistance in Figure II.1) is about 7.2 ohms with Mobile Equipment connected. Without the equipment the resistance is expected to be much higher.

This configuration presents an extremely hazardous situation for 67 kV ground faults at a Moveable Substation. The ground fault is indicated as 'A' in Figure II.1.

A fault calculation was done Assuming a 7.2 ohm ground resistance. The calculation was based on the following data:

B.C. Hydro 66 kV symmetrical component impedances of the source at Michelle Substation on 100 MVA 66 kV base:

Positive sequence impedance	0.025 + j0.1193 p.u.
Zero sequence impedance	0.0184 + j0.1235 p.u.

Average soil resistivity for line impedance calculations 271 ohm-metres

Line to fault location:

Height of each phase conductor	15.0 metres
Distance between phases	3.5 metres

Distance in feet	Conductor size
200	266.8 ACSR
7800	336.4 ACSR
10250	266.8 ACSR
4200	266.8 ACSR
2500	266.8 ACSR

Line positive and zero sequence impedances were calculated in two steps. First the self-impedance with ground return of the two conductor sizes and the mutual impedance with ground return, between two conductors spaced 3.5 metres, were calculated using Carson's equation. The relationships:

$$Z\ pos = Z_s - Z_m \quad \text{and} \quad Z\ zero = Z_s + 2\ Z_m$$

where:

Z_s = self impedance with ground return
Z_m = mutual impedance with ground return

were used to calculate the symmetrical component impedances for the overhead lines. The single-line-to-ground fault current with a 7.2 ohm ground resistance, ignoring the B.C. Hydro source ground resistance R1 in Figure II.1, can then be calculated to be:

Single-line-to-ground fault current	2306 amps
Ground potential rise	16604 volts

This is clearly a very high ground potential rise. It would be transferred to all equipment connected to that Substation and would be lethal for anyone in the vicinity of or getting on or off the Substation or Mobile Equipment. A person inside a shovel or drill would be at the same potential as the shovel and would be unaffected (in the same way as a bird can sit on a high voltage line).

As no overhead ground wire is used, ground faults at other locations on the distribution system or even a ground fault on the 230 kV side of the B.C. Hydro Michelle Substation, fault 'B' in Figure II.1, will not be transferred to the pit equipment.

4.6.2 Mine #2 (Figure II.2)

Mine #2 has two stages of voltage step-down from the B.C. Hydro source. The incoming 132 kV supply is first reduced to 13.2 kV at the Main Substation and then to 4160 volts for the Mobile Equipment. The 13.2 kV circuit has an 800 amp neutral grounding resistor. Separate ground beds (R2 and R3 in Figure II.2) are used for the transformer and Mobile Equipment. The ground bed resistance is about 15.5 ohms. No overhead ground wires are taken into the Pit area.

The mine uses an effective method to ensure that the two ground systems are kept separated. The trailing cables to the Mobile machines are coupled to sockets mounted on a separate trestle structure a few metres from the Substation. Short lengths of trailing cable are taken from there to the Substation where the internal cable ground conductors and transformer neutral resistor are bonded to a separate ground bus.

The ground potential rise at a typical Pit Moveable Substation has been discussed in Section 4.3.3. Although the resistor grounding and resistance of the Moveable Substation ground bed, limits the ground fault current to 299 amps, fault 'A' in Figure II.2, this can still result in 4629 volts GPR at the transformer ground of which 657 volts be transferred to the Mobile Equipment. The amount transferred to the Mobile Equipment would be reduced by the additional grounding afforded by the contact between the Mobile Equipment and the soil. However, in the worst case, a mine worker could be attempting to connect a trailing cable to a Mobile machine at the time of the fault. The full 657 volts could then appear between the two couplers.

There is also the possibility of a primary 13.2 kV to secondary 4160 volt fault within the Moveable Substation transformer. This can result in secondary insulation failure with the full 4600 volts GPR then appearing on the mobile equipment. In any event, the primary to secondary fault could cause a current of about 80 amps to flow through the secondary neutral grounding resistor to the mobile equipment ground, resulting in about 1270 volts GPR on the mobile equipment.

As there is no overhead ground wire, a ground fault at other locations in the distribution system is not transferred into the Pit. This includes a 132 kV ground fault such as 'B' in Figure II.2 which, assuming a 1 ohm ground resistance at the Main Substation, may produce a GPR of 1800 volts.

4.6.3 Mine #3 (Figure II.3)

As for Mine #2, Mine #3 has two stages of voltage step-down from the B.C. Hydro source. The incoming 138 kV supply is first reduced to 13.8 kV at the Main Substation and then 4160 volts for the Mobile Equipment. At the time a grounding study was carried out for the mine, the 13.8 kV circuit had a 400 amp neutral grounding resistor. With a new Main Substation configuration, it is understood that this is being reduced to a lower current.

A common ground system is used to ground the Mobile Equipment and Moveable Substations. Each Moveable Substation is provided with a local ground bed with resistance about 30 ohms as described in Section 4.3.2. Overhead ground wires are run along all 13.8 kV transmission lines. There are many ground electrodes along the transmission lines formed by other Moveable Substations, pole ground rods and conveyor systems and pumps that are bonded to the overhead line ground wire. The ground wire extends back to the Main Substation where the ground resistance (R1 in figure II.3) is very low due to interconnection between the Main Substation and the Concentrator buildings.

A ground fault at a Moveable Substation ('A' in Figure II.3) therefore has many return paths. Some of the current will return through the soil from the Moveable Substation ground bed. The rest will return via the overhead ground wire system. At each other ground electrode, some of the current will enter or leave the soil. In calculating the fault current return mechanism, the mutual coupling between the faulted phase conductor and the overhead ground wire has an additional beneficial effect. More current is forced to return in the overhead ground wire than if the mutual coupling were ignored.

The ground network therefore becomes quite complex. In the study carried out for the mine, a computer program was developed to model the distribution loop around the Pit, including the many ground locations, phase and ground wire impedances and mutual coupling effects. With the 400 amp neutral grounding resistor, the worst case ground potential rise at a Moveable Substation was found to be 472 volts at the side of the Pit most remote from the Main Substation power source. The ground fault current was then less than 400 amps, being reduced by the transmission system impedance.

As there is an overhead ground wire, a primary ground fault in the Main Substation causes a ground potential rise there that is transferred into the Pit by the overhead ground wire system. There is, however, appreciable attenuation of the ground potential rise as it propagates through the ground wire network.

As part of the study done for the mine, another network was developed and analyzed to investigate this aspect. With the B.C. Hydro system anticipated fault level in effect at the time, the ground potential rise at the Main Substation was calculated to be 451 volts. The highest GPR transferred to the Pit was 228 volts at the feed point of the Pit distribution loop. Further around the Pit, the transferred potential decreased to values that were sometimes less than 100 volts.

Some of these values exceed the 100 volt limit of the Electrical Code for Mines [1].

4.6.4 Mine #4 (Figure II.4 & 5)

As for Mines #2 and #3, Mine #4 also has two stages of voltage step-down from the B.C. Hydro source. The incoming 138 kV supply is first reduced to 13.8 kV at the Main Substation and then 4160 volts for the Mobile Equipment. The 13.8 kV circuit has a 25 amp neutral grounding resistor.

Figure II.4 shows the grounding arrangement used for 4160 volt Mobile Equipment Moveable Substations. Two separate ground beds (R3 and R4 in Figure II.4) are used to ground the Mobile Equipment and Moveable Substations. One bed is intended to be used for the transformer ground and the other for the Mobile Equipment ground. The beds which are formed of a few rods usually driven into the bottom of a hole, treated with salt and backfilled were measured to have a ground resistance of about 20 ohms.

As shown in the figure, the Moveable Substation transformer and skid breaker are separate assemblies that are linked by lengths of high voltage trailing cable. There is no ground fault detection on the neutral resistor and the secondary zero sequence relay C.T. is in the skid breaker. The 4160 volt neutral resistor is located on the transformer structure and the neutral is taken to the skid breaker by a length of insulated wire.

A few weeks before the field measurement trip, a minor shock incident was experienced at a shovel connected to this Substation. A welder was attempting to plug a welding machine into an outlet on the shovel when he received a shock between the plug and the shovel chassis. It is evident that the shovel had a ground potential rise while the welding machine was at the potential of the soil on which it was placed. The open circuit voltage was measured at around 98 volts. Only a small current of a few milliamps could be drawn, indicating a high resistance circuit, probably due to the poor resistance of the welding machine to ground. A ground potential rise of about 325 volts was also measured on the transformer ground. The fault causing the ground potential rise on the Mobile Equipment did not trip the secondary ground fault protection.

The fault was traced to a damaged secondary conductor on the transformer. This is indicated as fault 'A' in Figure II.4. A flying piece of rock from a previous blast had crushed the conductor onto the transformer tank resulting in a line-to-ground fault. It is understood that at the time, the ground beds were separated. The ground fault current, which was limited to 10 amps by the neutral grounding resistor, had to pass through the transformer ground bed resistance R4 to the soil and then back through the Mobile Equipment ground bed resistance R3 to return to the neutral. The voltage developed across the Mobile Equipment ground bed resistance results in the shock potential experienced at the shovel.

Assuming approximately 10 amps flowed 10 X 20 = 200 volts should have developed on the shovel. There are two possible reasons for only 98 volts being measured. First, the combined resistance of the Mobile Equipment and the ground bed was lower than 20 ohms at the time of the shock due to different equipment locations. Second, the welding machine was located quite close to the shovel where, due to the ground contact of the shovel, the soil potential was not zero. The measured voltage is the difference between the shovel chassis and the soil voltage where the welding machine made ground contact.

This shock incident illustrates one of the problems of using separate ground systems in an attempt to isolate the Mobile Equipment from ground potential rise due to ground faults on the primary of the Moveable Substation. The use of separate grounds does, however, reduce the transfer of ground potential rise due to Moveable Substation primary faults (Fault 'B' in Figure II.4)

This problem could also occur at Mine #2, but it is far less likely because the length of secondary wiring that is unprotected by the zero sequence relay is only a short length of enclosed bus.

A 13.8 kV ground fault ('B' in Figure II.4) is limited by a 25 amp neutral grounding resistor at the Main Substation. This results in a ground potential rise at the Moveable Substation transformer ground. Depending on the spacing between the transformer and Mobile Equipment ground beds, a fraction of this ground potential rise will be transferred to the Mobile Equipment. As a 25 amp resistor is used vs 10 amp for the 4160 volt Moveable Substation secondary, the ground potential rise at the transformer will be greater and could reach 825 volts if the ground bed resistance is 33 ohms.

If the two ground beds are coupled, ground potential rise problems as occurred for the shock incident, are avoided. The ground resistance and ground fault potential rise for Moveable Substation primary faults is reduced by having the two ground beds operate in parallel. Due to the proximity of the two beds, the combined resistance is not just a simple parallel combination, but a somewhat higher value probably in the order of 15 ohms. Up to 375 volts ground potential rise could then occur.

Figure II.5 shows the grounding arrangement for a 15 kV Dragline used at this mine, which is fed directly from the 13.8 kV supply. An overhead ground wire is installed from a separate ground bed, R2 in Figure II.5, at the Main Substation. It should be noted that a change-over switch is installed at the Main Substation to select one or other 25 amp resistor, depending on which 138/13.8 kV transformer is being used. It is therefore not possible to unintentionally switch both resistors in parallel. The separate ground bed is provided to reduce the transfer of 138 kV primary ground fault potential rise to the feeder and dragline.

As there is a metallic return path to the source neutral, ground faults at the dragline such as 'A', will have a well controlled ground potential rise. The measured ground impedance of 6.6 ohms at the dragline, includes the overhead ground wire and the remote ground bed at the Main Substation. It is unclear why this impedance is as high as it is, however, it is still low enough that ground potential rise will be held to less than 100 volts at the dragline.

A ground fault on the B.C. Hydro 138 kV primary as indicated by 'B' in Figure II.5, would cause a ground potential rise of about 6321 volts. It is not known what percentage of this GPR would be transferred to the dragline. It appeared that the remote ground bed is close enough to the Main Substation ground grid that 30% could be transferred. A potential rise of 1900 volts could appear on at the dragline.

4.6.5 Mine #5 (Figure II.6)

Mine #5 also has two stages of voltage step-down from the B.C. Hydro source. The incoming 230 kV supply is first reduced to 67 kV at the Main Substation and then 7.2 kV for the Mobile Equipment. The 67 kV circuit has a 25 amp neutral grounding resistor. There is a distance of several km between the Main Substation and the Pit areas. No overhead ground wire is installed along the 67 kV lines between the Main Substation and Pit areas, so there is no transfer of primary ground fault ('B' in Figure II.6) potential rise through a ground wire to the Pit Equipment. Conversely, there is no ground fault return path for 67 kV faults at the Pit Moveable Substations other than through the soil.

Figure I.6 shows the grounding arrangement used for 7.2 kV Mobile Equipment moveable substations. The principle used at this mine is to establish a permanent remote ground bed near the Pit, R3 in Figure II.6, and run an overhead ground wire along the 67 kV transmission lines to each Moveable Substation. Another temporary higher resistance ground bed, R2 is created at each Moveable Substation. With mine growth, several such remote ground beds have been created and interconnected, including a bond to a massive metal conveyor structure, resulting in an even lower ground impedance. Some remote ground bed resistances are given in Section 4.2.6. Typically, with the #3/0 ACSR overhead ground wire used, the bed ground resistance must be somewhat less than 4 ohms to ensure that ground fault potential rise is held to less than 100 volts. The Moveable Substation ground beds have a ground resistance of typically 20 ohms.

Fault current due to a fault 'A' is limited to 25 amps at the source. As the return path has a resistance of less than 4 ohms, the ground potential rise at the Moveable Substation and Mobile Equipment is limited to less than 100 volts.

4.6.6 Mine #6 (Figure II.7 & 8)

The older part of Mine #6 has one stage of voltage step-down from the B.C. Hydro source. As shown in Figure II.7, the incoming 138 kV supply is reduced to 4160 volts at the Main Substation for the Mobile Equipment. A new Pit presently being developed is too far away to be supplied at 4160 volts. The step up - step down arrangement shown in Figure II.8 has therefore been used to transmit power to the new Pit at 25 kV.

Considering the older part first (Figure II.7), only one 138 kV transformer is used at a time so that ground fault current is limited to 25 amps by one neutral grounding resistor. A fault 'A' has a metallic return path to the source. As the distances between the Main Substation and Pit are not too great, it is unlikely that such a fault will cause ground potential rise in excess of 100 volts.
Current from fault 'B' has to pass through the Main Substation ground resistance, R1 and the Mobile Equipment ground system impedance to return to the neutral. The Mobile Equipment ground impedance consists of a remote ground bed resistance, R2 and various other grounds along the Pit distribution system R3. The combination of these was measured to be about 0.4 ohms so that only about 10 volts ground potential rise should occur. This type of fault will therefore also be within the Mining Code requirements.

A ground fault on the B.C. Hydro 138 kV primary as indicated by 'C' in Figure II.7, would cause a ground potential rise of about 2070 volts. Field measurements showed that about 30.7% of this potential rise or 635 volts, will appear on the remote ground bed due to its proximity to the Main Substation.

For the new Pit, Figure II.8, the resistance of the ground bed at the Pit is less than 4 ohms. As the 25 kV system ground current is limited to 25 amps, the ground potential rise due to a fault 'A' is limited to 100 volts. For a fault 'B' at the Main Substation, there is no ground wire between the Main Substation and the new Pit and the distance between it and the new Pit ground electrode is so great that negligible potential rise will be transferred.

4.7 SAFETY CONSIDERATIONS

The Canadian Electrical Code Part I [12] requires that step and touch voltages be held to within certain limits dependent on the effective surface layer soil resistivity and fault duration. These limits are summarized in Table 52 of the Code [12]. Table 52 lists some useful spot step and touch voltages for typical soil types and fault clearing times of 0.5 and 1.0 seconds.

Table 52 of the Code is based on equations from the IEEE Guide for Safety in AC Substation Grounding [16]. The IEEE equations allow tolerable step and touch voltage to be calculated for different effective surface layer soil resistivities and fault durations up to 3 seconds. These equations assume good contact between the feet and soil. Dry shoes or boots will reduce the severity of the shock. References [13,14,15] contain some of the basis for determining the tolerable step and touch limits for persons. The limits used by the IEEE [16] are believed to be limits that can be withstood by 95% of males with body weight 50 kg. 5% of males could therefore not withstand these step and touch potential limits. Females and children are found to have even lower tolerance, but are not covered by the IEEE [16] or Code [12]. Appendix VI contains the equations used by the IEEE Guide in determining tolerable step and touch potentials and figures describing the step and touch potential situations.

Reference [11] is the most comprehensive and up to date document that covers the whole question of Electrical Shock Safety. It is evident on reviewing Reference [11] that current passing through the body and the path is takes, are the principle factors in electrical shock incidents. Quite small currents that pass through the chest and heart area, e.g. hand to foot, can be fatal while heavy current can be experienced through other parts of the body, e.g. hand to elbow on same arm, with minimal injury. The seriousness of the shock appears to be related to the I^2t energy of the current passing through the body so that much higher currents are tolerable if the duration is short. Also, the mechanism of heart failure is related to the instant during the heart's cycle than the shock occurs. The impressed shock apparently has an effect on the natural electrical signals of the heart and can cause fibrillation of the heart muscle resulting in blood circulation failure and death if the fibrillation is not corrected. A particular shock level at one point in the heart cycle may have no effect while at another, fibrillation will result.

The touch limitation in the Code [12] for 'Wet organic soil' and a 1.0 second fault clearing time, is 118 volts. This is about the same order as the 100 volt maximum ground potential rise limit of the Mining Code [1].

Assuming that:

(a) fault clearing may be as slow as 1.0 second for say a relatively low zero sequence current of 10 or 25 amps

(b) although soil resistivity at mines in British Columbia generally appears to be higher than that of wet organic soil, the person may be standing in wet boots in a muddy patch.

the 100 volt limit is probably reasonable on a worst case basis.

APPENDIX I
FIELD MEASUREMENT RESULTS

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 1

MEASURED ON: 17-October-88

CONDITIONS: Sunny. Temperature 4 degree C.

DESCRIPTION: Near 15 kV breaker for dragline at Mine #4 in N-S direction.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

	--PROBE SPACING--		PROBE	METER	RANGE	IND.	RESISTIV	---REMARKS---
	a	b	DEPTH	READING		RES.	MEAS	
#	metres	metres	metres	ohms		ohms	ohm-m	
1	1	1	.1	138.20	Low	138.20	873.36	DET-2
2	2	2	.1	70.20	Low	70.20	883.44	DET-2
3	2	2	.1	704.00	.1	70.40	885.96	ET3
4	4	4	.1	367.00	.1	36.70	922.71	ET3
5	4	4	.1	36.40	Low	36.40	915.17	DET-2
6	6	6	.1	25.50	Low	25.50	961.48	DET-2
7	8	8	.1	17.60	Low	17.60	884.75	DET-2
8	12	12	.1	9.83	Low	9.83	741.19	DET-2
9	16	16	.1	6.18	Low	6.18	621.30	DET-2
10	20	20	.1	4.65	Low	4.65	584.34	DET-2
11	24	24	.1	3.63	Low	3.63	547.40	DET-2
12	30	30	.1	2.59	Low	2.59	488.21	DET-2
13	36	36	.1	2.16	Low	2.16	488.58	DET-2

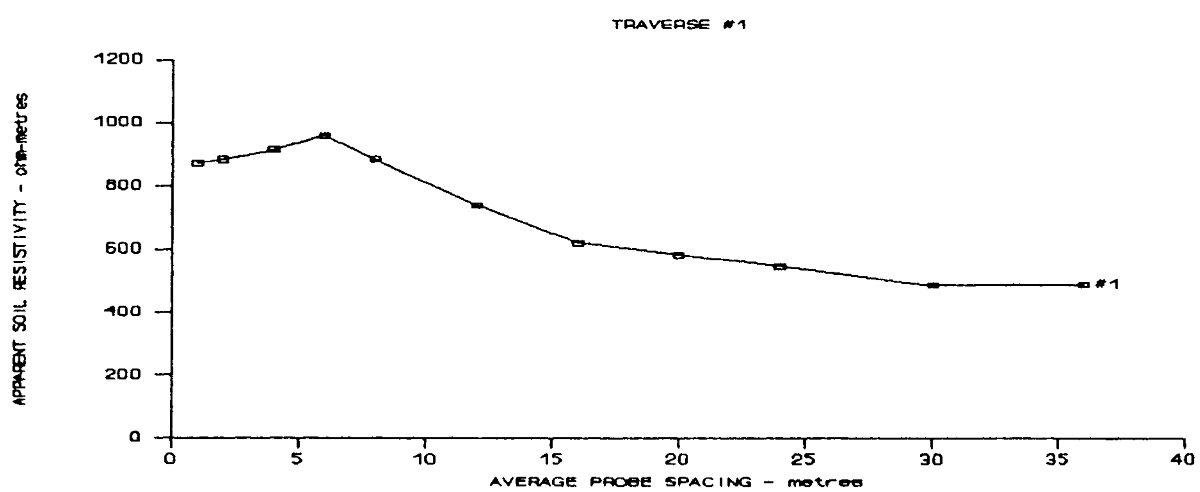

Figure I.1 Plot of Soil Resistivity Traverse #1 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 2

MEASURED ON: 17-October-88

CONDITIONS: Sunny. Temperature 4 degree C.

DESCRIPTION: Near 15 kV breaker for dragline at Mine #4 in E-W direction.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

	--PROBE SPACING--		PROBE	METER	RANGE	IND. RESISTIV		---REMARKS---
	a	b	DEPTH	READING		RES.	MEAS	
#	metres	metres	metres	ohms		ohms	ohm-m	
1	1	1	.1	125.70	Low	125.70	794.37	DET-2
2	2	2	.1	66.40	Low	66.40	835.62	DET-2
3	4	4	.1	34.90	Low	34.90	877.45	DET-2
4	6	6	.1	22.70	Low	22.70	855.91	DET-2
5	8	8	.1	17.66	Low	17.66	887.77	DET-2
6	12	12	.1	11.24	Normal	11.24	847.51	DET-2
7	16	16	.1	6.70	Normal	6.70	673.57	DET-2
8	20	20	.1	4.56	Normal	4.56	573.03	DET-2
9	24	24	.1	3.34	Low	3.34	503.67	DET-2
10	30	30	.1	2.66	Low	2.66	501.40	DET-2

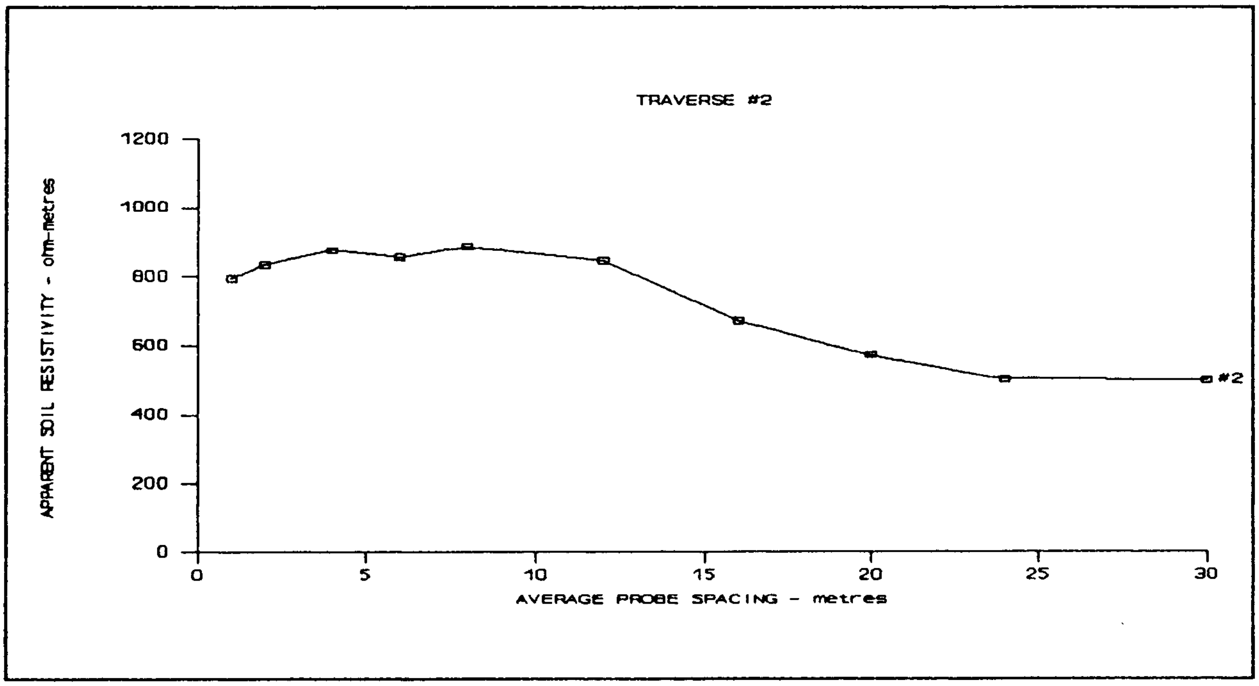

Figure I.2 Plot of Soil Resistivity Traverse #2 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

Average of Traverse #1 & #2 Measurement Results

Spacing	Trav 1	Trav 2	Ave 1&2
1	873.36	794.37	833.87
2	883.44	835.62	859.53
4	915.17	877.45	896.31
6	961.48	855.91	908.70
8	884.75	887.77	886.26
12	741.19	847.51	794.35
16	621.30	673.57	647.44
20	584.34	573.03	578.69
24	547.40	503.67	525.54
30	488.21	501.40	494.81
36	488.58		

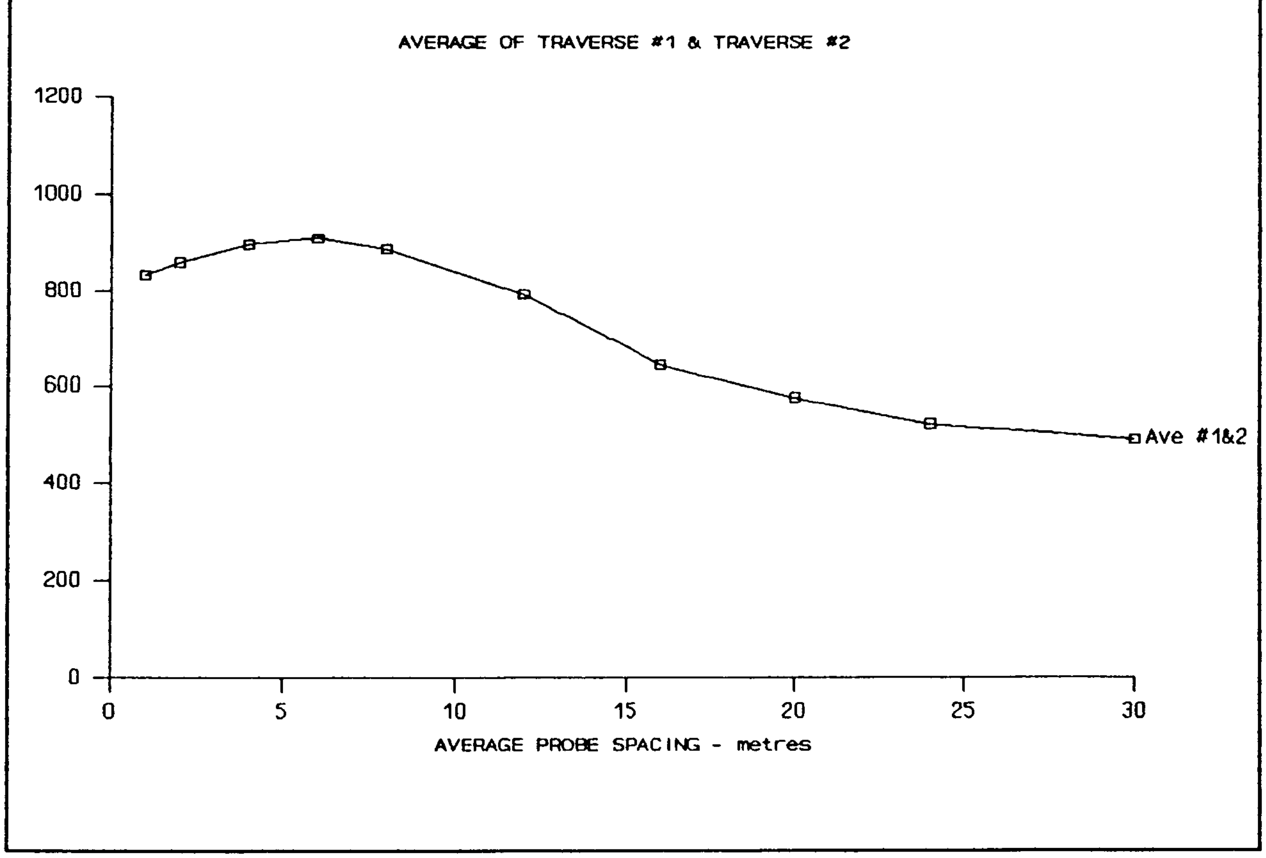

Figure I.3 Plot of Average of Soil Resistivity Measurement Traverses #1 and #2

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 3

MEASURED ON: 18-October-88

CONDITIONS: Cloudy. Temperature 4 degree C.

