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Considerations for good performance in deep anode beds

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ABSTRACT

This paper is a discussion of the necessary geological factors which need to be investigated to ensure good performance in deep anode ground beds. The key to good performance is the resistivity of strata over the length of the anode column. The proper selection of the correct geologic strata within which to place deep anode beds is crucial to the overall performance, not only initially, but over the operating life, and can substantially affect the overall cost of the system. Proper strata selection requires a composite analysis of all available factors such as geologic data, measured or calculated resistivities with borehole control in the form of lithologic logs, and electrical (resistivity) logs to enhance the chances for success.

Keywords: Geologic Factors; Deep Anode Beds; Resistivity of Strata; Groundwater Characteristics; Design Determinations.

INTRODUCTION

Deep anode ground beds are being used extensively in the application of cathodic protection to various underground structures. The growth in the use of deep anode beds has been dramatic in the last twenty years even though these types of systems in various forms have been used for over forty eight years [1,2]. The early deep anode ground beds, although often satisfactory initially, failed with time and the industry became plagued with failures with an average ground bed life of less than seven years. Although many of these were component failures, quite often inadequate performance was the result of the strata in which the deep anode bed was installed. This general problem was masked by the severe problems that were experienced by use of various types of carbonaceous backfill which were not capable of discharging current efficiently without excessive gas buildup in the backfill voids. Chlorine and oxygen generated at the anode also had a very detrimental effect on the cable insulation and there were numerous cable failures [2,3]. To a lesser extent, anode material and anode connection failures contributed to the overall problem. Recent years have seen a dramatic improvement in the quality of the installations, due to improved materials, to the point where many of the deep anode beds are replaceable using a unique method in conjunction with backfill materials that are capable of discharging currents and dissipating gases very efficiently[2] (Figure 1).

Surface soils can readily be accurately measured for resistivity level and anode ground beds designed accordingly. In deep anode beds, however, accurate resistivity measurements are more difficult to obtain and do not maintain the same degree of accuracy from readings obtained from the ground surface[3]. Thus, although these readings are useful if obtainable, the results should not be relied upon solely without the support of other geological data. The several types of surface field measurement techniques, i.e., the Wenner Four Electrode configuration, the Schlumberger Array and the Central Electrode System have been adequately discussed in the literature and will not be focused upon herein. However, they remain a desirable component in the overall analysis for deep anode beds applications.

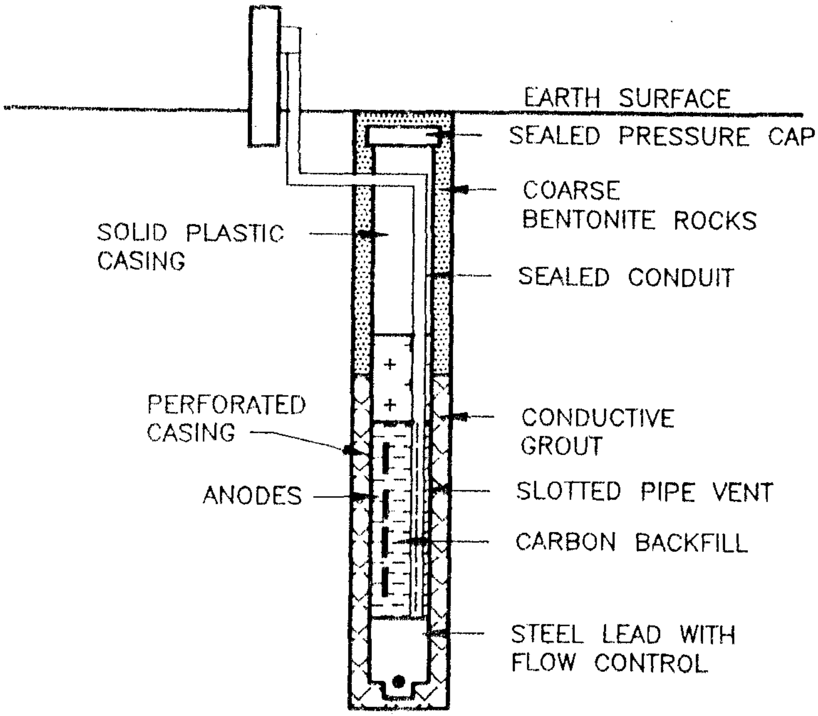

Figure. 1: A Deep Anode System

Specific resistivity readings obtained from oil well electric logs would be extremely useful, but the data is not normally available for deep anode because the logging operation is not initiated until a 150 - 300 metre depth is reached[4].