DESCRIPTION: Near Moveable Substation at Mine #1 in E-W direction.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	--PROBE SPACING-- a metres	b metres	PROBE DEPTH metres	METER READING ohms	RANGE	IND. RES. ohms	RESISTIV MEAS ohm-m	---REMARKS---
1	1	1	.1	46.30	Normal	46.30	292.60	DET-2
2	2	2	.1	21.30	Normal	21.30	268.05	DET-2
3	2	2	.1	216.00	.1	21.60	271.83	ET3
4	4	4	.1	734.00	.01	7.34	184.54	ET3
5	4	4	.1	7.96	Low	7.96	200.13	DET-2
6	6	6	.1	6.24	Low	6.24	235.28	DET-2
7	8	8	.1	5.60	Low	5.60	281.51	DET-2
8	12	12	.1	4.47	Low	4.47	337.04	DET-2
9	16	16	.1	3.48	Low	3.48	349.86	DET-2
10	20	20	.1	3.63	Low	3.63	456.17	DET-2
11	24	24	.1	2.36	Normal	2.36	355.88	DET-2
12	30	30	.1	2.21	Low	2.21	416.58	DET-2
13	36	36	.1	1.68	Low	1.68	379.56	DET-2

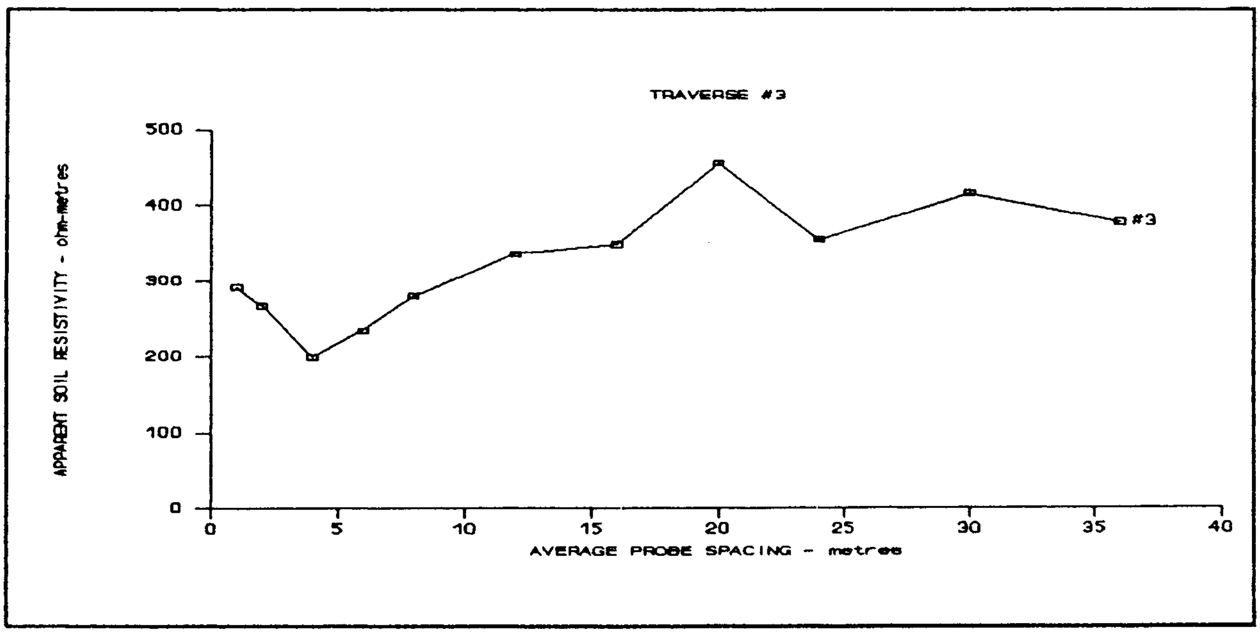

Figure I.4 Plot of Soil Resistivity Traverse #3 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

Average of Traverse #3 & #4 Measurement Results

Spacing	Trav 3	Trav 4	Ave 3&4
1	292.60	298.28	295.44
2	268.05	336.01	302.03
4	200.13	291.39	245.76
6	235.28	308.05	271.67
8	281.51	343.85	312.68
12	337.04	248.07	292.56
16	349.86	327.74	338.80
20	456.17	420.98	438.58
24	355.88	435.81	395.85
30	416.58	469.36	442.97
36	379.56		

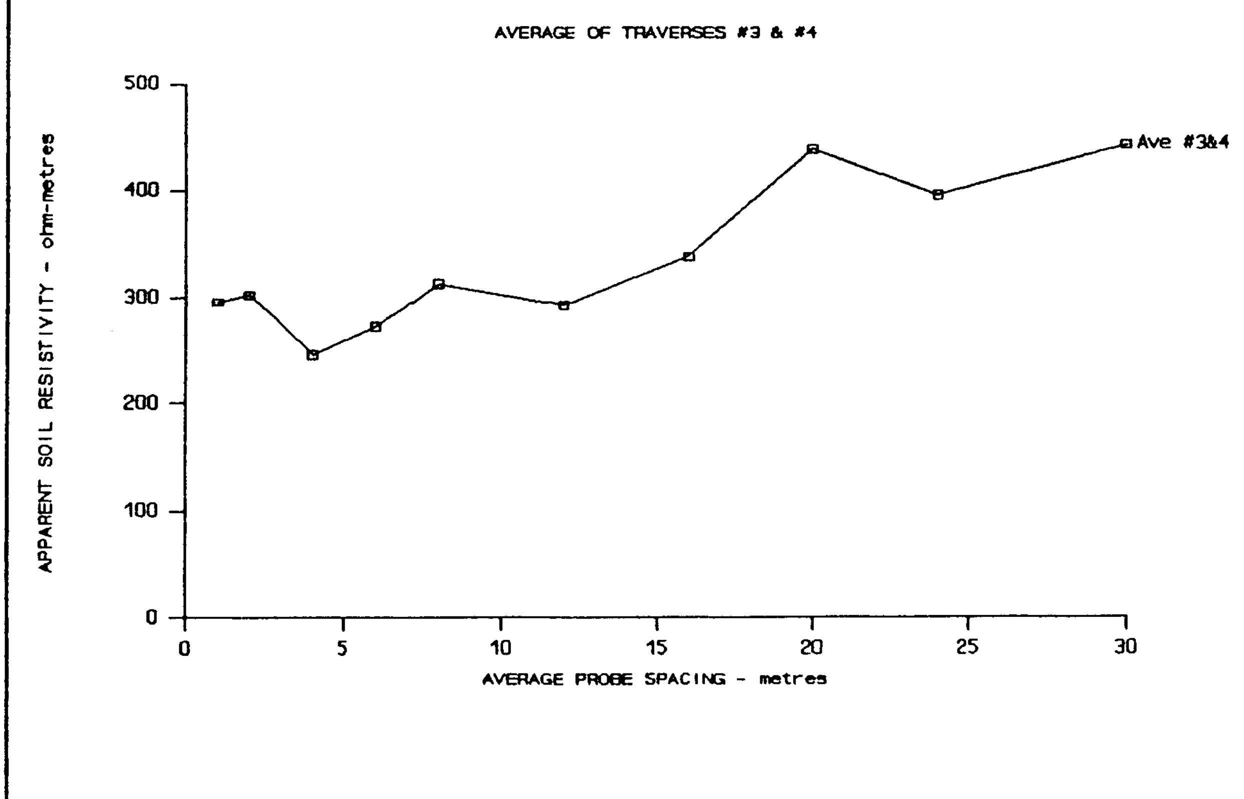

Figure I.6 Plot of Average of Soil Resistivity Measurement Traverses #3 & #4

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 5

MEASURED ON: 18-October-88

CONDITIONS: Cloudy. Temperature 4 degree C.

DESCRIPTION: Near Moveable Substation Mine #1 in SW-NE direction. Soil is loose dump rock.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	--PROBE SPACING-- a metres	b metres	PROBE DEPTH metres	METER READING ohms	RANGE	IND. RES. ohms	RESISTIV MEAS ohm-m	---REMARKS---
1	1	1	.1	128.00	Low	128.00	808.90	DET-2
2	2	2	.1	60.30	Low	60.30	758.86	DET-2
3	4	4	.1	24.30	Normal	24.30	610.95	DET-2
4	6	6	.1	17.00	Low	17.00	640.99	DET-2
5	8	8	.1	15.00	Low	15.00	754.05	DET-2
6	12	12	.1	10.12	Low	10.12	763.06	DET-2
7	16	16	.1	7.60	Low	7.60	764.05	DET-2
8	20	20	.1	5.20	Normal	5.20	653.46	DET-2
9	24	24	.1	3.81	Low	3.81	574.54	DET-2
10	30	30	.1	2.81	Low	2.81	529.68	DET-2
11	36	36	.1	2.18	Normal	2.18	493.11	DET-2

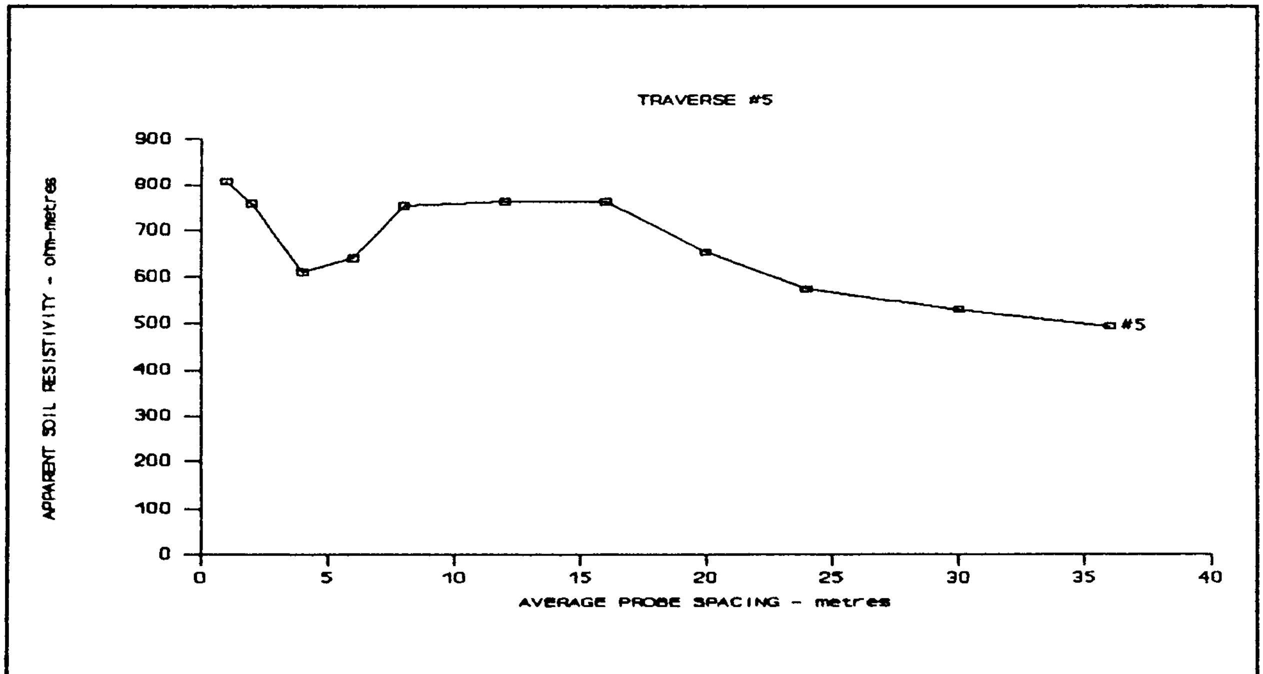

Figure I.7 Plot of Soil Resistivity Traverse #5 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 6

MEASURED ON: 17-November-88

CONDITIONS: Sunny and cold. About 5 degree C.

DESCRIPTION: At the bottom of the pit at Mine #2.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	--PROBE SPACING-- a metres	b metres	PROBE DEPTH metres	METER READING ohms	RANGE	IND. RES. ohms	RESISTIV MEAS ohm-m	---REMARKS---
1	1	1	.1	24.300	Normal	24.300	153.57	DET-2
2	2	2	.1	11.580	Normal	11.580	145.73	DET-2
3	4	4	.1	7.620	Normal	7.620	191.58	DET-2
4	6	6	.1	7.700	Normal	7.700	290.33	DET-2
5	6	6	.1	783.000	.01	7.830	295.23	ET3
6	8	8	.1	357.000	.01	3.570	179.46	ET3
7	8	8	.1	6.260	Normal	6.260	314.69	DET-2
8	12	12	.1	4.050	Normal	4.050	305.38	DET-2
9	16	16	.1	3.200	Normal	3.200	321.71	DET-2
10	20	20	.1	2.860	Normal	2.860	359.40	DET-2
11	24	24	.1	2.060	Normal	2.060	310.64	DET-2
12	30	30	.1	1.500	Normal	1.500	282.75	DET-2
13	36	36	.1	1.383	Normal	1.383	312.83	DET-2
14	42	42	.1	1.139	Normal	1.139	300.58	DET-2

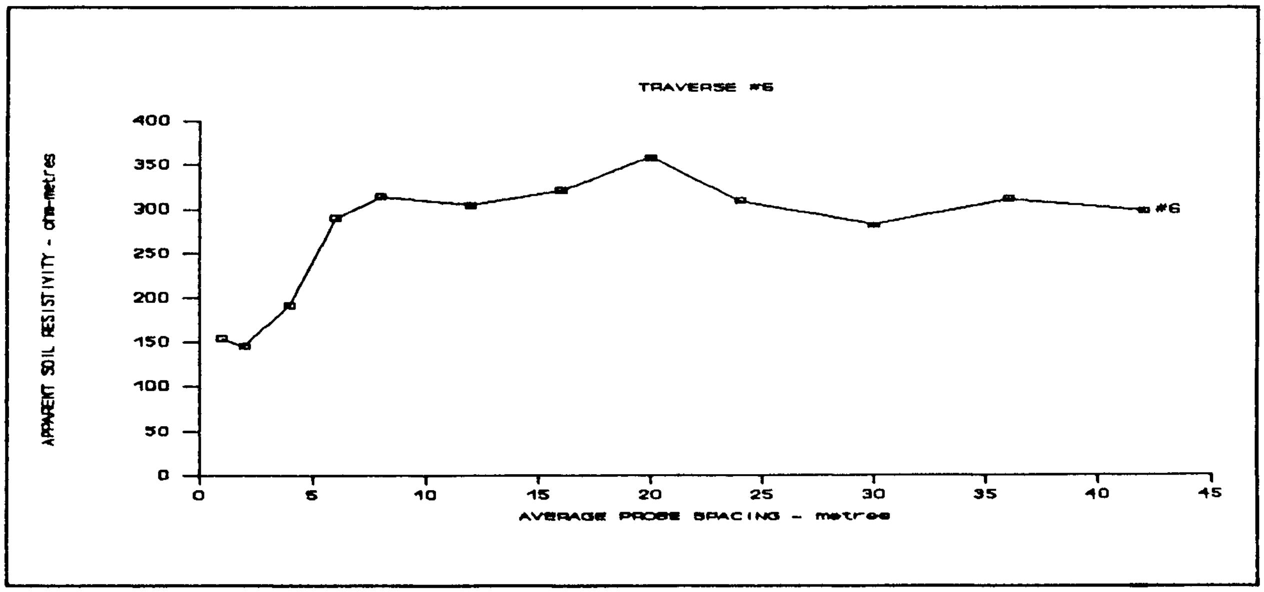

Figure I.8 Plot of soil Resistivity Traverse #6 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 7

MEASURED ON: 17-November-88

CONDITIONS: Sunny and cold. About 5 degree C.

DESCRIPTION: At the bottom of the pit. Orthogonal to Traverse 6.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	--PROBE SPACING-- a metres	b metres	PROBE DEPTH metres	METER READING ohms	RANGE	IND. RES. ohms	RESISTIV MEAS ohm-m	---REMARKS---
1	1	1	.1	27.400	Normal	27.400	173.16	DET-2
2	2	2	.1	12.950	Normal	12.950	162.97	DET-2
3	4	4	.1	7.010	Normal	7.010	176.24	DET-2
4	6	6	.1	5.520	Normal	5.520	208.13	DET-2
5	8	8	.1	4.490	Normal	4.490	225.71	DET-2
6	12	12	.1	3.980	Normal	3.980	300.10	DET-2
7	16	16	.1	3.330	Normal	3.330	334.78	DET-2
8	20	20	.1	2.730	Normal	2.730	343.07	DET-2
9	24	24	.1	2.210	Normal	2.210	333.26	DET-2
10	30	30	.1	1.701	Normal	1.701	320.63	DET-2

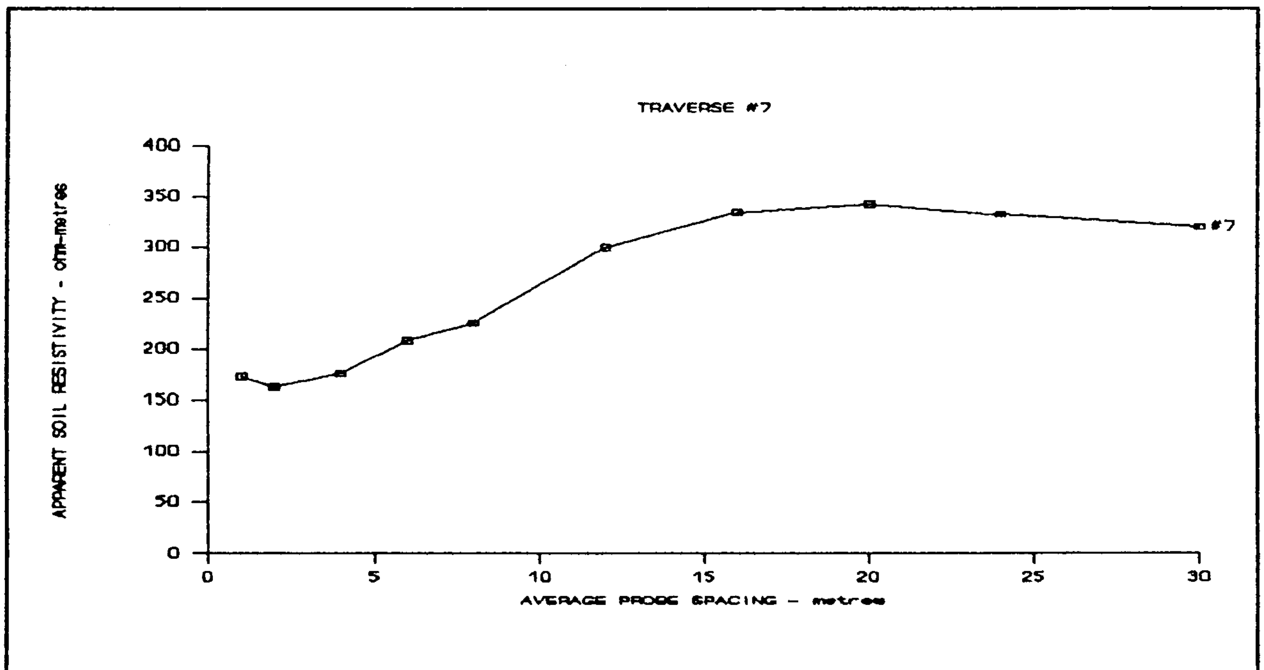

Figure I.9 Plot of Soil Resistivity Traverse #7 Measurement Results

Average of Traverse #6 & #7 Measurement Results

Spacing	Trav 6	Trav 7	Ave 6&7
1	153.57	173.16	163.37
2	145.73	162.97	154.35
4	191.58	176.24	183.91
6	290.33	208.13	249.23
8	314.69	225.71	270.20
12	305.38	300.10	302.74
16	321.71	334.78	328.25
20	359.40	343.07	351.24
24	310.64	333.26	321.95
30	282.75	320.63	301.69
36	312.83		
42	300.58		

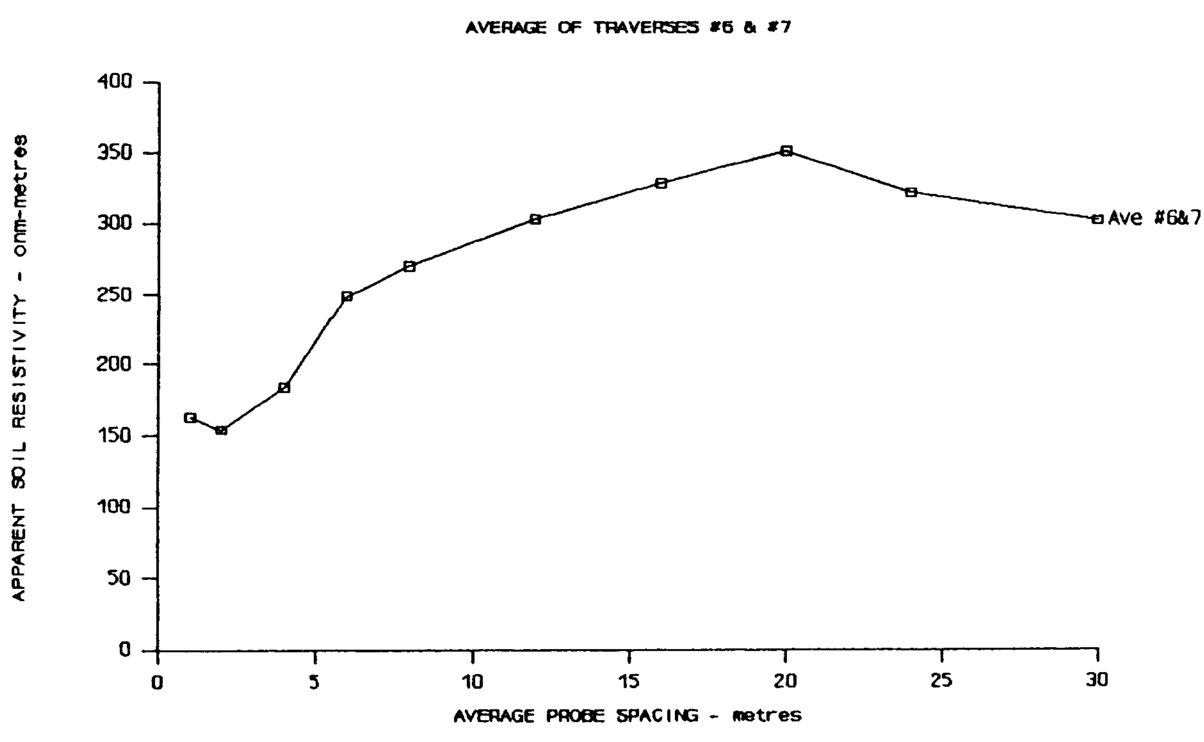

Figure I.10 Plot of Average of Resistivity Measurement Traverses #6 & #7

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 8

MEASURED ON: 17-November-88

CONDITIONS: Dark and cold. About 5 degree C.