Table 1: Typical groundwater ion concentrations (ppm) and resistivities[7]

	Well 1	Well 2	Well 3
Depth (cm)	65	60	75
Diameter (mm)	300	300	300
Silica (S_iO_2)	13	20	21
Iron (Fe)	1.3	1.4	0.56
Calcium (Ca)	98	80	82
Magnesium (Mg)	32	30	25
Sodium (Na)	15	25	30
Potassium (K)	2.8	3.0	3.8
Carbonate (CO_3)	0.0	0.0	0.0
Bicarbonate (HCO_3)	347	390	330
Sulphate (SO_4)	92	32	7.8
Chloride (Cl)	17	22	31
Fluoride (F)	0.4	0.5	0.6
Nitrate (NO_3)	1.0	2.5	1.0
Dissolved solids	472	408	345
Resistivity (mhos)	1324	1530	1811

Table 2: Water Quality characteristics of Agbada field *

Parameters / Sample code	pH	Temp (^0C)	Cond. (s/cm)	Tot. Alk (mg/l)	Tot. Hard-ness (mg/l)	TDS (mg/l)	TSS (mg/l)	NH_3N (PPM)	NO_3-N (PPM)	FTU Turb.	SO_4 (mg/l)	Cl (mg/l)	PO_4 (mg/l)	D.O (mg/l)	BOD_5 (mg/l)	COD (mg/l)	Oil & grease (mg/l)
Agbada I	5.03	26	40	30.0	9.50	22	2.0	0.263	7.60	NIL	2.00	7.5	1.50	4.20	3.6	0	0
1	5.90	26.5	289	35.0	39.50	97	2.0	0.263	5.20	"	1.00	10.0	2.00	6.30	5.2	0	0
2	5.04	28	35	25.0	9.50	13	4.0	0.395	6.00	"	2.00	8.5	1.13	2.45	2.10	10	0
3	4.39	26	18	17.5	1.00	10				"		10.5	2.25	7.05	6.20	0	0
4	3.91	30	20	72.5	5.50	12	3.0	0.263	7.40	"	1.00	6.0	1.75	5.40	1.80	0	0
5	4.73	28	21	72.5	5.00	13	5.0	0.395	6.00	1.44	2.00	9.0	2.50	3.15	2.75	2	0
6	8.51	28	16	25.0	8.00	9	34.0	1.184	10.60	1.04	3.00	8.0	1.88	3.85	3.20	41	0.50
7	3.80	32	13	25.0	1.00	7	0.0	0.0	4.00	-	1.00	7.0	1.25	7.40	1.50	0	0
8	6.29	32	61	37.5	7.50	33	8.0	1.315	7.80	-	4.00	9.5	3.75	7.30	6.00	52	10.33
9	6.42	30	84	52.5	14.00	49	22.0	1.710	5.20	-	5.00	9.0	4.25	5.00	3.60	54	10.33
11	5.57	30	32	32.5	4.50	18	23.0	2.104	8.00	-	5.00	7.0	4.00	7.60	6.00	32	133.8
12	4.01	30	88	57.5	2.10	49	19.0	2.367	7.60	1.00	6.00	7.05	4.75	7.30	6.10	44	8.98
13	6.16	??	74	25	12	42	2.0	0.16	5.20	1.00	-	10	1.50	6.0	1.0	2.8	0.20
BH-1	6.17	"	40	30	17	24	3.0	0.20	6.00	1.50	-	13	1.80	5.00	1.2	2.5	0.10
BH-2 BH-3	6.34	"	73	35	24	39	2.5	0.18	5.60	1.50	-	14	1.25	7.10	0.5	2.0	0.20
Agbada II 1	4.87	28	18.2	27.5	4.0	10	25.0	2.365	5.60	0.60	5.00	8.0	4.13	2.55	1.85	52	331.57
2	5.63	28	37.10	37.5	11.50	19	22.0	2.893	6.00	0.60	4.00	8.0	3.00	1.65	1.15	58	16.16
3	4.38	27	14.40	35.0	0.50	10	1.0	0.00	3.20	-	1.00	9.0	1.25	7.60	6.70	0	0
4	5.00	26	25.2	30.0	11.50	13	30.0	0.789	11.20	2.70	2.00	9.0	3.63	1.40	1.10	44	0.50
5	4.72	31	59.60	25.0	12.00	30	110.0	0.263	4.00	-	2.00	13.0	1.50	4.50	3.70	14	0
6	4.71	29	128.2	35.0	19.00	70	10.0	0.263	4.80	-	1.00	12.5	1.13	5.50	4.50	2	0
7	5.02	28	26.7	32.50	21.00	14	34.0	0.789	10.40	3.04	2.00	8.0	2.25	2.90	2.30	53	0.50
8	4.62	30	21.40	32.50	10.50	12	30.0	1.052	9.60	2.53	1.00	7.0	1.88	0.90	0.50	47	0.50
Control x	4.78	28	38.10	32.50	8.50	20	15.0	1.184	11.80	2.04	2.00	13.0	2.13	4.90	3.85	43	0.30
BH-1	6.44	-	22	17.5	8	14	2.0	0.22	3.20	1.00	-	10	1.50	5.50	0.8	2.0	0.10
BH-2	6.42	-	27	20	6	17	1.5	0.27	4.00	1.50	-	10	1.75	7.30	1.0	2.8	0.20
BH-3	6.24	-	19	20	7	11	12.0	0.26	4.80	1.00	-	7	1.13	6.50	1.4	3.0	0.20