DESCRIPTION: Along the roadside and then move down to the ditch at Mine #2.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

	--PROBE SPACING--		PROBE	METER	RANGE	IND.	RESISTIV	---REMARKS---
	a	b	DEPTH	READING		RES.	MEAS	
#	metres	metres	metres	ohms		ohms	ohm-m	
1	1	1	.1	28.500	Low	28.500	180.11	DET-2
2	2	2	.1	11.200	Low	11.200	140.95	DET-2
3	4	4	.1	6.190	Low	6.190	155.63	DET-2
4	6	6	.1	4.220	Low	4.220	159.12	DET-2
5	8	8	.1	2.940	Low	2.940	147.79	DET-2
6	12	12	.1	1.881	Normal	1.881	141.83	DET-2 relocate traverse to ditch
7	16	16	.1	1.468	Normal	1.468	147.58	DET-2
8	20	20	.1	1.170	Normal	1.170	147.03	DET-2
9	24	24	.1	.935	Normal	.935	141.00	DET-2
10	30	30	.1	.684	Normal	.684	128.93	DET-2
11	36	36	.1	.532	Normal	.532	120.34	DET-2

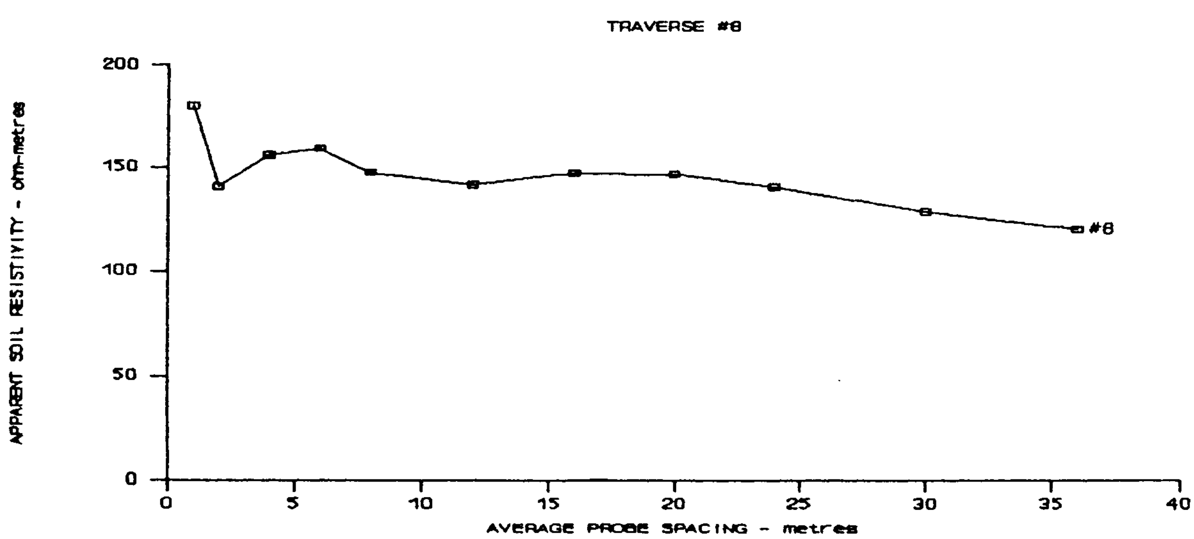

Figure I.11 Plot of Soil Resistivity Traverse #8 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

TRAVERSE: 9

MEASURED ON: 21-November-88

CONDITIONS: Cloudy and cold. About 5 degree C.

DESCRIPTION: At the site of future 25 kV Substation at Mine #6.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

	--PROBE SPACING--		PROBE	METER	RANGE	IND.	RESISTIV	---REMARKS---
	a	b	DEPTH	READING		RES.	MEAS	
#	metres	metres	metres	ohms		ohms	ohm-m	
1	1	1	.1	38.60	Normal	38.60	243.94	DET-2
2	2	2	.1	20.10	Normal	20.10	252.95	DET-2
3	4	4	.1	12.08	Normal	12.08	303.71	DET-2
4	6	6	.1	10.45	Normal	10.45	394.02	DET-2
5	6	6	.1	104.00	.10	10.40	392.13	ET3
6	8	8	.1	919.00	.01	9.19	461.98	ET3
7	8	8	.1	9.17	Normal	9.17	460.98	DET-2
8	12	12	.1	7.06	Normal	7.06	532.33	DET-2
9	16	16	.1	5.04	Normal	5.04	506.69	DET-2
10	20	20	.1	4.27	Normal	4.27	536.59	DET-2
11	24	24	.1	3.53	Normal	3.53	532.32	DET-2
12	30	30	.1	2.70	Normal	2.70	508.94	DET-2
13	36	36	.1	2.14	Normal	2.14	484.06	DET-2

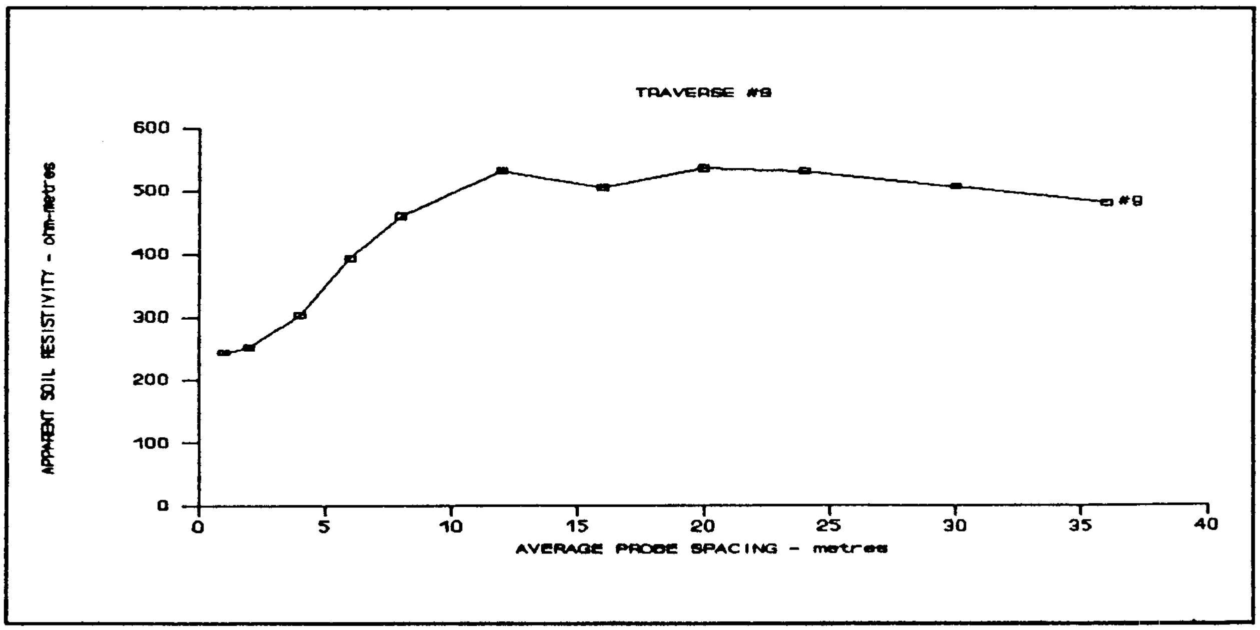

Figure I.12 Plot of Soil Resistivity Traverse #9 Measurement Results

TRAVERSE: 10

MEASURED ON: 21-November-88

CONDITIONS: Cloudy and cold. About 5 degree C.

DESCRIPTION: At the site of future 25 kV Substation at Mine #6. Orthogonal to Traverse 9.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	--PROBE SPACING-- a metres	b metres	PROBE DEPTH metres	Metre READING ohms	RANGE	IND. RES. ohms	RESISTIV MEAS ohm-m	---REMARKS---
1	1	1	.1	38.200	Normal	38.200	241.41	DET-2
2	2	2	.1	19.200	Normal	19.200	241.63	DET-2
3	4	4	.1	13.200	Normal	13.200	331.87	DET-2
4	6	6	.1	10.320	Normal	10.320	389.12	DET-2
5	8	8	.1	8.440	Normal	8.440	424.28	DET-2
6	12	12	.1	5.880	Low	5.880	443.36	DET-2, C2 on rock.
7	16	16	.1	5.040	Low	5.040	506.69	DET-2, C2 on rock.
8	20	20	.1	4.130	Normal	4.130	519.00	DET-2
9	24	24	.1	3.420	Normal	3.420	515.73	DET-2
10	30	30	.1	2.360	Normal	2.360	444.85	DET-2
11	36	36	.1	1.477	Low	1.477	334.09	DET-2

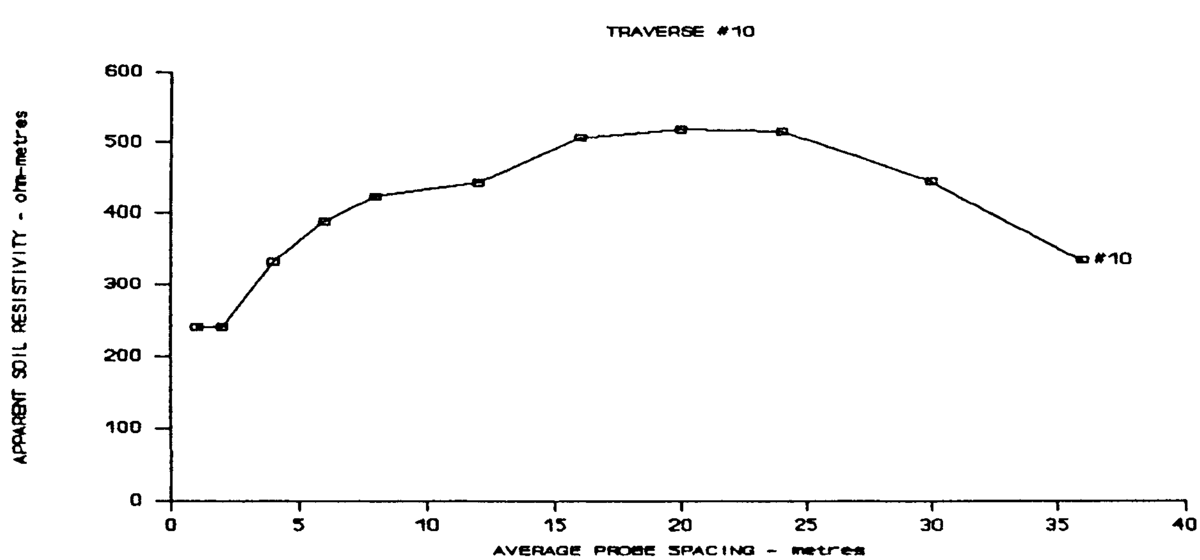

Figure I.13 Plot of Soil Resistivity Traverse #10 Measurement Results

Average of Traverse #9 & #10 Measurement Results

Spacing	Trav 9	Trav 10	Ave 9&10
1	243.94	241.41	242.68
2	252.95	241.63	247.29
4	303.71	331.87	317.79
6	394.02	389.12	391.57
8	460.98	424.28	442.63
12	532.33	443.36	487.85
16	506.69	506.69	506.69
20	536.59	519.00	527.80
24	532.32	515.73	524.03
30	508.94	444.85	476.90
36	484.06	334.09	409.08

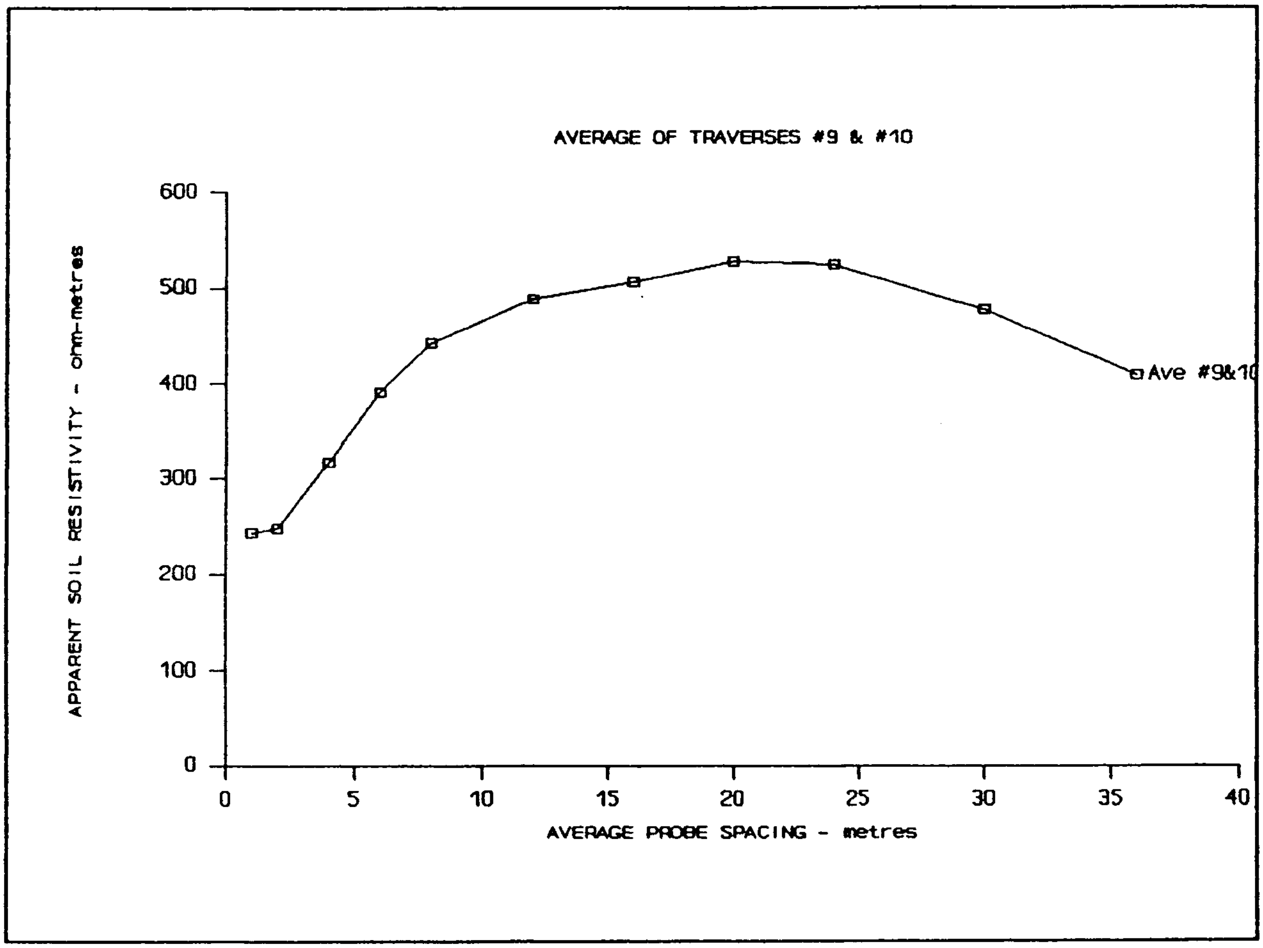

Figure I.14 Plot of Average of Soil Resistivity Measurement Traverses #9 & #10

TRAVERSE: 11

MEASURED ON: 22-November-88

CONDITIONS: Cloudy and cold. About 5 degree C.

DESCRIPTION: Along the BCH power line and dirt road near the Main Substation of Mine #6.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	--PROBE SPACING-- a metres	b metres	PROBE DEPTH metres	METER READING ohms	RANGE	IND. RES. ohms	RESISTIV MEAS ohm-m	---REMARKS---
1	1	1	.1	3.330	Normal	3.330	21.04	DET-2
2	2	2	.1	1.330	Normal	1.330	16.74	DET-2
3	4	4	.1	.671	Normal	.671	16.87	DET-2
4	6	6	.1	.464	High	.464	17.50	DET-2
5	8	8	.1	.374	Normal	.374	18.80	DET-2
6	12	12	.1	.296	Normal	.296	22.32	DET-2, C2 on rock.
7	16	16	.1	.249	Normal	.249	25.03	DET-2, C2 on rock.
8	20	20	.1	.215	Normal	.215	27.02	DET-2
9	24	24	.1	.188	Normal	.188	28.35	DET-2
10	30	30	.1	.155	Normal	.155	29.22	DET-2
11	36	36	.1	.125	Normal	.125	28.27	DET-2

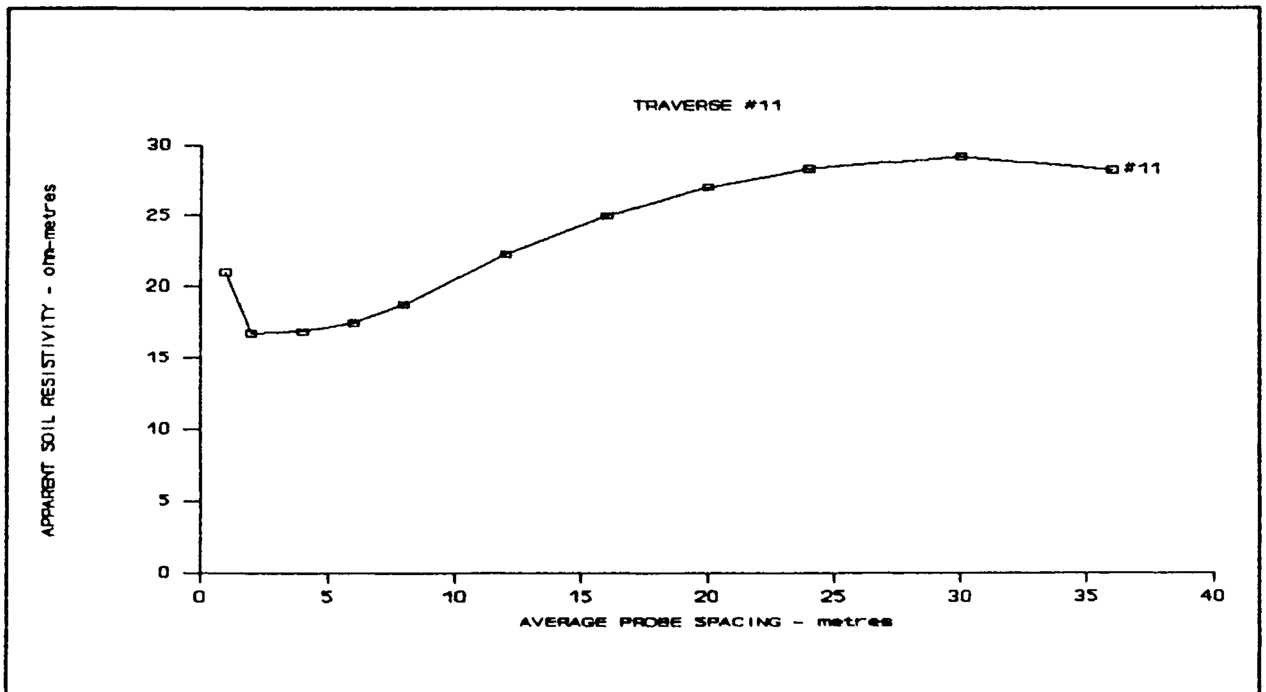

Figure I.15 Plot of Soil Resistivity Traverse #11 Measurement Results

APPENDIX I SOIL RESISTIVITY FIELD MEASUREMENT RESULTS

NOTES:

1. Probe Spacing: a is distance between outer (current) probes and inner (potential) probes.
   b is distance between inner potential probes.
2. MEAS resistivity is calculated using equations which accurately include the effect of rod depth. Results are different from those obtained using equations from IEEE Guide 81 which are for point source electrodes at the depth of the probe length.

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 1

MEASURED ON: 17-Oct-88

CONDITIONS: Sunny.About 4 deg C.

DESCRIPTION: Mine #4. Traverse from Moveable Substation. C1 & P1 were located on neutral or transformer ground. Both C2 & P2 are 100 m away from C1 & P1 but in opposite direction. Single point measurement was done before by mill people who obtained 2 ohms impedance value.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter. Check readings with ET3 hand crank meter.

#	C2 LOCATION meters	RANGE	MEASURED RESISTANC ohms	P1 & C1 LOCATION	--REMARKS--
1	100	M	13.50	Neutral ground	Noisy DET-2
2	150	M	14.04	Neutral ground	Noisy DET-2
3	150		13.70	Neutral ground	Noisy ET-3
4	150	M	13.83	Neutral ground	Power off DET-2
5	150	M	18.84	Transformer ground	Power off DET-2

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 2

MEASURED ON: 17-Oct-88

CONDITIONS: Sunny.About 4 deg C.

DESCRIPTION: Mine #4. Traverse from Moveable Substation. C1 & P1 located on transformer ground. C2 175 metres away. Traverse from C1 to C2.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter. Check readings with ET3 hand crank meter.

#	C2 LOCATION meters	RANGE	MEASURED RESISTANCE ohms
1	5	N	11.35
2	15	N	15.38
3	25	N	16.21
4	35	N	17.22
5	45	N	17.85
6	55	N	18.52
7	65	N	18.94
8	75	N	19.37
9	85	N	19.75
10	95	N	20.10
11	105	N	20.70
12	115	N	21.20
13	125	N	21.80
14	135	N	23.00
15	145	N	25.40
16	155	N	30.10
17	165	N	41.50
18	175	N	1889.00 on C2

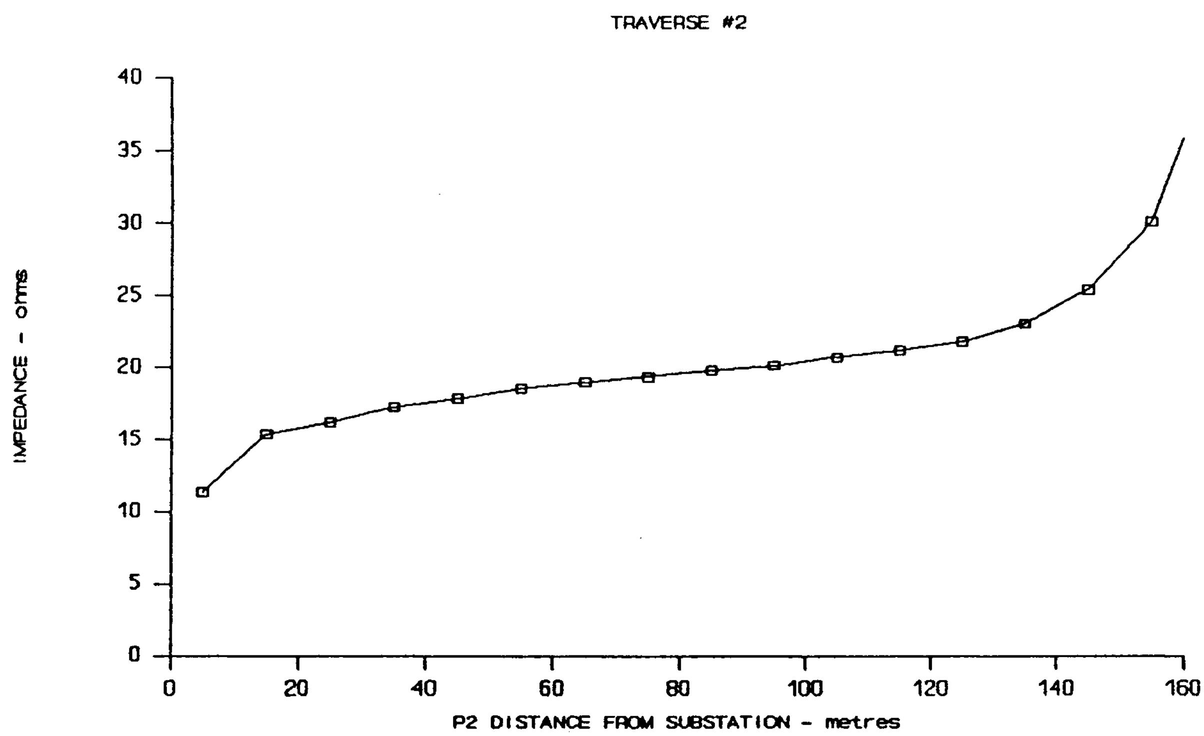

Figure I.17 Plot of Fall-of-Potential Measurement Traverse #2

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 3

MEASURED ON: 17-Oct-88

CONDITIONS: Sunny.About 4 deg C.

DESCRIPTION: Mine #4. Traverse from old ground bed at 15 kV dragline switch house. C2 at 100 metres distance. Traverse from ground bed towards C2.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	C2 LOCATION meters	RANGE	MEASURED RESISTANCE ohms
1	5	N	105.20
2	10	N	117.10
3	20	N	125.20
4	30	N	127.20
5	40	N	127.60
6	50	N	128.00
7	60	N	129.20
8	70	N	130.10
9	80	N	131.40
10	90	N	135.40
11	95	N	143.20
12	100	N	1488.00 on C2

Using 60 m P2 location to measure O/H ground wire ground: R = 6.1 ohms.
Estimated distance to 138 kV Substation - 1.5 km.

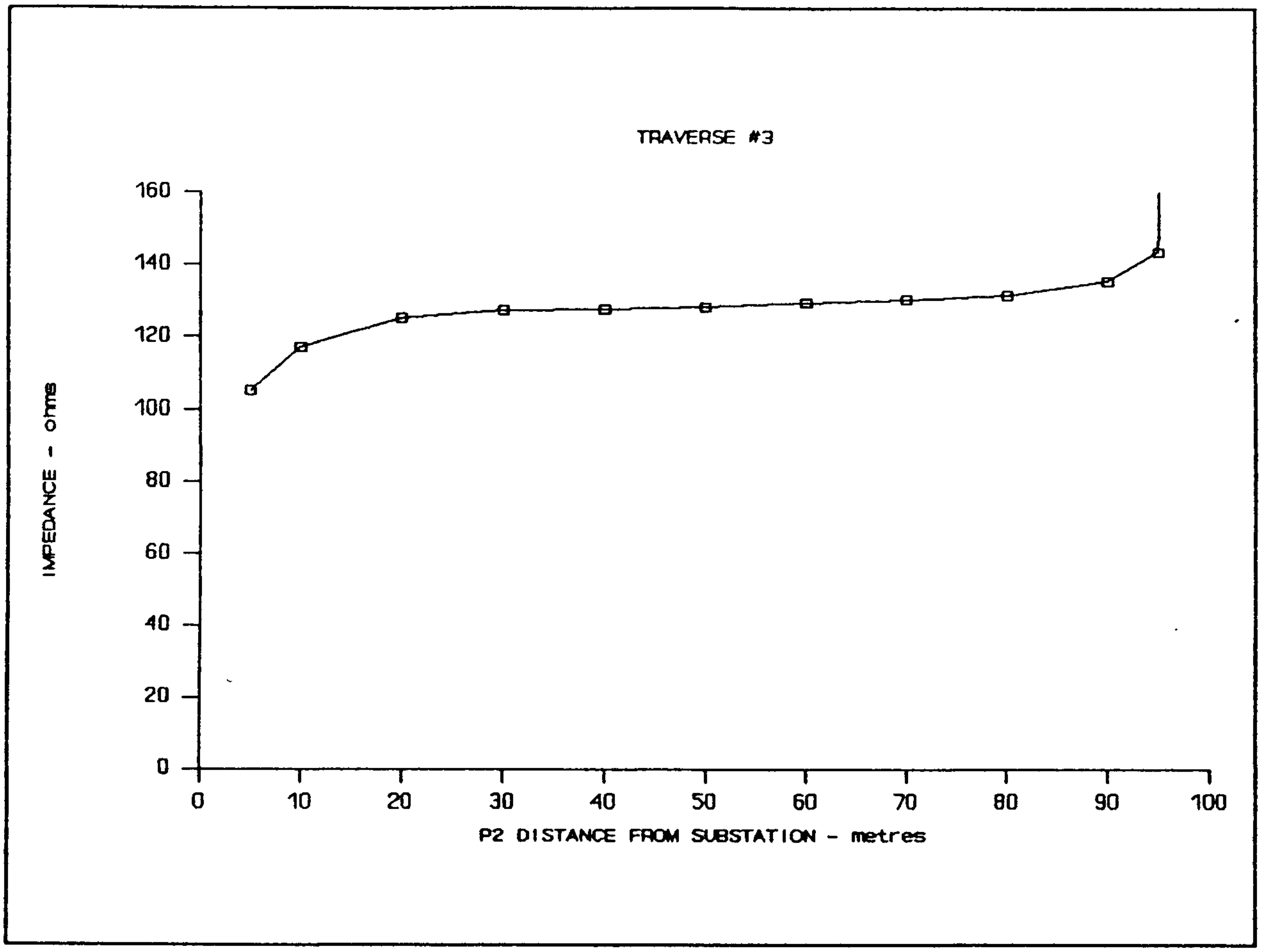

Figure I.17 Plot of Fall-of-Potential Measurement Traverse #3

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 4

MEASURED ON: 18-Oct-88

CONDITIONS: Cloudy.About 4 deg C.

DESCRIPTION: Traverse from Moveable Substation at Mine #1, with C1 & P1 on perimeter ground of the sub. C2 at a distance approximate 175 m.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	C2 LOCATION meters	RANGE	MEASURED RESISTANCE ohms
1	5	X	4.42
2	10	X	5.12
3	20	X	5.42
4	30	X	5.72
5	40	X	5.85
6	50	X	6.07
7	60	X	6.11
8	70	X	6.26
9	80	X	6.45
10	90	X	6.55
11	100	X	6.70
12	110	X	6.84
13	120	X	7.08
14	130	X	7.44
15	140	X	7.89
16	150	X	8.65
17	160	X	11.14
18	170	X	23.10
19	175	X	1721

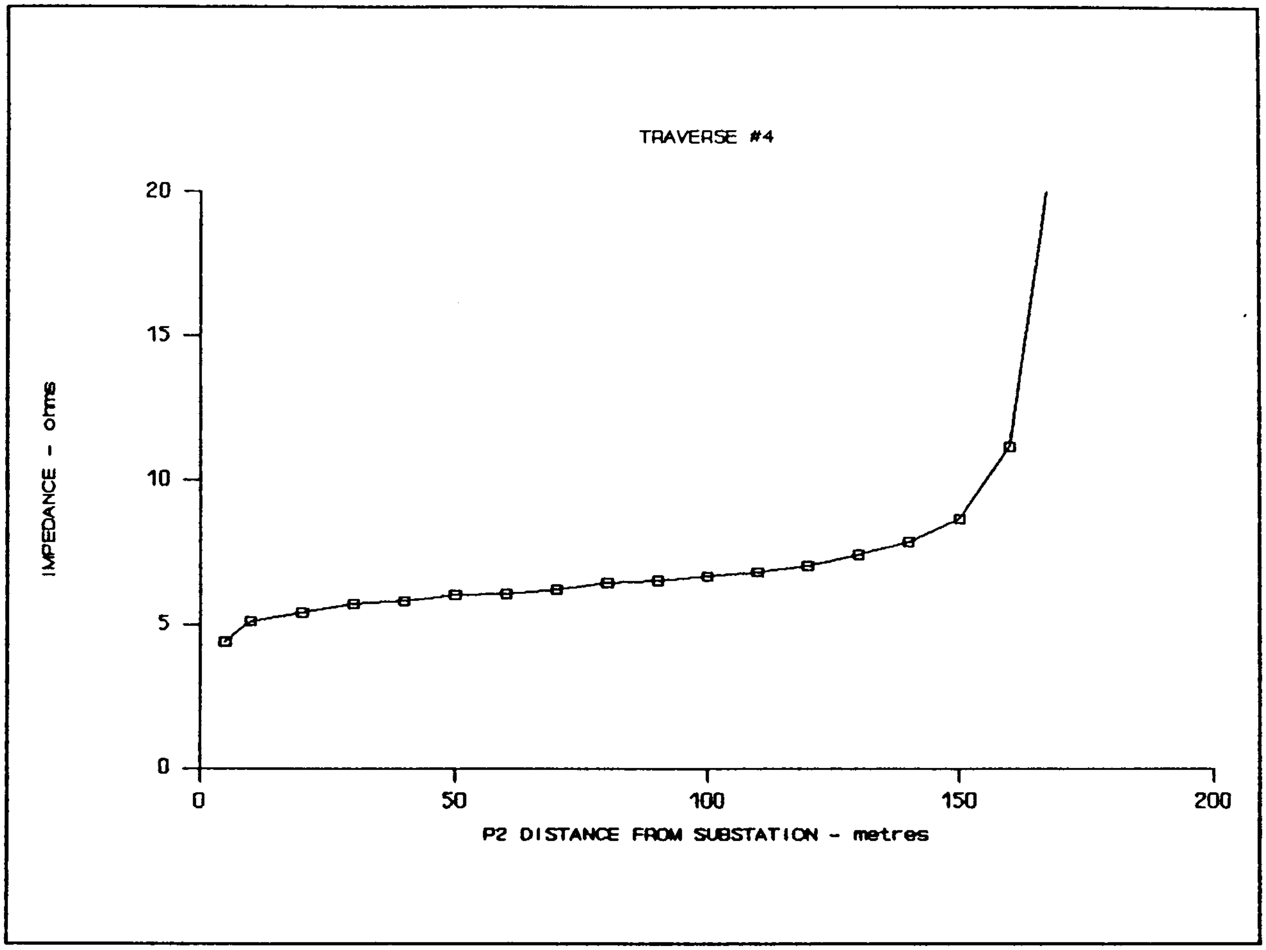

Figure I.18 Plot of Fall-of-Potential Measurement Traverse #4

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 5

MEASURED ON: 18-Oct-88

CONDITIONS: Cloudy.About 4 deg C.

DESCRIPTION: Traverse from Moveable Substation at Mine #1, with C1 & P1 on grid conductor to transformer tank with common neutral & sub grounds.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	P2 LOCATION meters	RANGE	MEASURED RESISTANCE ohms	
1	5	N	6.54	
2	10	N	7.12	
3	20	N	6.90	
4	30	N	6.33	
5	20	N	6.10	repeat 20
6	40	N	7.00	
7	50	N	5.96	

Abandoned FOP due to excess noise.
One measurement was done with primary 69 kV disconnect open.
P2 at 60% of C2 distance : R = 7.20 ohms.

TRAVERSE: 6

MEASURED ON: 19-Oct-88

CONDITIONS: Cloudy.About 4 deg C.

DESCRIPTION: Traverse from Moveable Substation at Mine #4, with C1 & P1 on remote ground. C2 at a distance approximate 100 m. Location of shock incident.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	C2 LOCATION meters	RANGE	MEASURED RESISTANCE ohms	
1	5	N	11.59	
2	10	N	13.12	
3	20	N	14.58	
4	30	N	15.67	
5	40	N	16.79	
6	50	N	17.96	
7	60	N	19.46	
8	70	N	21.60	
9	80	N	24.90	
10	90	N	36.00	
11	95	N	53.40	#6
12	100	N	1188.00	on C2
13	62	N	19.81	
14	62	198.5x0.1	19.85	ET-3
15	62	N	33.00	Move C1 & P1 to station ground
16	62	197x0.1	19.70	with mine Megger
17	62	216x0.1	21.60	3 terminal measurement with mine Megger
18	8	171x0.1	17.10	at mine reference with mine Megger

Resistance between station & remote ground: R = 39.1 ohms

Measurement of remote ground bed using references placed by mine.
Remote bed is bonded to O/H skyline to equipment up hill.
C2 is 16 m from bed.

P2 loc.	Range	R (ohm)
8 m	N	17.09 (mine location)
3 m	N	10.89

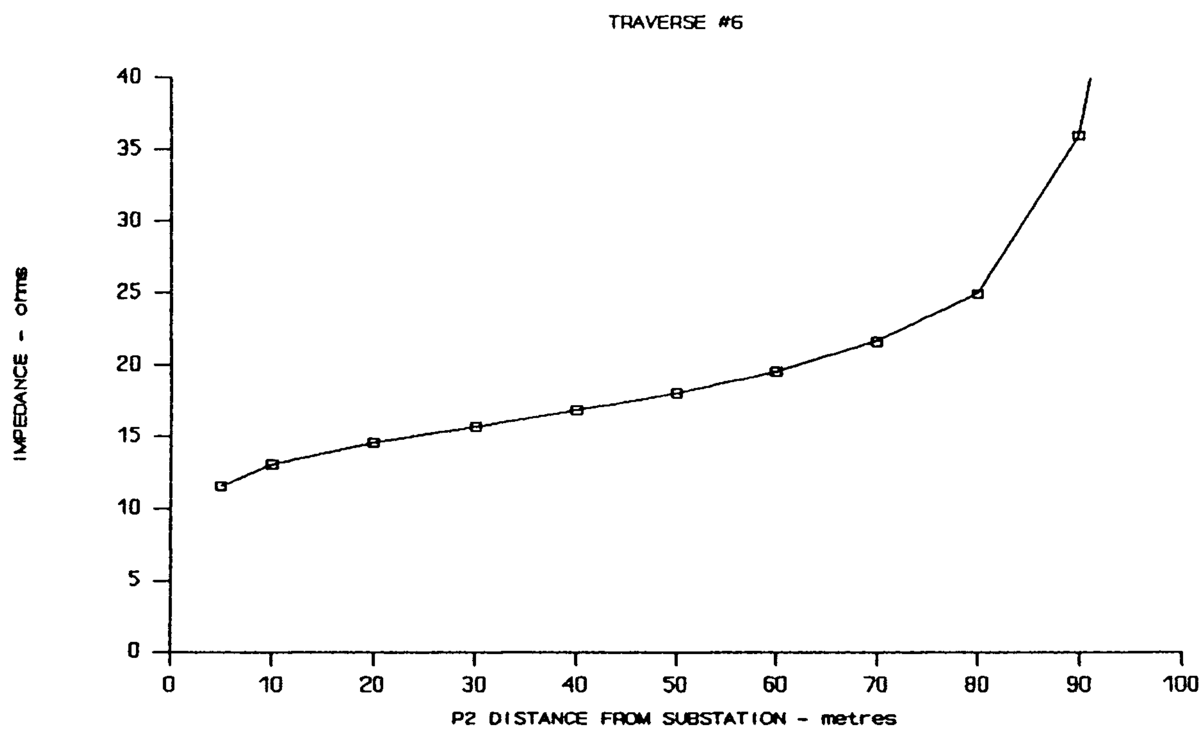

Figure I.19 Plot of Fall-of-Potential Measurement Traverse #6

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 7

MEASURED ON: 19-Oct-88

CONDITIONS: Cloudy. About 4 deg C.

DESCRIPTION: Traverse from existing Substation at Mine #4. C2: group of 3 rods about 350 meters from East fence of Sub in North direction. P2 electrode in E direction starts 5 meters from fence of the NE corner of the Sub.

EQUIPMENT: ac and dc test currents generated by a 400 watt Honda portable generator and interface unit. Frequency changed by varying speed of generator. Current measured with Beckman DM25L digital multimeter. dc potentials measured with Fluke 8050A digital multimeter ac potentials measured with HP 3581C frequency selective voltmeter.

#	P2 LOCATION meters A	RESIDUAL DC POT'L volts B	CURRENT amps C	FREQ. Hz D	P2 POTENTIAL volts E	MEAS IMP ohms F	-----REMARKS----- G
1	5	N/A	.87	50	1.09	1.253	C1 & P1 at remote ground bed
2	10	N/A	.88	51	.91	1.034	
3	20	N/A	.88	51	.89	1.011	
4	40	N/A	.89	51	1.45	1.629	
5	60	N/A	.89	51	1.80	2.022	
6	80	N/A	.90	52	2.00	2.222	
7	100	N/A	.90	52	2.15	2.389	
8	120	N/A	.91	51	2.25	2.473	voltmeter battery failure
9	180	N/A	.89	51/52	2.75	3.090	60 Hz residual potential .2 V
10	180	N/A	.97	69	2.89	2.979	
11	180	N/A	.98	70	3.60	3.673	Move C1 & P1 to sub ground
12	180	N/A	.89	51	3.30	3.708	
13	180	.5	.55	dc	2.35	4.273	standing -.5 V
14	180	.4	.55	dc	1.82	3.309	standing -.4 V, move back to remote ground bed
15	180					2.890	DET-2
16	180					3.500	DET-2, C1 & P1 moved to station fence riser
17	180					3.500	DET-2, C1 & P1 moved to different different station fence riser

BOND TEST: Sub grid to remote ground = 3.01 ohms DET-2.

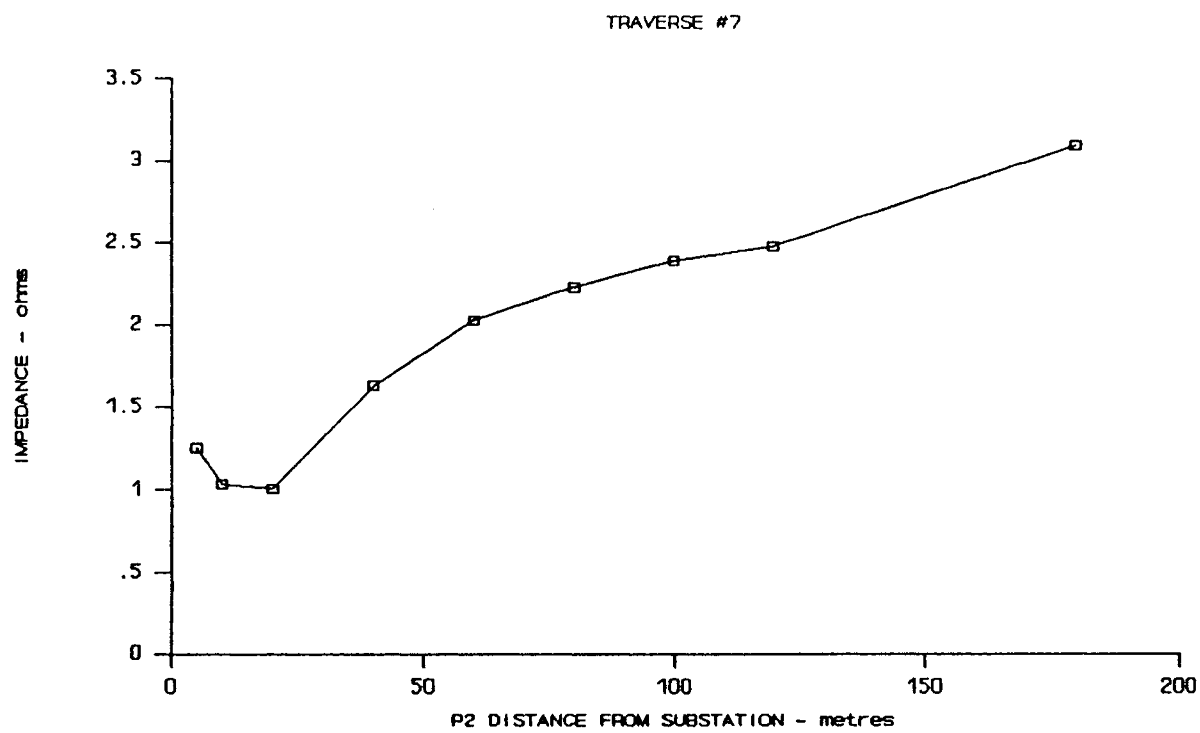

Figure I.20 Plot of Fall-of-Potential Measurement Traverse #7

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 8

MEASURED ON: 19-Oct-88

CONDITIONS: Cloudy. About 4 deg C.

DESCRIPTION: Traverse from Dragline Switch at Mine #4. C2 at old 100 m position. P2 electrode at 62 m position.

EQUIPMENT: ac and dc test currents generated by a 400 watt Honda portable generator and interface unit. Frequency changed by varying speed of generator. Current measured with Beckman DM25L digital multimeter. dc potentials measured with Fluke 8050A digital multimeter ac potentials measured with HP 3581C frequency selective voltmeter.

#	P2 LOCATION meters	RESIDUAL DC POT'L volts	CURRENT amps	FREQ. Hz	P2 POTENTIAL volts	MEAS IMP ohms	-----REMARKS-----
	A	B	C	D	E	F	G
1	62	N/A	.25	51	1.63	6.520	60 Hz resid potl 1 to 2.5 V
2	62	N/A	.36	70	2.40	6.667	
3	62	.04	.15	dc	1.00	6.897	
4	62					6.180	DET-2

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 9

MEASURED ON: 17-Nov-88

CONDITIONS: Sunny and cold. About 5 deg C.

DESCRIPTION: Traverse from old equipment ground bed about 200' from pit bottom at Mine #2. C1 & P1 are clipped to the bed while C2 at a distance approximate 100 m.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

#	C2 LOCATION meters	RANGE	MEASURED RESISTANCE ohms	
1	5	N	5.49	
2	10	N	6.16	
3	20	N	6.73	
4	30	N	7.05	
5	40	N	7.33	
6	50	N	7.60	
7	60	N	7.88	
8	70	N	8.37	
9	80	N	10.40	
10	90	N	10.72	
11	95	N	13.02	#9
12	100	N	148.50	on C2
13	62	N	7.92	
14	62	N	9.49	Move copper tail to over the bed
15	62	N	9.51	Move C1 & P1 to other rods of the same bed
16	62	913x0.01	9.13	ET-3

With the same references, move C1 & P1 to the transformer ground bed
R = 19.00 ohms in High Range

Move P2 & C2 to get new 62% & 100% locations for the transformer ground bed
R = 19.02 ohms in Normal Range
R = 19.02 ohms in High Range

Set up new references with C2 & P2 100 m apart and 100 m away from both ground beds
With C1 & P1 on transformer ground bed : R = 18.51 ohms
Move P1 to equipment ground bed : R = 0.391 ohms
% of GPR of transformer ground bed to the equipment ground = 0.391/18.51 = 2.11%

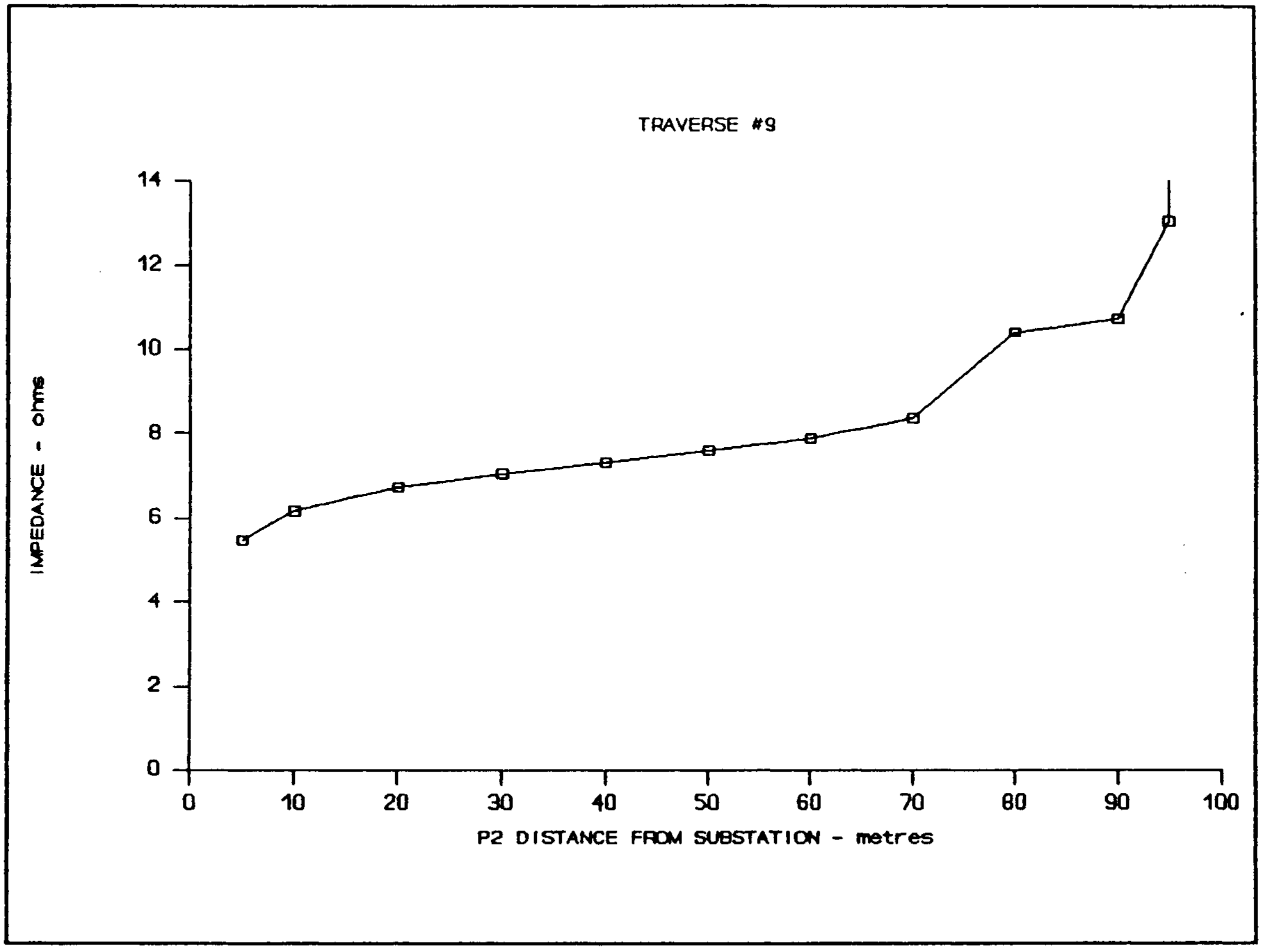

Figure I.22 Plot of Fall-of-Potential Measurement Traverse #9

TRAVERSE: 10

MEASURED ON: 17-Nov-88

CONDITIONS: Sunny and cold. About 5 deg C.

DESCRIPTION: Traverse from Moveable Substation at Mine #2. C1 & P1 are clipped to the equipment ground bed. P2 is 200 m away in E direction, C2 is 135 m away in SW direction.

EQUIPMENT: Evershed Vignoles Type DET-2 electronic meter.
Check readings with ET3 hand crank meter.

R = 0.811 ohm two shovels 136 & 137 connected. (error reading)
R = 6.21 ohms 137 disconnected
R = 21.2 ohms 136 & 137 disconnected
R = 7.35 ohms 137 connected back
R = 3.96 ohms 136 & 137 connected back
R = 3.98 ohms one switch closed
R = 3.98 ohms both switches closed
R = 4.01 ohms 136 energized
R = 3.99 ohms 136 & 137 energized

All above results are on High range.

Transfer P1 to transformer ground: R = -0.16 ohm poor measurement configuration

Relocate C2 to 160 m away in W direction : R = -0.6 ohm

Move C1 to transformer ground : R = 27.4 ohms

Move C2 & P2 to equipment ground : R = 32.2 ohms

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 11

MEASURED ON: 21-Nov-88

CONDITIONS: Cloudy. About 5 deg C.

DESCRIPTION: Traverse from existing Substation at Mine #6. C2 on Mine's reference C2(3). P2 in N direction starts 10 meters from fence of the NE corner of the Sub.

EQUIPMENT: ac and dc test currents generated by a 400 watt Honda portable generator and interface unit. Frequency changed by varying speed of generator. Current measured with Beckman DM25L digital multimeter. dc potentials measured with Fluke 8050A digital multimeter ac potentials measured with HP 3581C frequency selective voltmeter.