**Courtesy of Fabino Consult Ltd, Lagos*

2. GEOLOGIC FACTORS

The dominant factors in the performance of any deep anode system will be the selection of the most favorable strata in which to place the anode column. The characteristics of favorable strata are an overall low, relatively homogeneous resistivity over the length of the anode column. The resistivity of any stratum is dictated not by the composition of the stratum itself but by the water content and the ions it contains[5]. Common ions that contribute to good conductivity include Na^{+}, Cl^{-}, Ca^{+2}, SO_4^{-2}, HCO_3^{-1}, CO_3^{-2}, and Mg^{+2}. Table 1 shows an analysis of raw ground water samples from 3 wells showing ion concentrations and dissolved solids. Calculated resistivities are listed as derived from the equation:

$$R = \frac{625,000}{TDS(ppm)} \quad \text{.......................... (1)}$$

where 625,000 is a constant and TDS is total dissolved solids in parts per million. As some of these ions are found in most ground waters, the main factors contributing to lower overall strata resistivity are higher ion concentrations and larger amounts of water contained within the strata[6].

It is also discerned from Table 1 that while higher resistivities are generally associated with lower ion concentrations, Ca^{+2}, Mg^{+2}, HCO_3^{-1}, SO_4^{-2} ions, and perhaps most importantly, the total dissolved solids appear to have overriding influence on the resistivity of groundwater within strata. A similar trend is apparent in the water quality characteristics presented in Table 2 for Agbada I and II fields in the Niger Delta, Nigeria, except that metal ion concentrations were either very low or not detectable in the water samples analysed.

Table 3: Resistivity of sediments[6]

Rock Type	Resistivity Range
Consolidated shales	$20 – 2 \times 10^5$
Argillites	$8 – 10 \times 10^4$
Conglomerates	$2 \times 10^5 - 10^6$
Sandstones	$1 – 6.4 \times 10^{10}$
Limestones	50×10^9
Dolomite	$3.5 \times 10^4 – 5 \times 10^5$
Clays	1 – 10000
Alluvium and sands	10 – 80000
Oil sands	4 – 80000

Table 4: Resistivities of igneous and metamorphic rocks[6]