#	P2 LOCATION meters A	P2 LOCATION meters Real A	RESIDUAL DC POT'L volts B	CURRENT amps C	FREQ. Hz D	P2 POTENTIAL volts E	MEAS IMP ohms F	-----REMARKS----- G
1	10	9	N/A	2.38	50	.560	.235	60 Hz residual = 1.15 V
2	30	26	N/A	2.36	50	.700	.297	
3	50	43	N/A	2.36	50	.780	.331	
4	80	69	N/A	2.36	50	.830	.352	
5	110	95	N/A	2.35	50	.860	.366	
6	140	122	N/A	2.34	50	.870	.372	
7	170	148	N/A	2.35	50	.880	.374	
8	200	174	N/A	2.34	50	.890	.380	
9	230	200	N/A	2.35	50	.910	.387	About 30 m short of Mill P2(3)
10	265	230	N/A	2.34	50	.930	.397	On P2(3), 60 Hz residual 1.8 V
11	265	230	N/A	3.41	72	1.380	.405	
12	265	230	.352	3.64	dc	1.530	.420	
13	265	230	.015	3.64	dc	.470	.129	Reloc P1 to remote ground bed
14	265	230	N/A	1.89	49/50	.195	.103	
15	265	230	N/A	2.28	66/67	.305	.134	
16	265	230					.060	DET-2, noisy
17	265	230					.400	DET-2, relocate P1 to Sub grid
18	265	230					.430	Mine's meter
19	265	230						No reading ET3
20	265	230	N/A	2.03	51	.710	.350	Reloc P1 & C1 remote grnd bed
21	265	230	N/A	2.33	70	1.000	.429	
22	265	230	.352	4.80	dc	1.180	.246	

BOND TEST:

Sub fence to Sub grid riser (Pull box outside fence & T1 resistor structure)
5.33 A .0093 V .00174484 ohm

Sub fence to remote ground
4.96 A 2.89 V .58266129 ohm Residual = -.116 V

TRANSFERRED POTENTIAL :

50 Hz --> (0.195 V / 0.93 V) x (2.34 A / 1.89 A) = 25.95%

70 Hz --> (0.305 V / 1.38 V) x (3.41 A / 2.28 A) = 33.06%

dc --> (0.470 V / 1.53 V) x (3.64 A / 3.64 A) = 30.72%

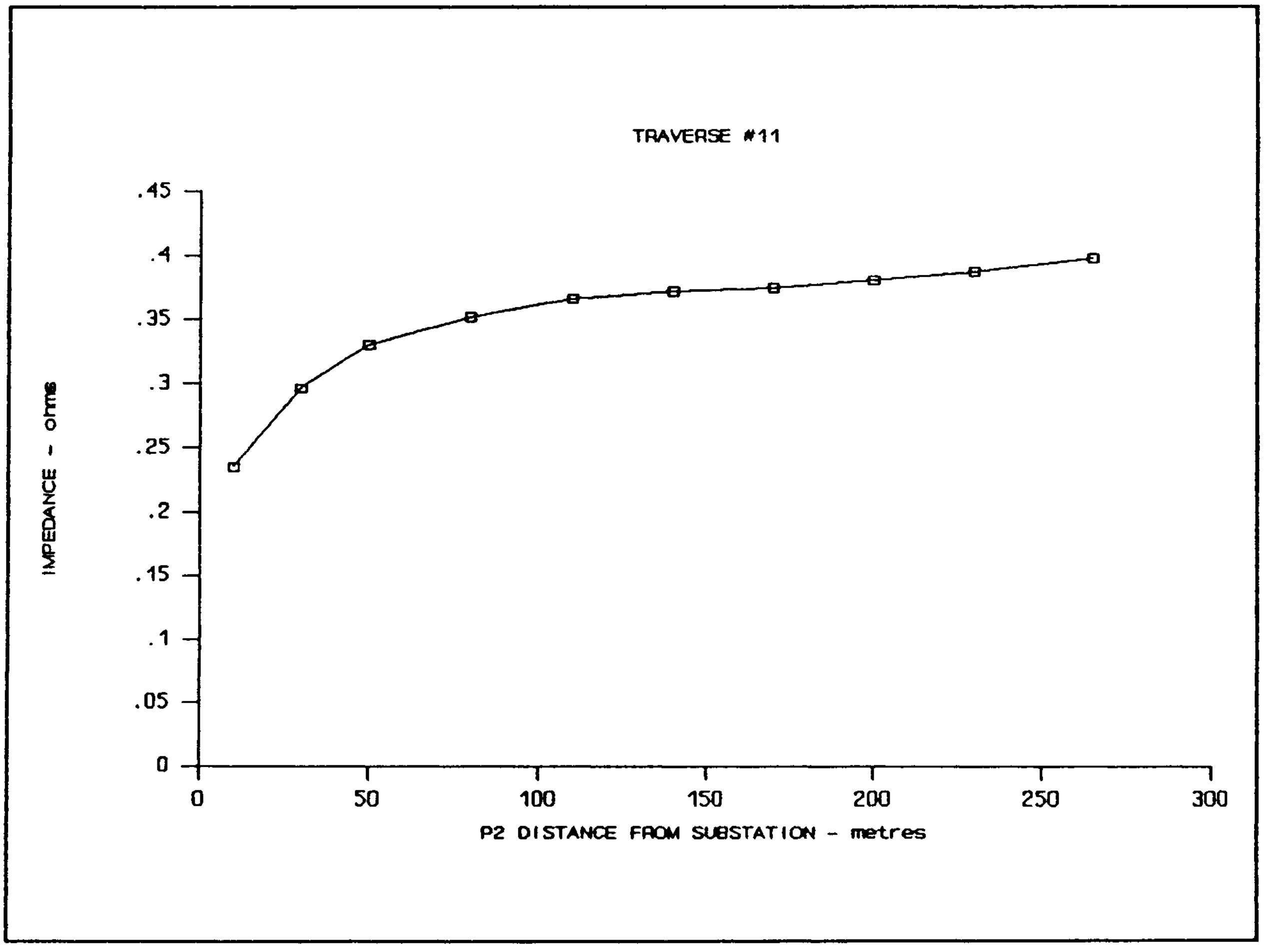

Figure I.22 Plot of Fall-of-Potential Measurement Traverse #11

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 12

MEASURED ON: 21-Nov-88

CONDITIONS: Cloudy. About 5 deg C.

DESCRIPTION: Traverse from Skid Breakers at Mine #6. C2 at 100 m distance.

EQUIPMENT: ac and dc test currents generated by a 400 watt Honda portable generator and interface unit. Frequency changed by varying speed of generator. Current measured with Beckman DM25L digital multimeter. dc potentials measured with Fluke 8050A digital multimeter ac potentials measured with HP 3581C frequency selective voltmeter.

#	P2 LOCATION meters	RESIDUAL DC POT'L volts	CURRENT amps	FREQ. Hz	P2 POTENTIAL volts	MEAS IMP ohms	-----REMARKS-----
	A	B	C	D	E	F	G
1	5	N/A	.52	51	1.15	2.212	
2	10	N/A	.52	51	1.16	2.231	
3	20	N/A	.52	51	1.17	2.250	
4	30	N/A	.53	51	1.18	2.226	
5	62	N/A	.53	51	1.28	2.415	
6	62	N/A	.75	69	2.16	2.880	
7	62	.1613	.26	dc	.49	1.885	
8	62					2.060	DET-2

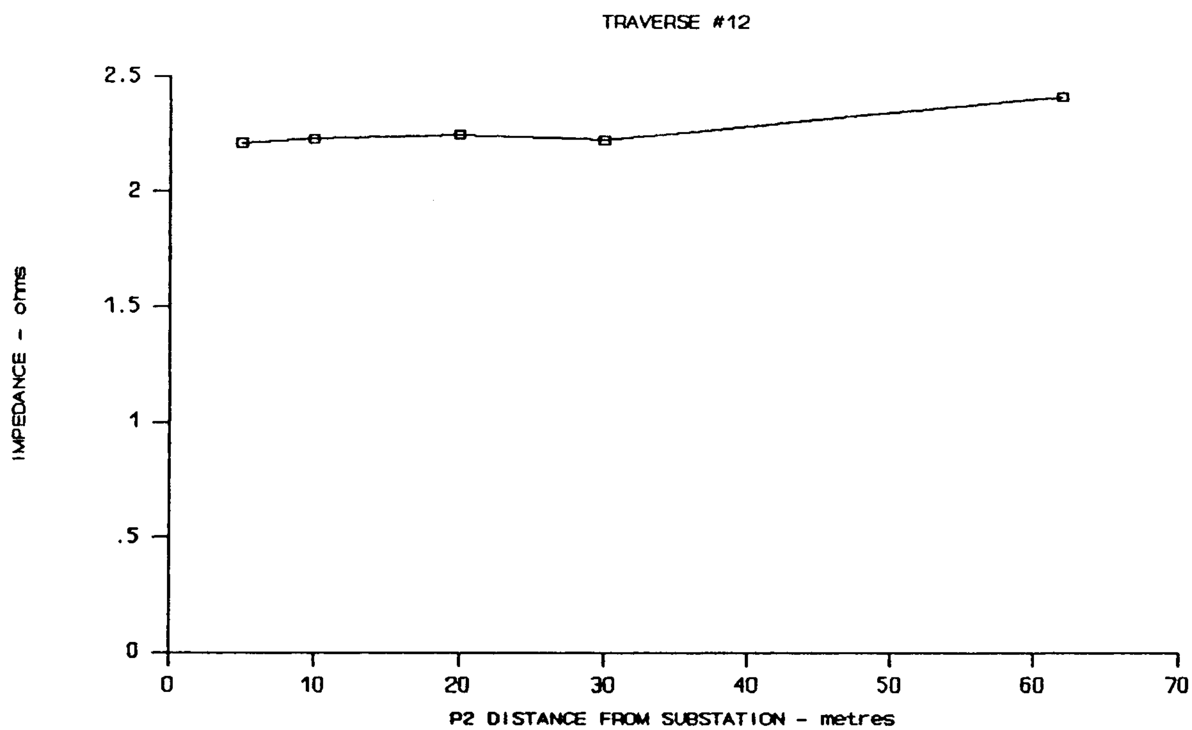

Figure I.23 Plot of Fall-of-Potential Measurement Traverse #12

APPENDIX I FALL-OF-POTENTIAL FIELD MEASUREMENT RESULTS

TRAVERSE: 13

MEASURED ON: 22-Nov-88

CONDITIONS: Snow and windy.

DESCRIPTION: Traverse from Moveable Substation at Mine #3. P2 at 62 m & C2 at 100 m.

EQUIPMENT: ac and dc test currents generated by a 400 watt Honda portable generator and interface unit. Frequency changed by varying speed of generator. Current measured with Beckman DM25L digital multimeter. dc potentials measured with Fluke 8050A digital multimeter ac potentials measured with HP 3581C frequency selective voltmeter.

Sub #	P2 LOCATION meters	RESIDUAL DC POT'L volts	CURRENT amps	FREQ. Hz	P2 POTENTIAL volts	MEAS IMP ohms	-----REMARKS-----
	A	B	C	D	E	F	G
7	62	N/A	.0925	49	.245	2.649	
7	62	N/A	.1385	73	.400	2.888	
7	62	.10	.0368	dc	.078	2.120	
7	62					2.640	DET-2
6	62	N/A	.6900	49	2.860	4.145	
6	62	N/A	.9100	71	3.700	4.066	
6	62	.47	.6900	dc	3.090	4.478	
6	62					3.980	DET-2
1	62		.0318	49/50	.280	8.805	
1	62		.0491	71	.510	10.387	
1	62		.0497	72	1.530	30.785	O/H ground wire disconnected
1	62		.0344	51	1.130	32.849	
1	62					36.100	DET-2
1	62					8.800	DET-2, O/H grnd wire connected
1	62					3.500	ET-3, no reading for the Mine's Vibraground meter

APPENDIX II
DRAWINGS

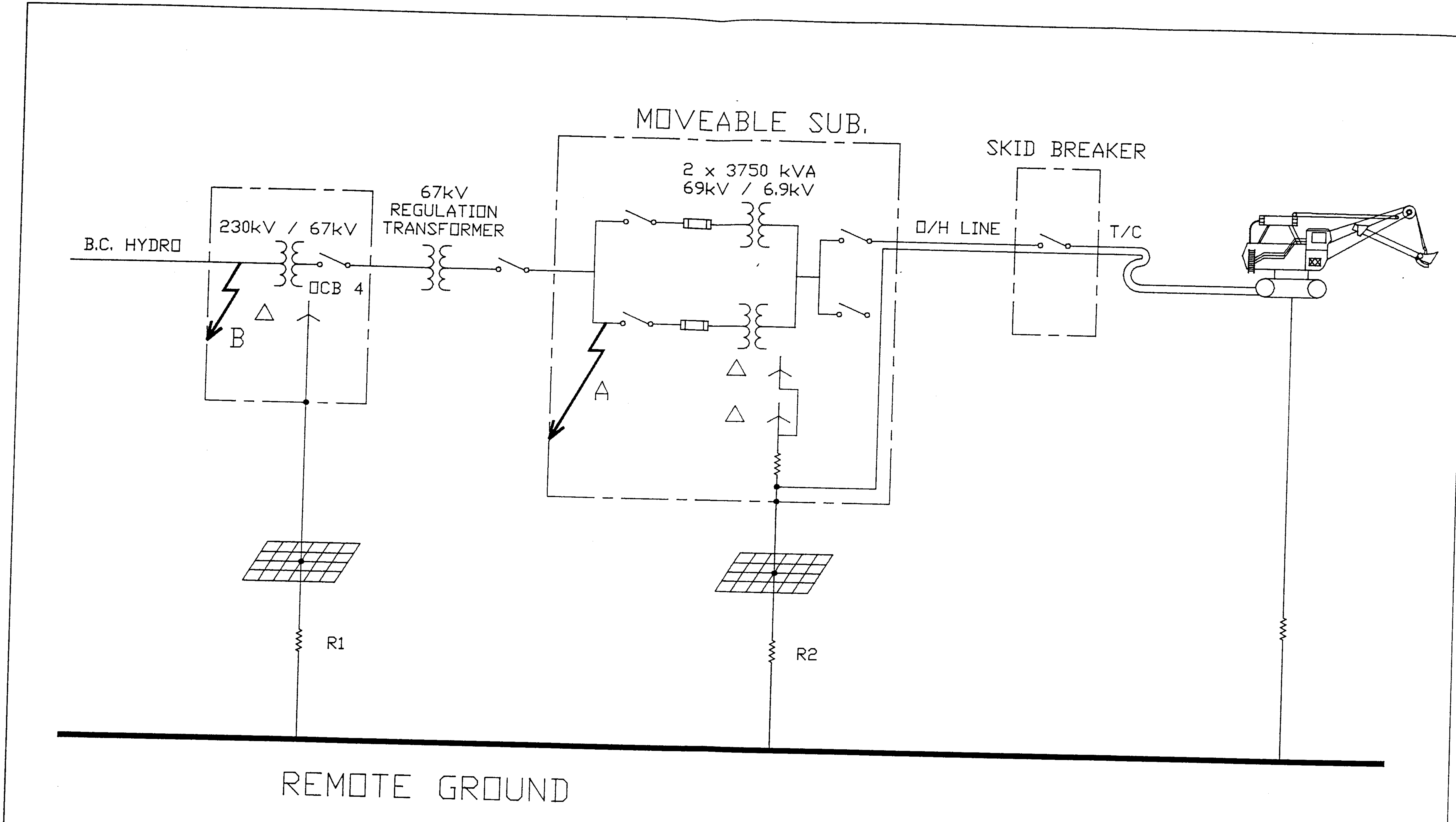

Figure II.1
Mine #1

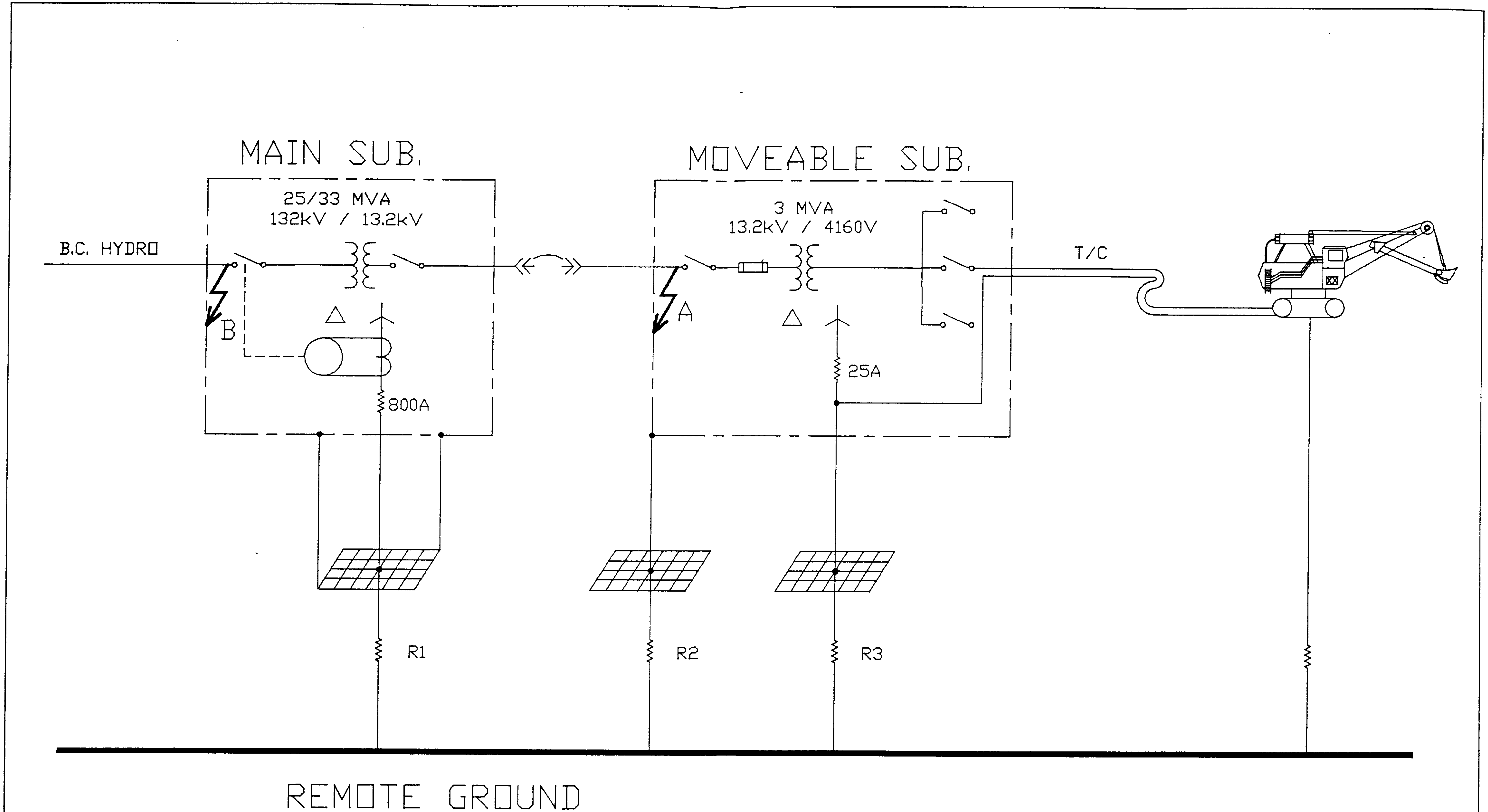

Figure II.2
Mine #2

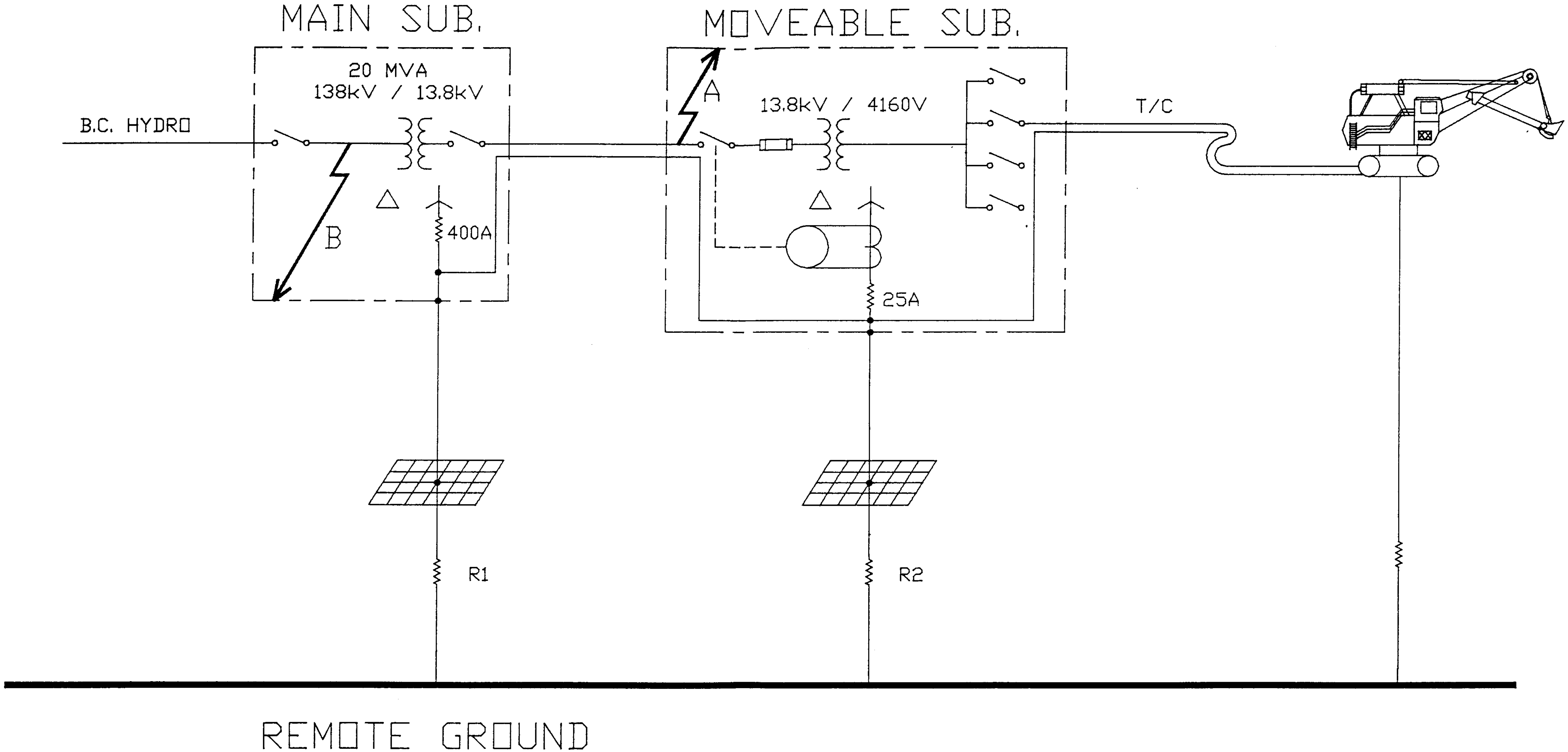

Figure II.3
Mine #3

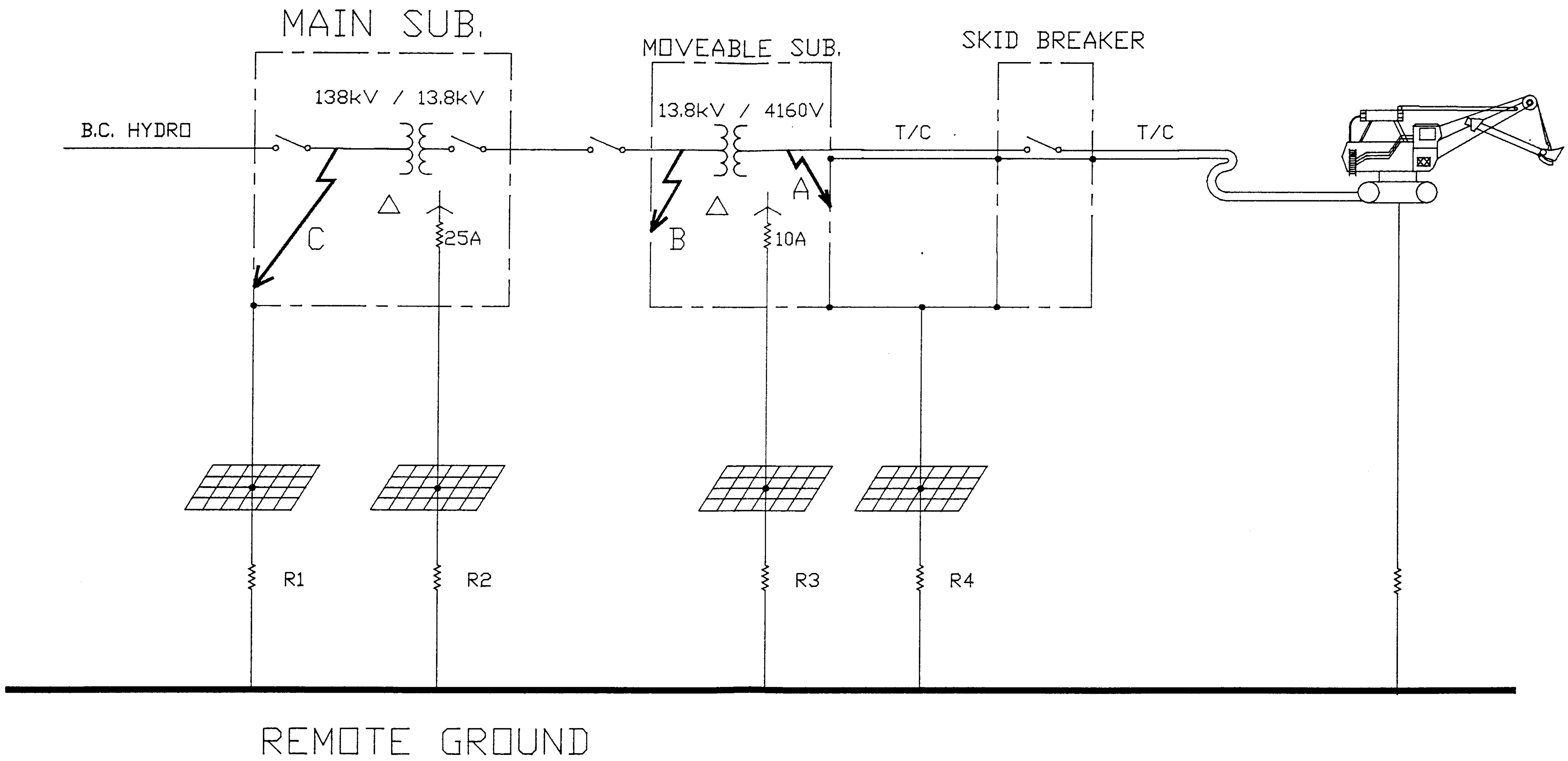

Figure II.4
Mine #4

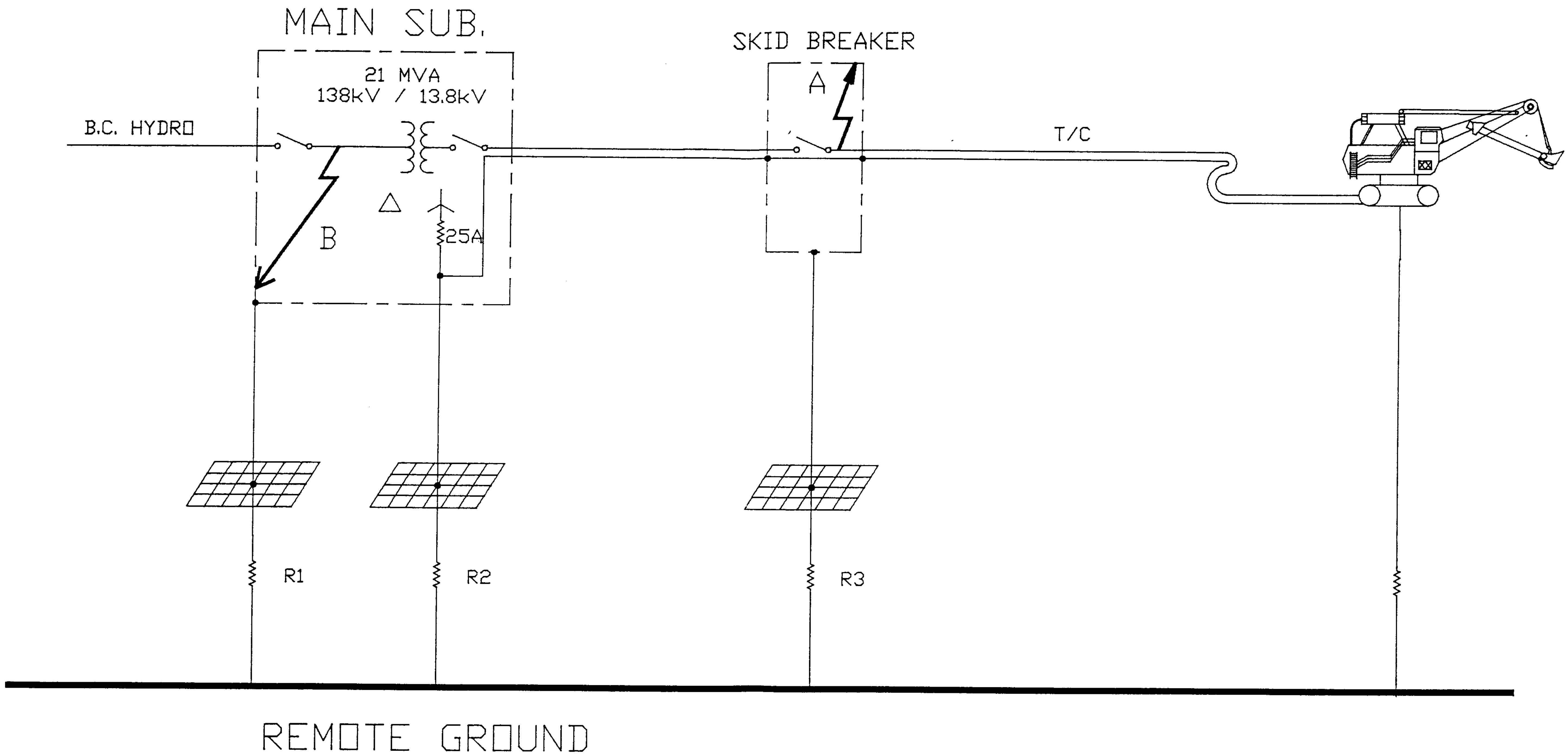

Figure II.5
Mine #4

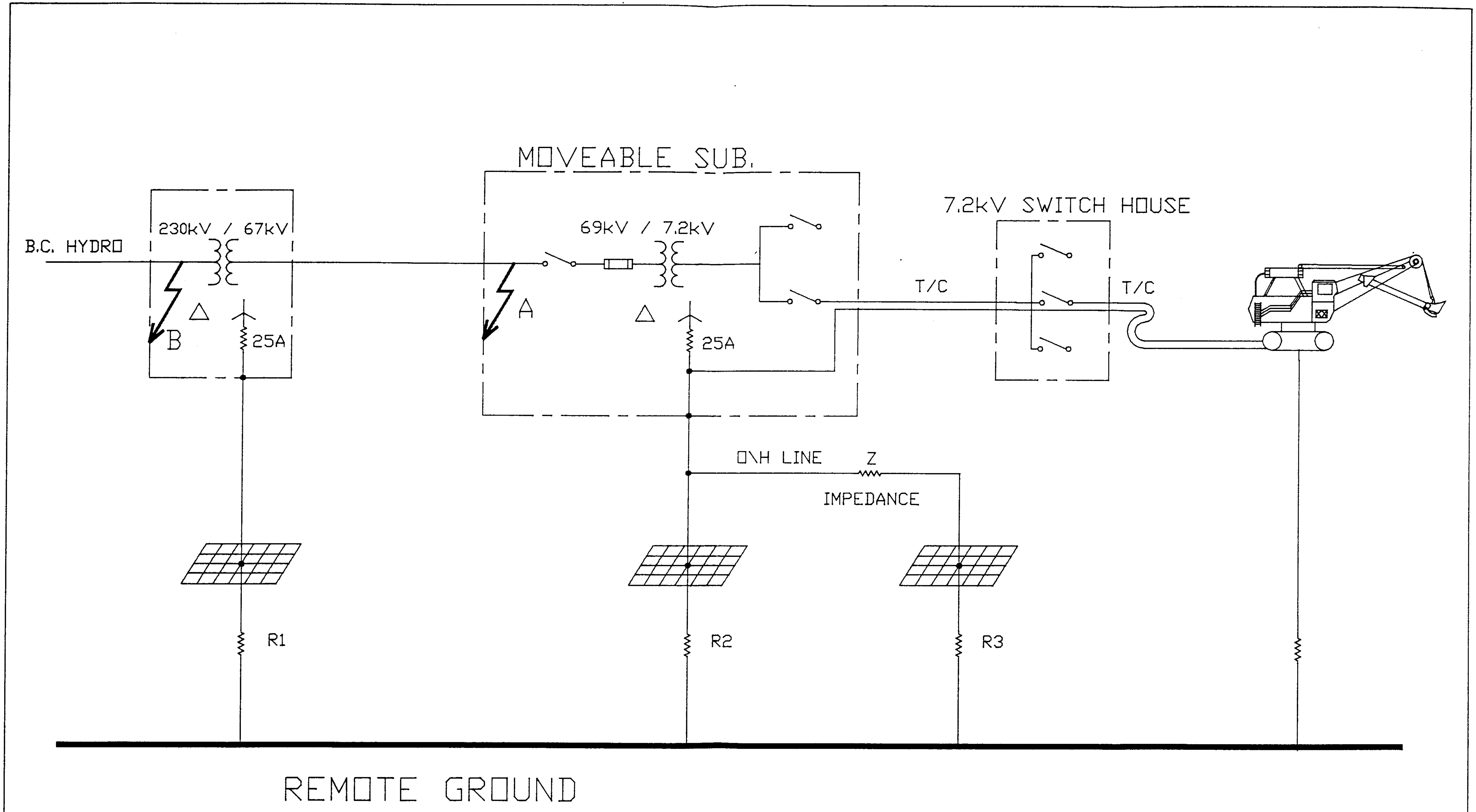

Figure II.6
Mine #5

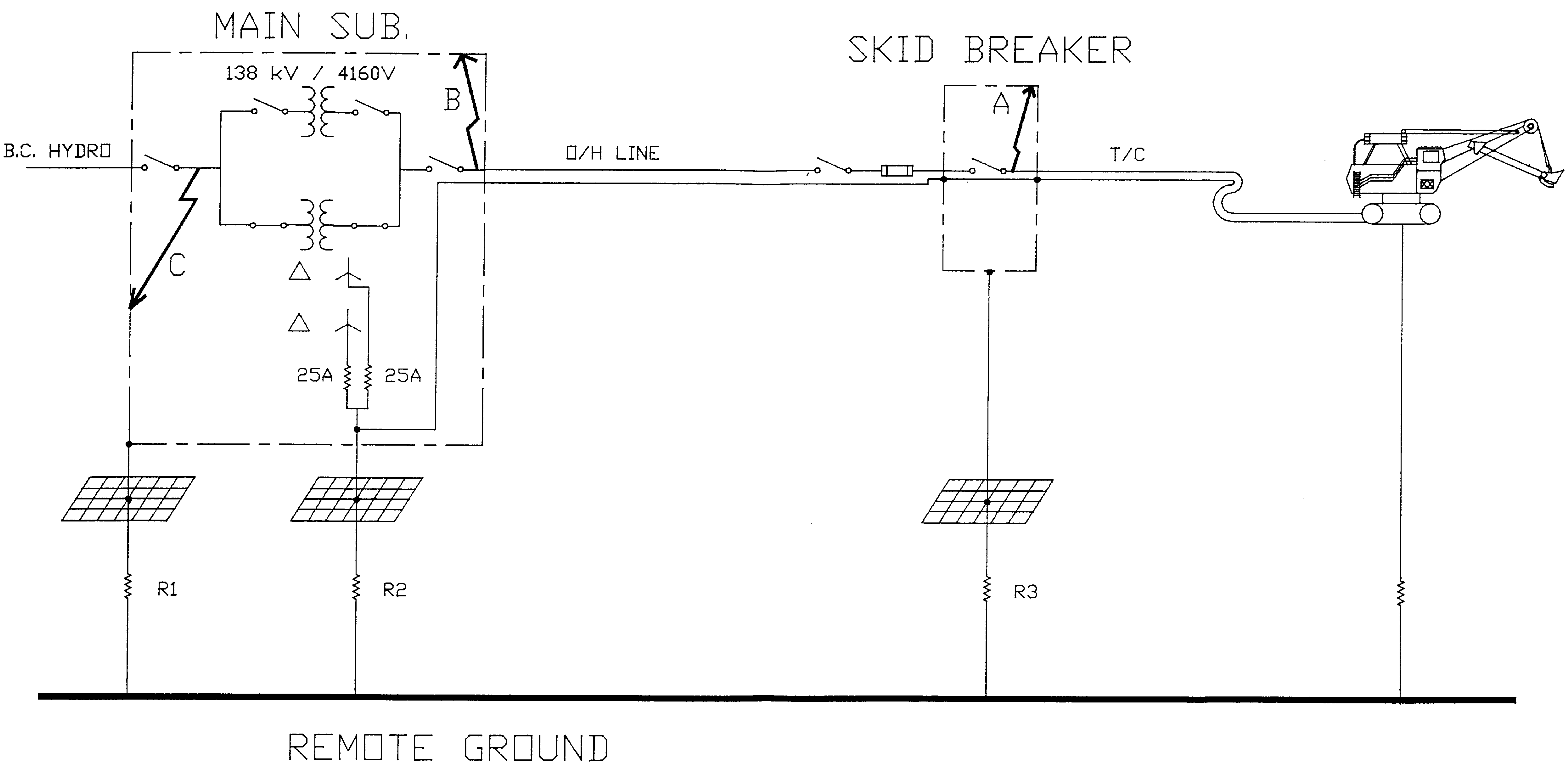

Figure II.7
Mine #6

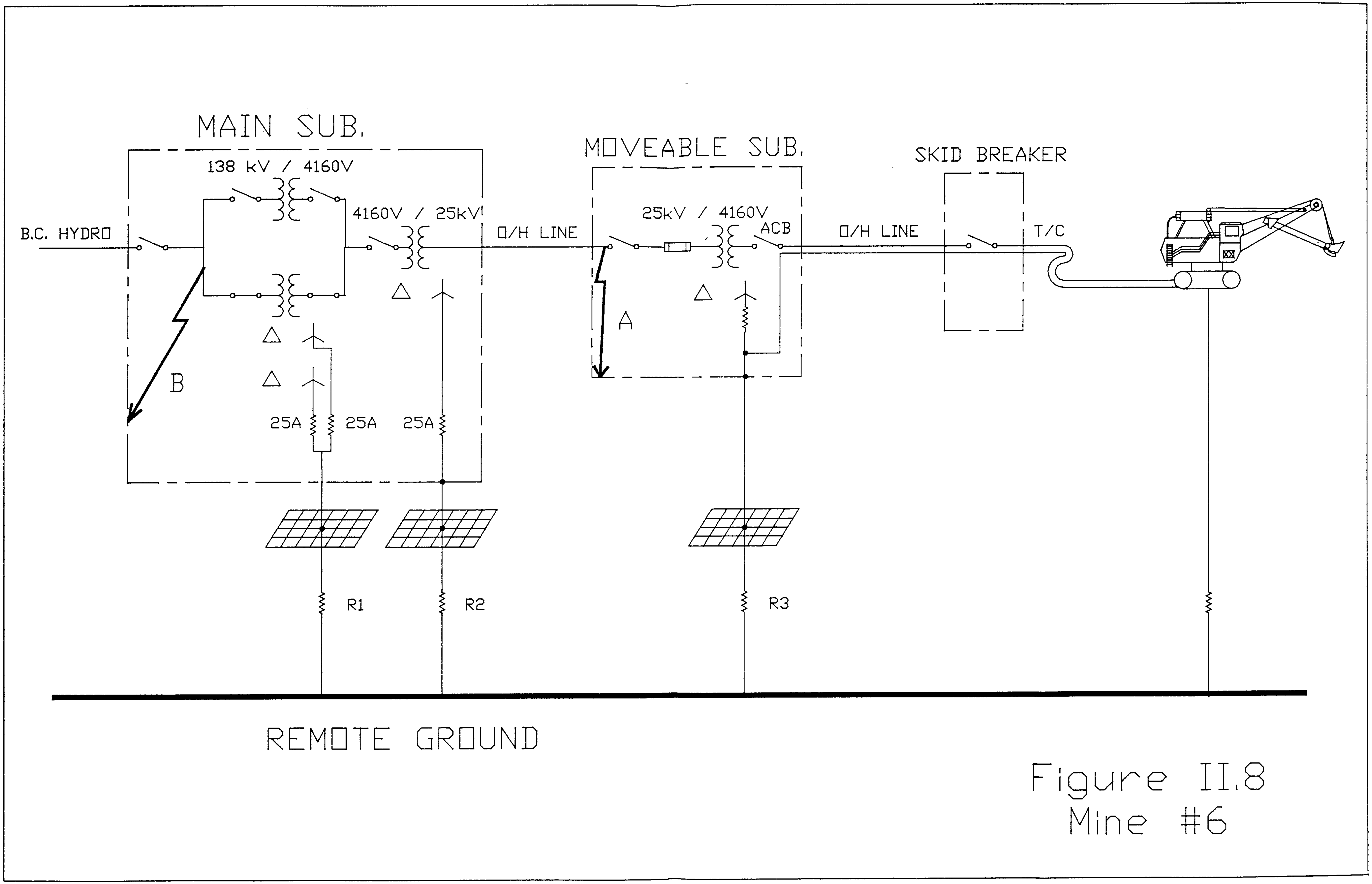

Figure II.8
Mine #6

APPENDIX III

SOIL RESISTIVITY AND GROUND BED IMPEDANCE MEASUREMENT METHODOLOGY

APPENDIX III SOIL RESISTIVITY MEASUREMENT

III.1 SOIL RESISTIVITY MEASUREMENT METHODOLOGY

The objective of soil resistivity measurement related to grounding system design and analysis, is to predict the effect of the underlying soil characteristics on the performance of the grounding system. Ideally, one could take a sample cube

$$\rho = \frac{R\,l}{A}$$

ρ - soil resistivity in ohm-metres
R - resistance between opposite faces of sample in ohms
l - length of sample in metres
A - cross sectional area of sample in square metres

Figure III.1 Equation for Resistivity of a Sample of Material

of the soil and determine its resistivity in a laboratory by placing it between two metal plates, measuring the resistance and applying the simple equation in Figure III.1:

This is not practical for a number of reasons which include:

- The soil sample is only representative of a small pocket of the native soil in the area where it was taken. It may be quite different from soil a few metres deep or a few metres away.

- Compaction, moisture content and temperature would be difficult to control while moving the sample from its natural location to the laboratory.

Although the earth's electrical characteristics vary in three dimensions as suggested above, they are usually sufficiently uniform over horizontal distances to permit the consideration of typical sites as a single structure, uniform in the horizontal dimension. Similarly, the vertical variability of resistivity can be practically described by one, or more frequently, two uniform layers of earth typically found to occur within a few metres of the surface. It must be appreciated that this earth structure model is a major simplification of the real situation, but, in practice, has been found to reasonably represent most conditions while keeping the design calculations within feasible limits, and producing acceptable design results.

Two classes of earth resistivity testing methods are in widespread use:

- Surface measurement methods where electrodes are placed on the earth surface and the underlying earth characteristics deduced from variations in these surface measurements.

- Well hole measurement methods where one or more electrodes are lowered into a well, and the earth resistivity characteristics are determined by noting the vertical variations in the results.

In the design of earth grounding structures, for electrical engineering purposes, the former surface constrained methods are almost exclusively used. The well hole methods are more commonly associated with geophysical applications and will not be discussed here.

II.1.1 Test Method

The measurement configuration most widely used, is based on a method developed by Dr. F. Wenner of the U.S. Bureau of standards, and schematically shown in Figure III.2. Using the Wenner method, four uniformly spaced measurement probes are inserted into the soil surface in a straight line. The outer pair of probes are used to inject a test current into the soil. The potential resulting from the test current is measured between the inner pair of probes to obtain an apparent resistance. It should be noted that this measurement or any measurement involving test probe to soil contact cannot be carried out using pure dc because the dc test current will polarize the electrolytic cell formed by the metal to soil contact, leading to drifting of the readings and indeterminate results. Either ac or switched, reversed dc is therefore used in most instances.

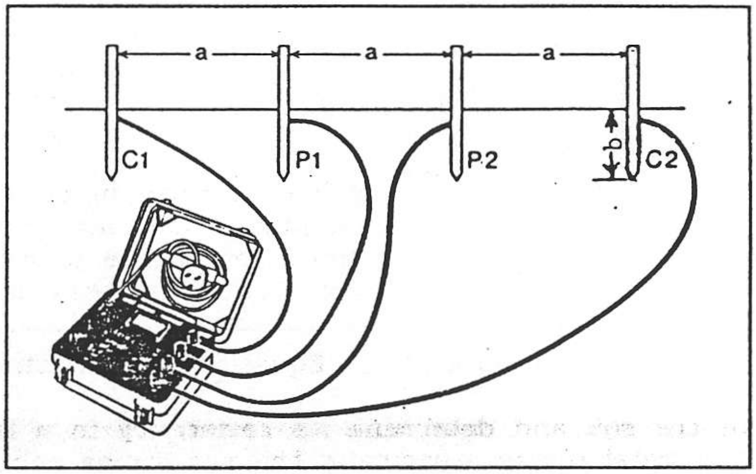

Figure III.2 Wenner Method of Determining Apparent Earth Resistivity

The simple equation in Figure III.3 can then be used to determine the apparent soil resistivity for the measurement configuration.

$$\rho = 2\pi a R$$

where:

ρ	=	apparent soil resistivity in ohm-metres
a	=	probe spacing in metres
R	=	measured apparent resistance in ohms

Figure III.3 Simple Equation for Calculating Soil Resistivity from Wenner Measurements

$$\rho = \left[\frac{4\pi a}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \right] R$$

where:

ρ	=	apparent soil resistivity in ohm-metres
R	=	ratio of induced voltage measured to source current in units of ohms
a	=	uniform probe spacing, in metres
b	=	uniform probe penetration depth, in metres

Figure III.4 Equation Widely Used for Calculating Soil Resistivity from Wenner Measurements Allowing for Probe Depth

This simple equation assumes that the probes make point contact with the surface of the soil. The more complex equation of Figure III.4 is widely used to determine the apparent resistivity from the Wenner geometry, making some allowance for the depth of the test probes:

$$\rho = \left[\frac{2\pi \ell}{2 \cdot \ln\left[\frac{2 + E}{1 + F}\right] + 2 \cdot F - E - \frac{a}{\ell}} \right] R$$

With $E = \sqrt{4 + (a / \ell)^2}$

$F = \sqrt{1 + (a / \ell)^2}$

where:

ρ	=	apparent soil resistivity in ohm-metres
R	=	ratio of induced voltage measured to source current in units of ohms
a	=	uniform probe spacing in metres
ℓ	=	length probe is driven into ground

Figure III.5 More Accurate Equation for Calculating Soil Resistivity from Wenner Measurements Allowing for Probe Depth

Unfortunately, although widely used, this equation is not correctly applied. It is true for point source electrodes at a depth equal to the probe depth, not cylindrical rods. A more accurate equation shown in Figure III.5, for cylindrical rod electrodes is developed in [2].

The error in using the simplified equations becomes insignificant for shallow probe depths and spacings greater than a few metres. Figure III.6 shows the error resulting from using the simpler equations for a probe depth of 1 metre, apparent resistance of 1 ohm and probe spacings of 1 and 10 metres.

Spacing	Depth	Exact "Rod"		"Point Source"		"Simplified"	
metres	metres	ohm-m	%	ohm-m	%	ohm-m	%
1	1	8.77	100.0	10.58	120.8	6.28	71.7
10	1	63.20	100.0	63.91	101.1	62.83	99.4

Figure III.6 Comparison of Results Using Different Equations

Generally, the probes are only driven in far enough to obtain adequate contact with the soil. Often, 0.1 metre probe depth is sufficient and the errors introduced by ignoring probe depth are relatively small.

Considering probe penetration depth to be a constant, these relations effectively describe the variation in measured resistivity as a function of probe spacing, "a". Physically, the greater the probe spacing, the greater the volume of earth encompassed by the test current in its traverse from C1 to C2 and hence the greater depth of earth involved in the measurement. The task of accurately relating the apparent resistivity measured by this procedure and the true resistivity at specific depths is complex, but to a first approximation, the apparent resistivity which is measured at probe spacing "a" may be considered indicative of the average resistivity to a depth "a".

Under certain conditions such as soil structures with a high resistivity surface layer and low resistivity deep layer, the induced potential signal can become relatively small. An unequal probe spacing method known as the Schlumberger-Palmer method can then be used to increase the potential signal by placing the potential probes nearer to the current probes. A different set of equations then applies.

III.1.2 Resistivity Measurement Instrumentation

In order to carry out resistivity measurements by the Wenner or similar methods, it is necessary to provide a source of test current, and either a means of measuring the voltage developed between the voltage sensing probes in the test electrode array, or a means of determining the ratio of test current to induced voltage.

Numerous instrumentation packages have been developed to carry out either of the above determinations. These packages vary considerably in portability, sensitivity, operating convenience and cost. According to a survey [3] of electrical utilities throughout the world, the Megger null-balance and direct ohm reading type instruments are by far the most widely used instruments for measuring earth resistivity. These instruments are both very well suited for field work, being small in size and weight and relatively easy to operate. However, the test current supplied by these and most portable instruments is relatively small, typically in the order of 40 mA. In areas of high ambient noise, very high or very low resistivity, and particularly at large probe spacings, sensitivity can be a problem and these instruments may not be suitable if accurate measurements are required. Another unfortunate aspect is that no indication of adequate probe/soil contact is given, leading to the possibility of apparently reliable but erroneous readings. This can be overcome by repeating readings with increased probe depth until constant, or inserting a milliammeter in the current loop to ensure that the test current is adequate.

To overcome the sensitivity limitations of portable instrumentation, a direct measurement technique using a voltmeter, ammeter and an ac current source, rated several hundred watts or more, can be used. In order to avoid interference problems with ambient 60 Hz fields or ground currents, it is usually necessary to use a power source which operates 5 Hz or more away from 60 Hz and to use a frequency selective voltmeter to measure the voltage between the voltage sensing points. The power source for such measurements can often be a portable generator which has been adjusted to a suitable frequency and the output transformed to an appropriate source voltage.

A portable instrument [4] introduced in the last few years, has significantly improved the state-of-the-art in portable instrumentation. Results using the Megger DET-2 Digital Earth Tester manufactured by Evershed and Vignoles in the United Kingdom indicate that soil resistivity tests can be accurately carried out to considerably wider probe spacings than the older instruments.

This instrument uses a phase sensitive detector to measure very low voltages induced by rapidly reversing (128 Hz) dc test currents of from 5 to 40 mA. The readout of apparent resistance is directly to a $3^1/_2$ digit liquid crystal display with resolution to 1 milli-ohm. The instrument also includes indication lights for high current probe resistance and excessive ambient noise.

Although the measurement results should, in theory, be free from test lead mutual coupling errors, tests have indicated that when very low impedances are being measured as is the case for low soil resistivities at wide probe spacings, the time constant due to the reactance of the test leads can introduce mutual coupling errors. Potential and current test leads should therefore be spaced as far apart as possible when carrying out wide probe spacing measurements.

A limitation in comparing this instrument with the variable frequency power source/frequency selective voltmeter method is that the two current probes must have a combined resistance of less than 7500 ohms. This may require salting and watering of current electrodes when surface soil resistivity is high.

III.1.3 Measurement Techniques

The measurement of earth resistivity using any of the instrumentation systems described previously is a relatively straightforward procedure. Obvious examples of good measurement practice such as ensuring good probe to soil contact, avoiding traverses adjacent to or across buried metallic structures and maximum separation of current and voltage leads, should always be observed.

As probe spacing increases, the susceptibility of the measurements to error increases. Instruments of the Megger category with range scales should always be operated at the maximum available sensitivity setting and should not be relied on when the most significant digit is down to zero, i.e. with two digit accuracy. When using Megger instruments of the type which do not provide current probe high resistance indication, it can be helpful to insert a milliammeter in series with the current leads, to monitor the applied test current. A drop in test current of 10% or less with a hand-cranked or vibrator type of instrument can often indicate a poor current probe contact and a possibly suspect reading.