Rock type	Resistivity Range
Granite	$3 \times 10^4 - 10^8$
Granite porphyry	4.5×10^5 (wet) – 1.3×10^8 (dry)
Feldspar porphyry	4×10^5 (wet)
Dacite	2×10^6 (wet)
Andesite	4.5×10^6 (wet)
Diabase (various)	$5 – 20 \times 10^6$
Lava	$10^4 – 5 \times 10^6$
Gabbro	$10^5 - 10^8$
Basalt	$1.3 – 10 \times 10^9$ (dry)
Peridotite	3×10^5 (wet) – 6.5×10^5 (dry)
Schists (calcareous & mica)	$20 - 10^6$
Slates (various)	$6 \times 10^4 – 4 \times 10^9$
Gneiss (various)	6.8×10^4 (wet) – 3×10^8 (dry)
Marble	$10^4 – 2.5 \times 10^{10}$ (dry)
Quartzites (various)	$10 – 2 \times 10^{10}$
Tuffs	2×10^5 (wet) – 10^7 (dry)

Table 3 shows typical resistivity values for unconsolidated and consolidated sediments while Table 4 presents typical resistivities for crystalline rock types. As would be expected, clays and argillites have much lower resistivities than sandstones, conglomerates and limestones.

Generally, rock-forming minerals are highly resistive to current flow, the presence of clay minerals being an exception. The exchangeable ions in the clays may separate from the lattice and make pore water conductive even though the formation water may not be saline. As a result, clays usually have low resistivities – whether occurring as clay – rich soils or as shales. Thus, if it is established with certainty that the groundwater in an area is fresh, then low resistivities are representative of clays. On the other hand, fresh water which is essentially a poor conductor, will cause high resistivities when present in the pore spaces of a clean or clay-free soil, or in the pores or joints of a porous or dense relatively clay-free rock. Based on these considerations, it should be noted that there is nothing very distinctive about the kind of material that has high or low resistivity values per se. Johnson and De Graff[8] state that: "it would be possible on the basis of high resistivity to drill expecting to encounter a porous, fresh water bearing sand and instead encounter a tight dense sandstone". This is because as deposits become more consolidated, the moisture content, porosity, and permeability generally decrease and the resistivity tends to be higher. Furthermore, saline pore water in a sand or porous highly fractured rock gives low resistivity values that are also indicative of clay or shale. In addition, the degree of saturation that varies with seasons, in turn affects conductance and, by implication, the resistivity. Seasonal fluctuations in resistivity by as much as 200% have been reported (Brooke[9]).

Similarly, in the crystalline igneous and metamorphic rocktypes, moisture content, permeability and porosity are low due to the massive dense constituents and the resultant resistivities are very high making them undesirable for deep anode bed applications.

The corrosion engineer when designing a deep anode ground bed is concerned with locating favorable strata or rock types, usually within the 15 to 250 metre range. An average depth for a standard deep anode application is probably 60 to 90 metres. This relatively shallow depth range (geologically speaking) encounters an extreme variety of materials depending on geographical location and can often vary locally to a great extent. The strata that are usually encountered in that depth range vary from unconsolidated sediments including soils, alluvial clays, silts, sands, and gravel to well consolidated sediments including shale, sandstone, conglomerates, and limestone. Metamorphic and igneous rock types may also be encountered at these depths but are typically encountered at greater depths. The exception to this is in areas of previous earth movement where previously almost horizontal sediments have been folded, and/or faulted, as in typical mountain range areas. Metamorphic rocks may also be present along with igneous intrusives. In the crystalline igneous and metamorphic rock types, moisture content, permeability and porosity are low and the resultant resistivities are very high making them undesirable for deep anode bed applications. Thus, it becomes an investigation to determine not only the type of material that is to be encountered at depth, but its characteristics in terms of water content, porosity and permeability and the possible elements present resulting in ions in the water formations.

One important factor is the interpretation of what is actually "rock". Several potential installations of deep anode ground beds have been avoided because someone reported that there was rock at depth or bedrock, another term often misinterpreted. In one instance, a major potential deep anode bed project was not accomplished because of reports of "rock" at the 15 metres depth. In fact, what existed at the site was a layer of fairly high resistance dolomite at depth of 15 to 45 metres. Below this, however, were consolidated zones of very favorable low resistivity shale suitable for deep anode beds. Thus, the entire strata to the maximum potential depth must be investigated and when "rock" is encountered it must be defined as to its type and composition. The "rocks" to be avoided are the highly crystalline igneous and metamorphic rocks that are not underlain by sediments, i.e., "bedrock".

In contrast, oil and gas producing regions are almost always suitable areas for deep anode beds because of the typically thick overlying sedimentary deposits which often occur in the 15 to 250 metres deep anode bed range. Prolific areas such as the Niger Delta Basin in Nigeria have overlying sediments of over 9,000 metres in thickness making them excellent areas for deep anode beds.

Even when suitable strata are located, some of these should be avoided for other reasons. For example, certain limestones that are termed "vuggy" have large cavities and voids that are formed by circulating ground water through joints and fractures and along bedding planes. Drilling through one of these cavities would result in loss of circulation in the hole and make backfilling difficult if not impossible. Strata which contain artesian water (ground water under head pressure) can also cause complications with deep anode installations and subsequent performance. Generally, heavy mud drilling will stop small flows while hole casing may be required for heavier flow rates. Areas of excessive water pressures should be avoided if possible.

DESIGN DETERMINATIONS

One of the initial choices in any cathodic protection application would be to determine which type of ground bed configuration would be most suitable for a given application. Deep anode beds have become very popular because of surface congestion, difficulties in obtaining rights-of-way, minimal interference effects, favourable current attenuation and good operating performance. In order for a deep anode bed to be favoured electrically over a surface bed, relatively low resistivities at depth must be identified and compared at a given location to the resistivity of the soils near the surface[8]. If the choice of a deep anode bed is obvious for other factors, then the task at hand is simply to determine the specific design of the deep anode bed at a given location. The corrosion engineer's role in deep anode bed design is to develop a composite type of analyses where all factors that may have an effect on the system will be considered. Figure [2] shows the information that should be obtained and analyzed to achieve a successful deep anode installation.