One of the most common faults in resistivity measurements is a failure to take measurements out to sufficiently wide probe spacings. Ideally, the maximum probe spacing should equal the dimensions of the electrode under consideration which extends the traverse to three times the electrode dimensions. In many cases this may not be possible and measurements should be taken to as wide a probe spacing as is possible.

At very large probe spacings, coupling between the voltage and current leads and interference in the voltage sensing leads can introduce measurement errors. Voltage and current leads should be separated as much as possible and probe resistances kept as low as possible. Mutual coupling between voltage and current leads will not normally be a problem if the measured apparent resistance is greater than 0.5 ohms. Below this, caution must be exercised.

A source of coupling between voltage and current leads that is often overlooked is the close proximity of test lead spools. Significant coupling can result when two spools are located close to each other with their centres on a common axis. The spools should always be separated as much as possible and oriented with the spool axes at right angles.

The reliability of field measurements can be improved considerably if the apparent resistivity for each probe spacing is calculated and plotted as the measurements are being taken. In this way, discontinuities in the measurements can be observed immediately and the source of the discontinuity identified. Buried pipes, tanks, recently excavated and filled areas and rock outcroppings are all examples of sources of discontinuities in resistivity data. Such anomalies should be identified, logged, and a determination as to whether or not the disturbance is entirely localized and can be ignored, or should be taken into account in the development of an appropriate soil model.

At each location, if the site restraints permit, two soil resistivity traverses should be taken at right angles to each other. The results should be similar and the average used.

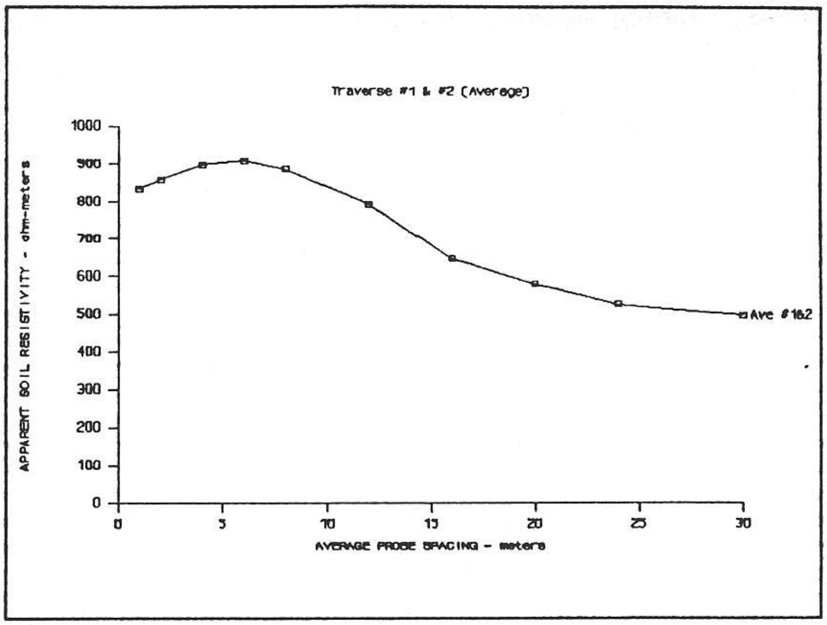

Figure III.7 Results of Typical Soil Resistivity Measurement at a Mine

III.1.4 <u>Interpretation</u>

Soil resistivity is often variable with depth and location making it difficult to model an actual soil for grounding calculation purposes. Fortunately, experience has shown that analysis of ground systems in a layered equivalent soil model can give a good approximation to the true situation.

The measurement results should be plotted. Figure III.7 shows the results of a typical soil resistivity measurement which has a change in resistivity with probe spacing.

As a first approximation, the results at a particular probe spacing can be taken to be an indication of the average soil resistivity to a depth equal to the spacing between the probes. This can be used to determine an equivalent layered resistivity model by inspection of the curve. The IEEE Guide for Measuring Earth Resistivity [5] discusses the interpretation of resistivity measurements and mentions techniques described by Gish and Rooney [6] and Lancaster-Jones [7] to interpret resistivity measurements. The Gish and Rooney method assumes that another resistivity layer is reached at a depth equal to the probe spacing where a break or change in curvature of the resistivity curve occurs. The Lancaster Jones method estimates the depth to the lower layer as $^2/_3$ of the probe spacing at which a point of inflection occurs.

Looking at the plot of Figure III.7, using the Gish and Rooney method, one might interpret them to indicate an equivalent two layer soil model with:

Upper layer resistivity	900 ohm metres
Upper layer height	15 metres
Deep layer resistivity	500 ohm metres

To be preferred, however, an analytical curve fitting method such as described

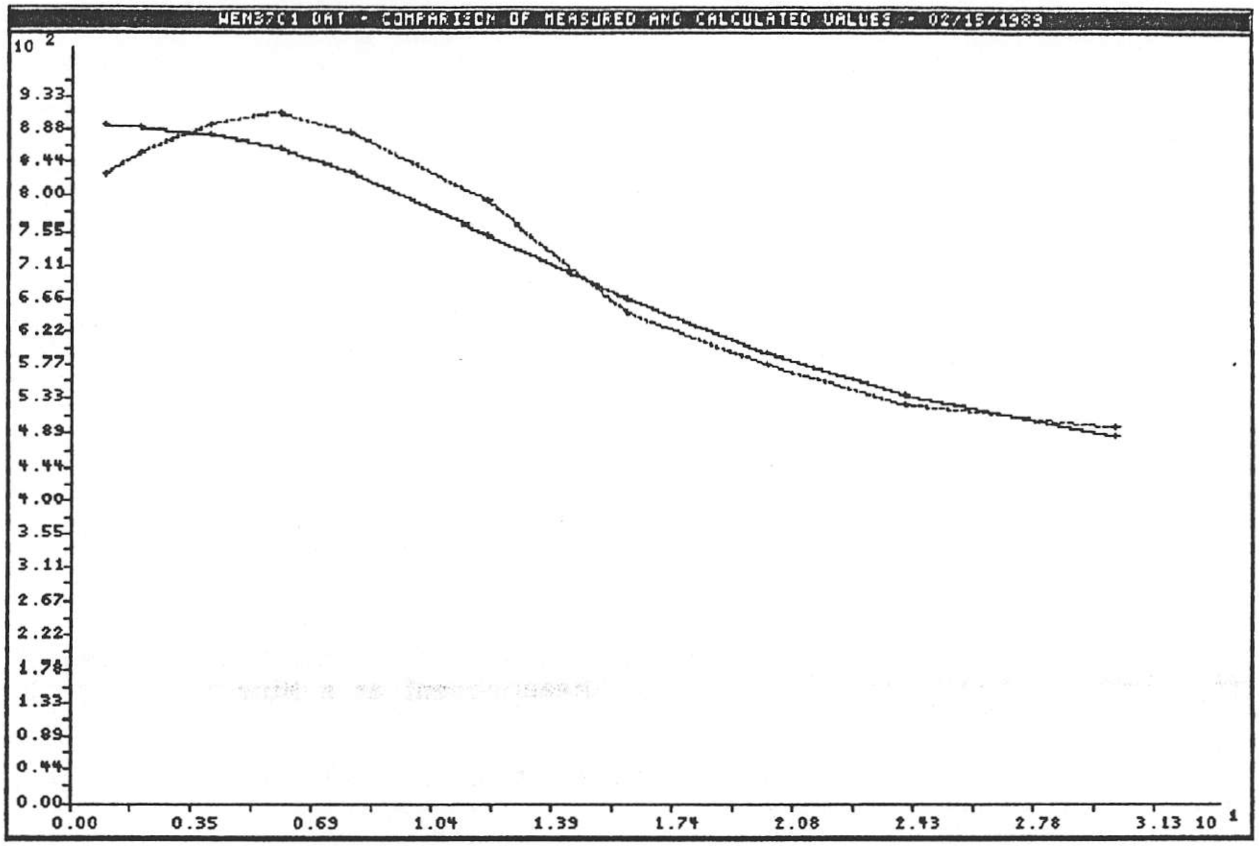

Figure III.8 Two Layer Equivalent Soil Model Curve Fit to Measurement Data

in Appendix B of [5], can be used to generate an equivalent layered soil model from the field measurement data. Figure III.8 shows the results of a curve fit for the measurement data of Figure III.7. The equivalent soil model is:

Upper layer resistivity	893.5 ohm metres
Upper layer height	11.28 metres
Deep layer resistivity	368.88 ohm metres

Measurement conditions and analysis requirements rarely require more than a two horizontal layer equivalent soil model.

The computer model generation can often resolve a series of measurements, which when plotted show a continued trend that cannot readily be resolved into an equivalent layered structure by inspection. Use of such a program can be valuable even in cases where an approximate uniform soil resistivity value is required, because a more definite two layer model can be used to determine the most appropriate uniform model depending on the depth and area encompassed by the ground system.

The soil resistivity nearer the surface is generally more variable than the deeper layers. It is therefore necessary to take measurements at relatively wide probe spacings to obtain a complete picture of the soil structure. The upper layers can also be affected by climatic changes. When the upper layers freeze, the resistivity increases dramatically to 4 to 10 times the unfrozen value. Rain or drought may also have an effect on the upper layer resistivity, however, this is believed to be fairly minor as the soil resistivity stabilizes once the moisture content reaches around 18%. Except for very near the surface, say less than 1 metre deep and for well drained, sandy soils, the effect of rain is minimal.

III.2 GROUND BED IMPEDANCE MEASUREMENT

Given the uncertainties in soil resistivity measurement and ground bed design calculations, the impedance of ground beds should be measured after construction. For small ground beds such as are associated with open pit mobile mining equipment grounding, the measured impedance can be considered as a pure resistance.

4.1 General Description

The principle of ground electrode impedance measurements is illustrated in Figure III.9 which shows, in schematic form, an earth electrode to be tested, a return electrode, which can be any other ground electrode sufficiently distant from the test electrode, and a power source which is used to pass current between the two electrodes. The measurement objective is to determine the rise in potential of the test electrode with respect to remote earth as a result of the test current, I.

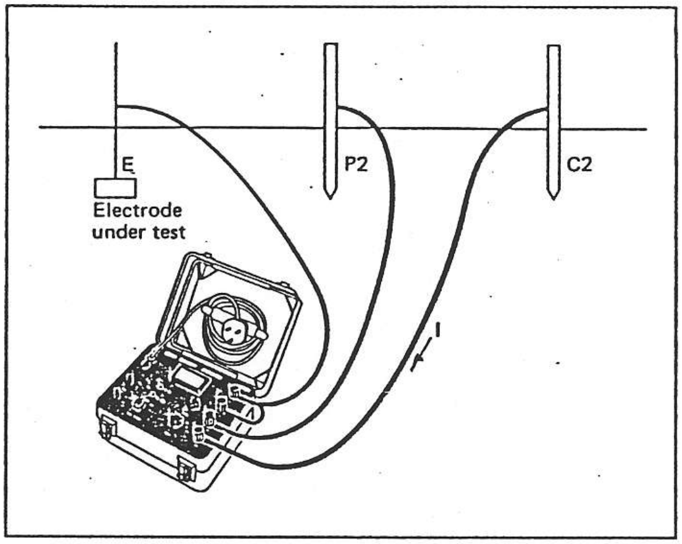

Figure III.9 Idealized Ground Impedance Measurement

The principle difficulty encountered in ground impedance measurements is in locating a suitable return electrode. To facilitate proper measurements, the electrode under test and return electrode must be completely isolated as far as any metallic conduction paths are concerned. If an existing structure is to be used as a return electrode, assurances must be obtained that there are no metallic connections, however indirect, between the two grounds. In practical terms, this assurance is very difficult to obtain and consequently, an electrode is usually constructed for the purpose of the tests. The requirements for the return electrode are dictated, to a large extent, by the characteristics of the electrode being measured, and, to a lesser degree, by the soil conditions. In general, the measurement problems become more difficult as the impedance of the test electrode decreases, as the dimensions of the test electrode increase and as the soil resistivity increases.

If it were possible to readily define an ideal remote ground reference point for any ground electrode impedance measurement and if the isolation of the test and return electrodes could always be assured, impedance measurement would be a very simple process as illustrated in Figure III.9. One voltage measurement between remote ground and the test electrode for a given test current would yield the desired result. In practice however, neither an ideal remote reference point nor an assurance of isolation is obtainable and a measurement technique must be used which compensates for, or identifies deviations from the ideal arrangement so that meaningful results can be obtained. One additional factor which is normally encountered in practice is electrical interference which may obscure the desired voltage readings or introduce erroneous data. This factor must also be accounted for in the measurement process.

There are three principal methods used to measure impedance of ground electrodes; the two-point method, the three-point method and the fall-of-potential method [5]. The fall-of-potential method is by far the most widely used in the electrical industry according to a survey conducted in 1976 [3].

III.2.2 Two Point Test Method

In this method the total loop impedance of the unknown and return ground electrodes is measured. The impedance of the return electrode is assumed to be negligible in comparison with the impedance of the unknown ground and the measured value in ohms is assumed to be the impedance of the unknown ground. The technique is obviously limited to the measurement of relatively high impedance grounds, such as a single ground rod, or small ground rod array where a suitable low resistance reference such as a buried metal water main exists. It is not practical for mining ground bed measurement.

III.2.3 Three Point Test Method

The three-point method involves the use of two auxiliary ground impedances designated r_2 and r_3. The unknown ground impedance r_1 is determined by

$$r_1 = \frac{(r_{12}) - (r_{23}) + r(_{13})}{2}$$

Figure III.10 Equation for Three Point Test Method

measuring the impedance between each pair of grounds and solving for r_1 from the equation in Figure III.10.

There are several limitations to this technique which restrict its use to the measurement of small, high impedance grounds in areas where the three grounds can be located well out of the zone of influence of each other.

Since neither this method nor the two-point method have any built-in checks to assure that significant errors are not being introduced into the measurements, the fall-of-potential technique has become the universally accepted test method. The two and three-point methods should only be used to obtain rough estimates of ground impedance or to perform repeated measurements for experimental purposes once the adequacy of the test configuration has been independently verified.

III.2 Fall-of-Potential Method

The fall-of-potential method of impedance determination involves the use of an auxiliary return current electrode and a series of surface potential measurements taken at increasing distances from the unknown electrode. Provided that the auxiliary electrode has been located sufficiently remote from the unknown electrode and coupling effects between voltage and current leads have not affected readings, the potential measurements will become asymptotic to a level which represents the rise in potential of the unknown electrode due to the test current. The general arrangement of electrodes is shown in Figure III.11. Current electrode C1 and the fixed potential electrode P1 are located on the unknown electrode. The remote auxiliary current electrode is designated C2. The IEEE Guide [5] recommends that the C2 electrode be placed 50 metres away for measuring small area grounds such as driven rods and tower footings. The potential electrode P2 is located at regular intervals moving away from P1 and voltage and current readings taken at each P2 location. An apparent impedance value is determined from each set of voltage and current readings. If the apparent impedance is plotted against distance, a levelling off of the apparent impedance values will be observed as the potential probe P2 becomes remote from the unknown electrode.

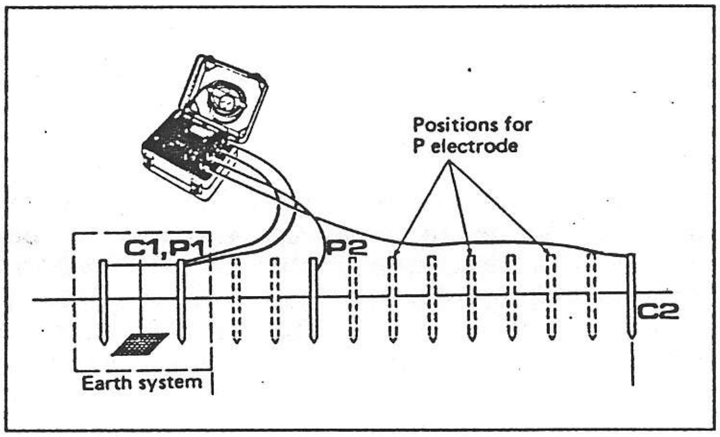

Figure III.11 Fall-of-Potential Impedance Measurement Illustration

There are two variations in the fall-of-potential method that are commonly used. The difference in the two methods is in the direction that the voltage profile is taken with respect to the current probe. The first alternative and the one most commonly used by utilities [3] in measuring the impedance of transmission towers and substations, employs a potential traverse between the unknown electrode and the remote current electrode. As for soil resistivity measurements, pure dc cannot be used as a test signal because of polarization of the metal to soil interface at the ground and return electrodes. An ac or switched reversed dc signal is therefore generally used. If ac is used, there will be inductive coupling between the test current lead and the potential lead where they are laid out parallel to each other. The coupling becomes significant at ground impedances of 1 ohm with test leads run out say 200 metres, and cannot be reduced much by spacing the test leads wider apart.

The second method is used to reduce the inductive coupling error of the first. In this method, the potential traverse is run out in the opposite direction or at right angles to the direction of the remote current probe. This method is primarily used in the measurement of impedance of very large ground electrodes but does have some limitations, as will be discussed.

If the unknown impedance is approximately one ohm or larger and the return electrode has been adequately located, a potential profile taken from the unknown electrode towards the return current electrode (method 1) will look similar to the curve of Figure III.12.

A distinct flat portion of the curve, indicating a zone under the influence of neither the unknown nor the return electrodes, can readily be observed. The apparent impedance observed in this portion of the curve is the impedance of the unknown electrode. The IEEE Guide [5] shows that for small ground electrodes, under ideal conditions, the correct impedance is obtained when the P2 potential reference is located 61.8% of the distance towards the C2 electrode. In many cases, however, the C2 reference cannot be placed far enough away, the curve obtained during a fall-of-potential measurements does not resemble the curve of Figure III.12 and other interpretation procedures must be applied to make use of the data or to correct the test setup. Some of these methods are referenced in the IEEE Guide [5].

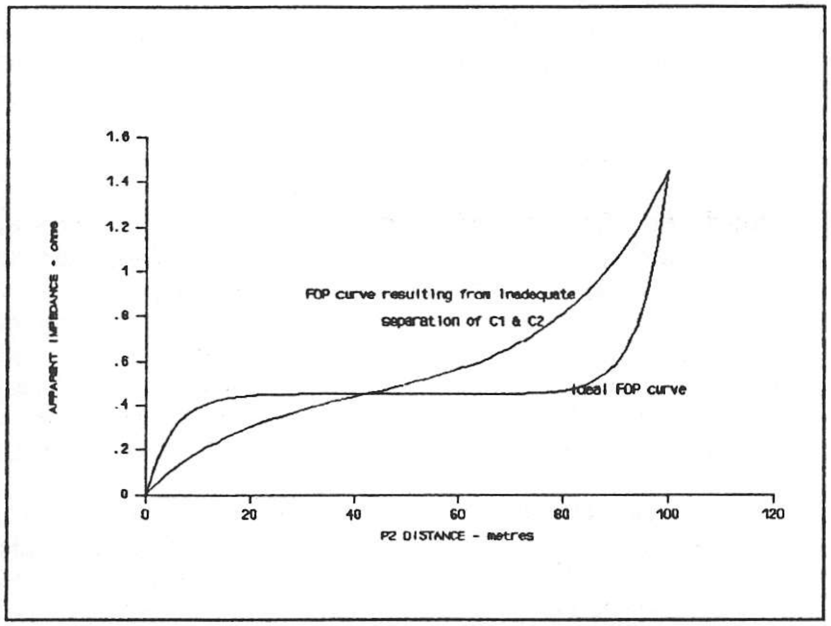

Figure III.12 Fall-of-Potential Curve Illustration

III.2.5 <u>Interpretation of Fall-of-Potential Data</u>

In order to carry out accurate impedance measurements using the fall-of-potential method, it is important that the theoretical limitations of the technique are understood. It is also important that the engineer or technologist conducting the measurement appreciate the effect that various deficiencies in a test setup will have on measurement data so that the deficiencies can be corrected on site and useful measurement data obtained.

As stated previously, the difficulties encountered with fall-of-potential measurements increase as the size of the ground electrode being measured increases and the impedance to be measured decreases [8]. The reasons for this increased difficulty in carrying out impedance measurements are numerous.

First, as the impedance of an unknown electrode decreases, the voltages to be measured in the vicinity of the electrode become lower while the electrical interference usually becomes greater because of increased power distribution at the large sites, be they substations or industrial facilities. For example, a large substation in an area of low resistivity could have an impedance of 0.25 ohms or less. The typical test current from a portable "Megger" type instrument is in the order of 40 mA. This combination results in a total induced voltage of 10 millivolts or less in the unknown electrode. Since it is not uncommon for residual voltages in the order of 1 to 10 volts to be present in a large grounding system, accurate measurement or even detection of the test signal can be a major problem.

Second, as the size of a greunding system increases, the zone of influence of the grounding system increases and it becomes more difficult to establish a return electrode that is completely isolated from the electrode being tested. For any facility other than a large utility substation, the problem is usually compounded by connection of numerous external grounds such as water mains, gas pipes, communication circuits and low voltage distribution neutrals to the main ground. These connections can effectively extend the zone of influence of the unknown ground considerably and in an unpredictable pattern.

Another significant, but less understood factor affecting fall-of-potential measurements, is soil structure. When the soil structure is not uniform, the shape of the fall-of-potential curve can be noticeably affected, as can the correct potential probe location for determining the true impedance of the unknown electrode when the traverse follows the same direction as the remote current probe.

The effects of soil structure on fall-of-potential measurements are discussed extensively in reference [8]. Generally, the zone of influence around a ground electrode in two-layered soil which has a higher resistivity deep layer is greater than one in soil with a lower resistivity deep layer. This effect can be best understood by considering the path of least impedance for current leaving the ground electrode. When the surface layer is more conductive than the bottom layer, ground currents will tend to flow out horizontally rather than penetrate the higher resistivity layer below. This effect can make accurate impedance measurements very difficult to obtain in areas where a ground electrode is buried in soil overlying bedrock or other high resistivity sub-layers.

Fortunately in measurements related to mobile and moveable mining equipment ground beds, the ground beds are often quite small, there is adequate space to locate the current return electrode say 10 times the dimension of the ground bed away, the soil is fairly uniform and undisturbed by buried metal and resistances are above the 1 ohm level where problems may be experienced. However, due to the relatively high ground impedance and operation of heavy equipment drawing several MW, noise levels can be quite high and equipment may have to be shut down before impedance measurements can be carried out.

III.2.6 Ground Impedance Measurement Instrumentation

The instrumentation required to carry out accurate ground impedance measurements depends, very significantly, on the structure being measured, soil conditions, and ambient electrical noise levels at the measurement site. For small, high impedance ground electrodes such as ground rods, transmission line towers or small substations, portable earth testers such as the "Megger" null-balance or direct reading earth testers such as the "Vibraground", are the most commonly used instruments [3]. The limitations of these instruments become apparent as the impedance being measured drops below 1 ohm and ambient electrical noise levels increase.

III.2.7 Portable Earth Testers

There are several models of portable earth testers on the market. Most employ either a hand crank magneto or internal battery powered inverter as a power source and some type of bridge circuit to simultaneously detect voltage and current and give a readout in ohms when the instrument is balanced. The most commonly used instruments of this type [3], the "Megger" hand cranked and battery powered earth testers, give a 3 digit readout in ohms via the three decade dials used to null the instrument galvanometer. A range selector switch is used to select a full scale reading of 9.99, 99.9, 999 or 9990 ohms. The hand-cranked version of the "Megger" instrument, by generating a variable frequency ac signal, dependant on the speed with which the handle is cranked, is somewhat less sensitive to stray ground currents than the battery powered models. As with all instruments of these types, the resolution becomes very poor as the measured apparent impedance drops to 1 ohm and below. In spite of some manufacturer's claims to the contrary, measurements below 1 ohm with most portable instruments should be considered as approximate at best. All instruments of this type can be used to carry out measurements by any one of the three methods described in section III.2.2 through III.2.4.

A recently introduced portable instrument, the Evershed and Vignoles Megger DET-2 digital earth tester [4] has significantly improved the state-of-the-art in portable instrumentation. Results using the DET-2 indicate that ground impedances as low as 0.1 ohms can be accurately measured, even in the presence of high ambient noise levels. Although the measurement result should, in theory, be free from test lead mutual coupling errors, tests have indicated that when very low impedances are being measured, the time constant due to the reactance of the test leads can introduce mutual coupling errors. Potential and current test leads should therefore be oriented at 90 degrees and the use of partially wound measuring spools should be avoided to reduce circuit inductance when measurements of the order of 0.1 ohms are being attempted with this instrument.

III.2.8 Voltmeter/Ammeter Method

Measuring instruments employing a null-balance bridge have offered an advantage of drawing no current through the voltage sensing leads in the balanced condition. Now, however, the availability of inexpensive, high impedance (greater than 1 megohm) direct reading digital voltmeters has made the voltmeter/ammetertechnique quite practical for ground impedance measurements. The main advantage this method offers over the use of portable earth testers is in the increased amount of current that can be passed between the ground electrode and reference current probe. The disadvantage is in considerably increased complexity and bulk of measurement apparatus.