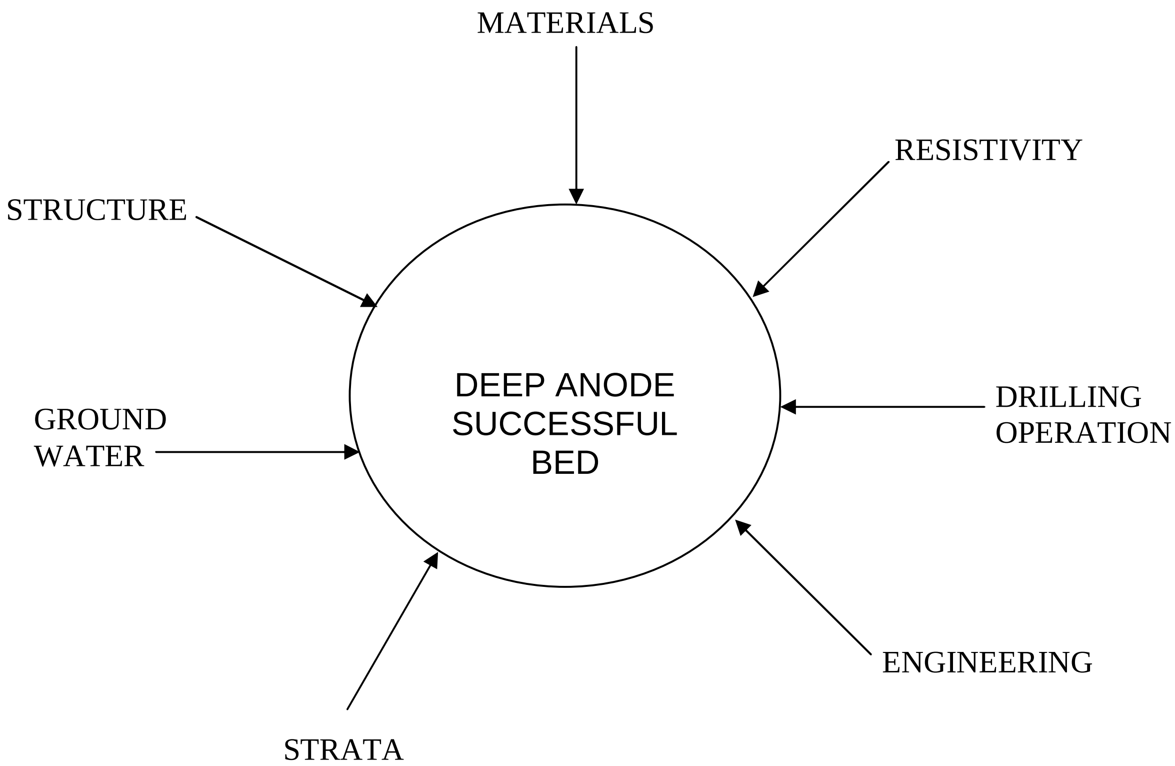

Figure 2: Key factors which incorporate a thorough composite analysis

Consideration of the geologic factors by the corrosion engineer searching for low resistivity strata is somewhat analogous to the approach taken by the petroleum geologist in his search for oil. Both gather as much data as possible for the proposed area and base their conclusions on all the data. The corrosion engineer is looking for relatively low and homogenous strata resistivity while the petroleum geologist is looking for oil. The problem with deep anode beds is that reliable and accurate resistivity measurements are often lacking. Thus, he must do other things to try to ascertain what the relative value might be. This requires studying and analyzing (1) geologic maps, (2) electric logs, (3) local drilling logs and conditions, (4) supportive geologic information such as water table depth, porosity, permeability or moisture content, (5) surface resistivity measurements to depth, and (6) existing cathodic protection of deep anode beds. After all of this information is analyzed, the corrosion engineer must make his decision based on an analysis of each of the factors. In large projects, a small diameter test hole might be drilled to actually verify for certain the suitability of the strata. The design is then completed by determining the current capacity, the desired ground bed resistance, and the design life of the cathodic protection system.

4. DRILLING OPERATIONS AND INSTALLATION

Once the deep anode design has been finalized, it is ready for installation. Optimum performance and ease of installation of the deep anode ground bed can be best achieved by using the drilling equipment which is best suited for the strata in which the ground bed would be installed. Typical requirements are a clean, straight hole, which will maintain circulation when backfill material is pumped. The normal choice in a drilling rig is a relatively small rotary rig, typically used by water well drillers. These rigs usually have the capability of drilling up to 300 metres. Alluvium and unconsolidated sedimentary strata including heavy gravel usually require a lined hole using a high viscosity drilling mud. The viscosity of the drilling mud is varied as needed by the driller to maintain the integrity of the hole and to be able to drill past areas of artesian ground water, cavities and weak areas in the strata. If it is not expected to encounter strata which require mud drilling, the strata may be drilled with the rotary rig on air. Hard rock drilling of sandstone and limestone would typically be drilled using the rotary rig on air with a hard rock bit. Cable tool type rigs should be avoided except in extremely hard strata where a vertical pounding cable tool rig may be the only feasible way to penetrate the strata. They are very slow and not suitable for most installations.

An important part of the deep anode ground bed installation is to conduct an electrical resistance log of the strata to verify the designed anode column position and to determine the most favorable areas for anode placement. The log is usually conducted using an anode as an electrode with reference to the structure to be protected. Another helpful measurement easy to obtain is the anode-to-anode resistance once the anode bed has been installed and back filled. These details assist in ensuring a more uniform current distribution over the anode column and more equal current output from the individual anodes. Strata resistance logs and anode-to-anode resistance logs may then be filed for future design use.

CONCLUSION

The information provided herein leaves us to conclude that the dominant factor in deep anode bed performance is the suitability of the strata where the deep anode bed column is installed. Therefore, it is necessary to:

1. Perform a thorough investigation of the geology at depth to determine the electrical and physical characteristics of the strata.
2. Base a decision on a composite analysis of the information obtained to determine if an acceptable deep anode bed can be achieved.
3. Avoid deep anode bed installations in unaltered crystalline, igneous and metamorphic rock types.
4. Adjust the length of anode column and number of anodes to suit the strata resistivity and adjust the anode location in the column for best performance.
5. Utilize the optimum drilling equipment and techniques for the strata expected to be encountered to provide a hole that is clean, straight and will maintain circulation.
6. Properly log the installation to ascertain anode column and position and use for future performance comparisons.

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