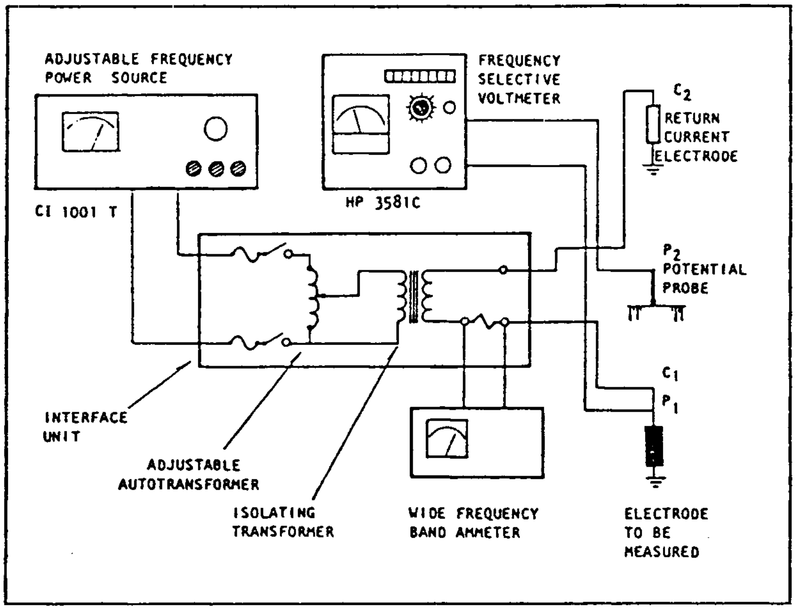

Figure III.13 High Current Voltmeter/Ammeter Test Configuration

A typical voltmeter/ammeter test setup for measuring earth impedance is shown in Figure III.13. The interface unit shown in Figure III.13 contains a variable transformer ("Variac") as well as step-up and step-down transformers for accommodating a wide range of loop impedances. Such equipment is usually constructed by the user or purchased as a custom assembly to meet specific testing requirements. The primary disadvantage of the arrangement shown in Figure III.13 is the inability to distinguish between ambient power frequency signals and the test signal. The setup is only suitable when the voltages induced in the earth by the test current significantly exceed the stray voltage levels. This may not always be possible, particularly with ground impedances in the range of 0.5 ohms or less.

A significant improvement in the usefulness of the circuit of Figure III.13 can be obtained if the frequency of the power source used can be adjusted to 5 Hz or more away from the frequency of the ambient interference and a frequency selective voltmeter substituted for the wide bandwidth digital meter shown. A meter such as the Hewlett Packard 3581C is capable of resolving a 3 Hz bandwidth signal with excellent rejection of out-of-band signals. Thus, test signal voltages well below the level of ambient interference can readily be measured with an accuracy of typically 1%.

An alternative, though even more complex, method which achieves similar results to the variable frequency power source/frequency selective voltmeter method is described in Reference [9]. In this method, a noise source is used and the current and voltage signals are simultaneously analyzed using a Fast Fourier Transform Digital Signal Analyzer, resulting in a "spectrum" measurement, typically from 0 to 400 Hz. Background 60 Hz and higher harmonic signals appear as peaks in this spectrum, but by drawing a smooth curve ignoring these peaks, the impedance at any frequency in the range can be interpolated.

It is also often possible to take dc measurements by injecting dc into the grid and measuring the potential rise with a digital meter. The dc test current can be generated by incorporating a bridge rectifier in the interface unit. In most instances, a significant polarizing potential will be found to exist before any test current is applied. The test current will cause the polarizing potential to drift, leading to indistinct readings. If the meter used has an offset feature and the injected current polarity is reversed about once per second, the dc polarization effects can be minimized. These readings are free of test lead coupling errors and form a useful addition to an overall understanding of the ground system impedance.

As the impedances of ground beds associated with mobile and moveable mining equipment are generally greater than 1 ohm, the more sophisticated measurement methods are not necessary and simple "Megger" type instruments can be effectively applied.

APPENDIX IV

GROUNDING PROGRAM DESCRIPTION AND SAMPLE FILES

APPENDIX IV GROUNDING PROGRAM DESCRIPTION AND SAMPLE FILES

The computer program KWIKGRID is a ground electrode analysis program developed by BSA for the IBM PC and compatible machines. The program was developed as part of the ongoing improvements in analytical techniques at BSA. It allows work to be done in house that would previously have required the use of a time share computer system.

Computer programs which analyze ground electrode performance are generally based on the concept that the electrode consists of a number of smaller conductor segments, each of which injects current into the soil. The current flowing from a segment causes potential rise in the soil and at every other segment. This is described as a mutual resistance between the injecting segment and the segment experiencing the potential rise. Each segment is therefore subject to a cumulative potential rise due to the currents injected by all the segments (including itself). The problem reduces to determining the mutual and self resistances and solving a set of simultaneous equations equal in number to the number of segments in the model. These are usually represented in matrix form and matrix based methods are used to solve them.

The program is based on Reference [10]. The program enables modeling of a ground electrode as an arrangement of buried conductors in the soil. It will calculate the resistance of the ground electrode and soil potentials at any point.

Some of the program applications are:

- Substation ground grid design. By calculating soil potentials, step and touch potentials can be determined. The ground grid design can then be modified to achieve desired step and touch potential limits or ground resistance. Also, for example, the effects of a frozen upper soil layer on touch potentials and the addition of rods to a grid, can be investigated.

- Interpretation or verification of grounding field measurements. For example, fall-of-potential resistance measurements of large ground systems where the reference electrodes cannot be placed far enough away, can be modeled to determine the effect of the test electrodes on the true resistance.

- Investigation of transfer of potential between energized grids and other structures. For example, calculation of soil potentials around a pipeline which is near a substation or transmission tower footing or the coupling between an "isolated" electronic equipment ground and the adjacent plant ground system formed by the plant footings.

- Determination of cathodic protection current flow. The program calculates flow of current into or out of each conductor segment. This can be used to assess the effectiveness of cathodic protection systems or their effect on other adjacent conductive systems.

The ground electrode may be a single structure with user specified injected current or several structures, some of which have injected currents. When analyzing electrodes in two-layer soils, the user can specify the accuracy to be used in the calculations.

The present program limitations are:

- Electrode conductors are assumed to have zero internal resistance so that the same potential will appear on all conductors of the same buried structure. All conductors of one electrode structure are therefore assumed to be interconnected even if some distance apart. A version of the program which allows several separate ground systems to be interconnected by complex impedances has been developed.

- Conductors must be horizontal in an east-west or north-south direction or vertical. They can have any specified radius and length. Conductors which cross the upper/deep soil layer interface, are automatically subdivided into two segments, one in each layer. The user can also select to have the program subdivide any conductor into a number of smaller segments to improve calculation accuracy.

- The soil may have a uniform resistivity or be two-layered where the upper layer has a resistivity either larger or smaller than the deep layer. The layer can be any thickness.

The data is prepared in an text file which is read by the program. The input consists of:

- Lines of user entered run description.

- Flags to indicate calculations required. For a first run with a particular model, the resistance matrix must be developed and solved. If no changes are made to the model configuration and subsequent runs are required only to calculate soil potentials at other locations, the matrix does not have to be developed and solved again. For large models, this can result in a considerable saving in computation time. The user must also specify whether the model is a single structure or multiple structures and whether soil potentials are to be calculated.

- Resistance matrix calculation accuracy. This is only required for two layer soils and defaults to 0.001 p.u. (or 0.1%). When calculations are carried out in two layer soil models, the mutual resistance is calculated from an infinite series. This parameter stops the infinite series calculation at a point where the error due to ignoring the remaining terms will be less than the selected accuracy. In uniform soils, the mutual resistance calculation has only two terms.

- Soil model data. Upper and deep layer resistivity and depth of upper layer.

- Current injected into the main electrode.

- Configuration of the main electrode. This is specified as a series of lines of data. Each line contains the x,y,z coordinates of the conductor ends related to an x and y axis location selected by the user. The positive z-axis is downward with zero at the soil surface. x and y may have any values. z may only be positive. Conductors must be buried to at least the depth of their radius. The data line also contains the conductor radius and desired subdivision. The program checks that the conductors are parallel to either the x, y or z axis and that no two conductors occupy the exact same location.

- Soil potential calculation locations. These are specified as a starting x,y,z coordinate using the same axis as the conductor data and x and/or y and/or z increment. Soil potential profiles can therefore be calculated in any direction.

- Other structure information. Current injected into other structures and the configuration of the conductors must be specified as for the main electrode.

The program output is sent to a file. The output consists of:

- Run start time and date.

- Lines of user entered run description.

- Soil model data and accuracy value used.

- Conductor segment configuration of the model after subdivision.

- Potential rise of each structure. In the case of structures with injected current, the injected current and structure ground resistance are also output.

- Detailed current flow from or to (-ve) each conductor segment in each structure with the accumulated total for each structure.

- Soil potentials at the locations specified.

- Run end time and date.

A separate program is used to plot the input data on a graphics screen with the option to print it in higher resolution on a matrix printer. The plots can be plan or isometric view. This is a useful check on the entry of bad data such as misplaced decimal points which show up as conductors that are too short or too long or at unexpected angles.

Another program can be used to interpolate equipotential contour lines from an array of typically 1,444 soil potential calculations. The procedure is to use KWIKGRID to calculate soil potentials at regularly spaced intervals in the area of interest. The contour program then uses the calculated soil potential information to plot the equipotential contours.

APPENDIX IV GROUNDING PROGRAM DESCRIPTION AND SAMPLE FILES

Some anticipated enhancements to be made to the program are:

- Considerable speed improvement in evaluating the infinite series.
- Option to include the impedance of grid conductors.
- Contour plotting on a digital pen plotter with better resolution.

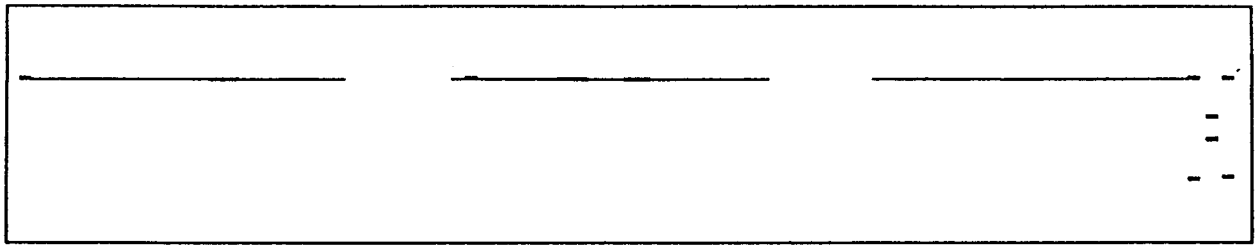

Figure IV.1 Plot of Ground Bed Model Showing Remote Electrode Placement and Fall-of-Potential Traverse

The following is a sample input data file for the program. It was used for this project to simulate the measurement of a ground bed at Mine #2 using references placed at 100 and 62 metres. See Section 4.3 in the main body of the report.

APPENDIX IV GROUNDING PROGRAM DESCRIPTION AND SAMPLE FILES

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PROJECT 4137. Mine #2, North feeder line C old equipment ground bed
Model of ground bed with test rods at 62 m & 100 locations.
Resistivity: Upper layer 151.36 ohm-meters 2.67 meters deep
          Deep layer 352.08 ohm-meters.
Data prepared by Esmond Chow, Dec 1, 1988.
FILE # KDA3702
END
888 0
0100
9
             .001
151.36352.082.67
1000.0
6
       0.0     0.0     .1     0.0     0.0     3.1     .019  4  1
       7.9     0.0     3.1    7.9     0.0     .1      .019  4  2
       3.      1.5     .1     3.      1.5     3.1     .019  4  3
       4.8     1.5     3.1    4.8     1.5     .1      .019  4  4
       0.0     3.      .1     0.0     3.      3.1     .019  4  5
       7.7     3.      3.1    7.7     3.      .1      .019  4  6
888999
Inactive Flag
1  1
-1000.0
1
       0.0     -100.0  .3     0.0     -100.0  .1      .013  1  7
1
       0.0     -62.0   .1     0.0     -62.0   .3      .013  1  8
888888
    1
 51    0.0     0.0     0.0    0.0     -2.0    0.0
999
```

The following are the results from the above input data file:

TIME: 10:54:55 DATE: 12/01/1988

PROJECT 4137. Mine #2, North feeder line C old equipment ground bed
Model of ground bed with test rods at 62 m & 100 locations.
Resistivity: Upper layer 151.36 ohm-meters 2.67 meters deep
Deep layer 352.08 ohm-meters.
Data prepared by Esmond Chow, Dec 1, 1988.
FILE # KDA3702

Upper layer resistivity: 151.3600 ohm-meters, depth 2.6700 meters.
Deep layer resistivity 352.0800 ohm-meters.

Calculation accuracy selected: 0.001000, used: 0.001000

#	X origin	Y origin	Z origin	X extrem	Y extrem	Z extrem	Radius
Structure: 1							
1	0.0000	0.0000	0.1000	0.0000	0.0000	0.9503	0.0190
2	7.9000	0.0000	0.1000	7.9000	0.0000	0.9503	0.0190
3	3.0000	1.5000	0.1000	3.0000	1.5000	0.9503	0.0190
4	4.8000	1.5000	0.1000	4.8000	1.5000	0.9503	0.0190
5	0.0000	3.0000	0.1000	0.0000	3.0000	0.9503	0.0190
6	7.7000	3.0000	0.1000	7.7000	3.0000	0.9503	0.0190
7	0.0000	0.0000	2.6890	0.0000	0.0000	3.1000	0.0190
8	7.9000	0.0000	2.6890	7.9000	0.0000	3.1000	0.0190
9	3.0000	1.5000	2.6890	3.0000	1.5000	3.1000	0.0190
10	4.8000	1.5000	2.6890	4.8000	1.5000	3.1000	0.0190
11	0.0000	3.0000	2.6890	0.0000	3.0000	3.1000	0.0190
12	7.7000	3.0000	2.6890	7.7000	3.0000	3.1000	0.0190
13	0.0000	0.0000	0.9503	0.0000	0.0000	1.8007	0.0190
14	0.0000	0.0000	1.8007	0.0000	0.0000	2.6510	0.0190
15	7.9000	0.0000	0.9503	7.9000	0.0000	1.8007	0.0190
16	7.9000	0.0000	1.8007	7.9000	0.0000	2.6510	0.0190
17	3.0000	1.5000	0.9503	3.0000	1.5000	1.8007	0.0190
18	3.0000	1.5000	1.8007	3.0000	1.5000	2.6510	0.0190
19	4.8000	1.5000	0.9503	4.8000	1.5000	1.8007	0.0190
20	4.8000	1.5000	1.8007	4.8000	1.5000	2.6510	0.0190
21	0.0000	3.0000	0.9503	0.0000	3.0000	1.8007	0.0190
22	0.0000	3.0000	1.8007	0.0000	3.0000	2.6510	0.0190
23	7.7000	3.0000	0.9503	7.7000	3.0000	1.8007	0.0190
24	7.7000	3.0000	1.8007	7.7000	3.0000	2.6510	0.0190
Structure: 2							
25	0.0000	-100.0000	0.3000	0.0000	-100.0000	0.1000	0.0130
Structure: 3							
26	0.0000	-62.0000	0.1000	0.0000	-62.0000	0.3000	0.0130

Maximum number of series terms required 8
Average number of series terms used 5

No.1 Main Electrode. Injected Current: 1000.0000 amps
Potential Rise: 15425.5405 volts, Resistance: 15.4255 ohms

Cond #	length	amps/meter	amps to soil	cum amps
1	0.850	64.46967619	54.8207147	54.820715
2	0.850	64.98748034	55.2610208	110.081735
3	0.850	49.52598341	42.1135946	152.195330
4	0.850	49.52066781	42.1090745	194.304405
5	0.850	64.30341547	54.6793376	248.983742
6	0.850	63.79170875	54.2442163	303.227958
7	0.411	39.39294521	16.1905005	319.418459
8	0.411	39.62800307	16.2871093	335.705568
9	0.411	32.61794865	13.4059769	349.111545
10	0.411	32.61604902	13.4051961	362.516741
11	0.411	39.30304543	16.1535517	378.670293
12	0.411	39.06652301	16.0563410	394.726634
13	0.850	61.27463402	52.1038638	446.830498
14	0.850	66.59201395	56.6254092	503.455907
15	0.850	61.74792071	52.5063152	555.962222
16	0.850	67.06150981	57.0246372	612.986859
17	0.850	47.55245181	40.4354349	653.422294
18	0.850	52.93648394	45.0136568	698.435951
19	0.850	47.54693837	40.4307466	738.866698
20	0.850	52.93169403	45.0095838	783.876281
21	0.850	61.11902266	51.9715423	835.847824
22	0.850	66.43040727	56.4879896	892.335813
23	0.850	60.65094464	51.5735199	943.909333
24	0.850	65.96315179	56.0906667	1000.000000

No.2 Return Electrode. Injected Current: -1000.0000 amps
Potential Rise: -335376.9077 volts, Resistance: 335.3769 ohms

Cond #	length	amps/meter	amps to soil	cum amps
25	0.200	-5000.00000000	-1000.0000000	-1000.000000

No.3 Isolated Buried Structure:
Potential Rise: -573.6960 volts

Cond #	length	amps/meter	amps to soil	cum amps
26	0.200	-0.00000000	-0.0000000	-0.000000

Soil Potential Profile No. 1

x	y	z	Soil Potl
0.000	0.000	0.000	12254.2706
0.000	-2.000	0.000	7616.2198
0.000	-4.000	0.000	5907.3535
0.000	-6.000	0.000	4812.2163
0.000	-8.000	0.000	4020.0268
0.000	-10.000	0.000	3414.7874
0.000	-12.000	0.000	2936.2788
0.000	-14.000	0.000	2548.2108
0.000	-16.000	0.000	2226.8612
0.000	-18.000	0.000	1955.9532
0.000	-20.000	0.000	1723.9346
[Data for y = 20 through 42 have been deleted to reduce printout]			
0.000	-44.000	0.000	216.2412
0.000	-46.000	0.000	131.1107
0.000	-48.000	0.000	47.0672
0.000	-50.000	0.000	-36.6191
0.000	-52.000	0.000	-120.6697
0.000	-54.000	0.000	-205.8176
0.000	-56.000	0.000	-292.8285
0.000	-58.000	0.000	-382.5239
0.000	-60.000	0.000	-475.8074
0.000	-62.000	0.000	-573.6966
0.000	-64.000	0.000	-677.3631
0.000	-66.000	0.000	-788.1835
0.000	-68.000	0.000	-907.8066
0.000	-70.000	0.000	-1038.2446
0.000	-72.000	0.000	-1181.9983
0.000	-74.000	0.000	-1341.9271
0.000	-76.000	0.000	-1521.8689
0.000	-78.000	0.000	-1728.6323
0.000	-80.000	0.000	-1968.6740
0.000	-82.000	0.000	-2252.1356
0.000	-84.000	0.000	-2593.5643
0.000	-86.000	0.000	-3014.6551
0.000	-88.000	0.000	-3549.3789
0.000	-90.000	0.000	-4254.4419
0.000	-92.000	0.000	-5233.3995
0.000	-94.000	0.000	-6704.0188
0.000	-96.000	0.000	-9257.5343
0.000	-98.000	0.000	-15764.3583
0.000	-100.000	0.000	-136328.3216

Average number of series terms used 6

TIME: 10:56:37 DATE: 12/01/1988

APPENDIX V

REFERENCES

APPENDIX V REFERENCES

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2. R.S. Baishiki, C.K. Osterberg, F. Dawalibi, "Earth Resistivity Measurements Using Cylindrical Electrodes at Short Spacings". Paper presented at IEEE PES Winter Meeting, New York NY, Feb 2-7, 1986.

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1972.

16. "IEEE Guide for Safety in AC Substation Grounding" IEEE Std 80-1986.

17. C.F. Dalziel, F.P. Massoglia, "Let-Go Currents and Voltages", AIEE Trans. Vol 75 Part II pp 49-56, 1956.

APPENDIX VI
SAFETY CONSIDERATIONS

APPENDIX VI SAFETY CONSIDERATIONS

All references [] are contained in Appendix V.

VI.1 GENERAL

The safety of an installation from ground potential rise hazards can be considered from two aspects:

1. Safety under normal operating conditions.

2. Safety under fault conditions.

Safety of electrical substations and equipment is usually expressed in terms of tolerable step and touch potentials [16]. The requirements of the IEEE Guide for Safety in Substation Grounding [16] are incorporated in Table 52 of the Canadian Electrical Code [12]. The step and touch potential situations are indicated in Figure VI.1.

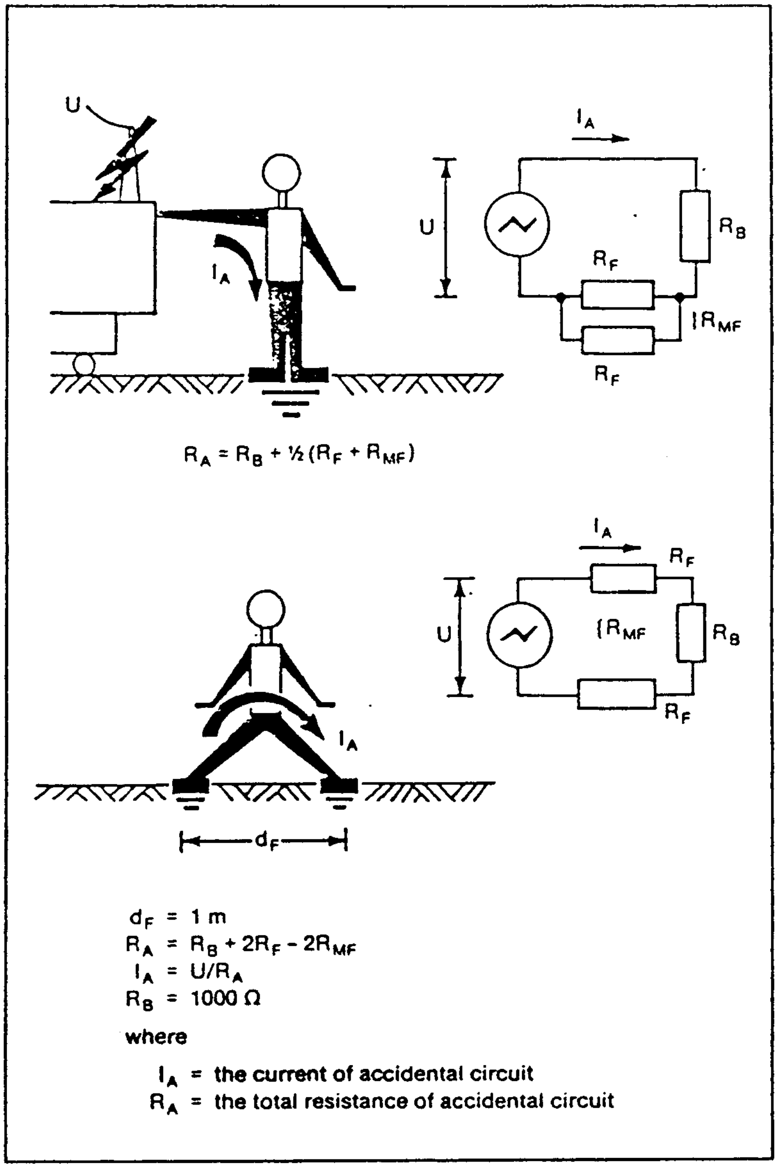

Figure VI.1 Touch and Step Potential Illustrations

The standard body resistance has been set at 1000 ohms from one hand to the two feet in parallel or 1000 ohms from foot to foot. The standard foot contact resistance is set at 3 times the effective surface layer soil resistivity so that in the case of a step potential, the body circuit is 6 times the effective surface layer soil resistivity plus 1000 ohms and in the case of a touch potential, it is 1.5 times the effective surface layer soil resistivity plus 1000 ohms [16]. The IEEE Guide gives a method for determining the effective surface layer soil resistivity if there is an appreciable difference in resistivity between the surface layer and underlying native soil.

VI.2 NORMAL OPERATIONS CONDITIONS

Due to stray currents, undetected faults, or the use of ground as a return conductor, normal operating conditions may allow continuous step and touch potentials to develop in and around a plant. The IEEE Guide [16] considers any

$$R_{2Fs} = 6(\rho)$$

$$R_{2Fp} = 1\tfrac{1}{2}(\rho)$$

$$E_{step} = (R_B + R_{2Fs})\, I_B$$

$$E_{step50} = (1000 + 6C_s(h_s,K)\,\rho_s)\,0.116/\sqrt{t_s}$$

or

$$E_{step70} = (1000 + 6C_s(h_s,K)\,\rho_s)\,0.157/\sqrt{t_s}$$

$$E_{touch} = (R_B + R_{2Fp})\, I_B$$

$$E_{touch50} = (1000 + 1.5C_s(h_s,K)\,\rho_s)\,0.116/\sqrt{t_s}$$

or

$$E_{touch70} = (1000 + 1.5C_s(h_s,K)\,\rho_s)\,0.157/\sqrt{t_s}$$

where

C_s = 1 for no protective surface layer

ρ_s = the resistivity of the surface material in Ω-m

t_s = duration of shock current in s

Figure VI.2 Formulae for Calculation of Tolerable Step and Touch Potentials when the Duration is less than 3 seconds

step or touch potential duration of more than 3 seconds to be continuous.

The maximum safe continuous body current is established as the let-go current of 99.5 percent of a large group of people. 60 Hz values for men and women are 9 and 6 mA respectively [17]. In one publication, dc values are stated to be 62 and 41 mA respectively [17]. In another, dc shock toleration is stated to be 5 times as high as 60 Hz ac toleration [13]. Applying the resistances mentioned above, for a typical surface soil resistivity of 150 ohm-metres for 60 Hz shocks, the tolerable continuous touch potential can be calculated to be 11 volts for men and 7.4 volts for women, while the tolerable continuous step potentials are 17.1 and 11.4 volts respectively. dc values will be correspondingly higher.

VI.3 FAULT CONDITIONS

Research [14] & [15] has shown that the body can tolerate much higher currents for short durations. The IEEE Guide [16] contains formulae which can be used to calculate tolerable step and touch potentials under fault or momentary conditions where the fault duration is less than 3 seconds. These formulae are given in Figure VI.2. The formulae are based on a body weight of 50 kg. The 1986 edition of the Guide [16] suggests that a body weight of 70 kg may be more appropriate. Table 52 of the Canadian Electrical Code [12] uses these formulae, based on the 50 kg body weight, to determine tolerable step and touch voltages for clearing times of 0.5 and 1.0 seconds.

To allow for dc offset effects in fast fault calculations, a decrement factor must be applied to the symmetrical ac fault calculation. For clearing times of 0.5 seconds or greater, the decrement factor is 1.0.

As in the case of continuous potentials, it is evident that the tolerable step potential will be appreciably higher than the corresponding touch potential. Similarly, the indications are that the tolerable levels are increased for dc shocks.

To ensure the safety of an installation, step and touch potentials anywhere in or around the installation must be held below the tolerable levels for both short duration and continuous potentials.