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Depth of penetration of geophysical exploration methods as applied in shallow engineering geological investigations

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Abstract: This note discusses the depth of penetration of seismic refraction surveys and d.c. geoelectrical soundings. Field examples from studies carried out in the vicinity of the Ruhr-Universitaet, Bochum, Federal Republic of Germany are presented to illustrate the variation of a defined depth of penetration for both these methods.

For seismic refraction surveys it was found that the ratio of the depth of penetration to the length of the profile, a certain depth factor varies between 1/2 to 1/10. This illustrates the difficulty of estimating the depth of penetration before conducting seismic refraction surveys and shows the dependence of the depth of penetration, in addition to the length of the seismic profile, on the p-wave velocity of each subsurface layer and the layer's thickness.

Similarly for d.c. geoelectrical soundings, the depth factor, a ratio of depth penetration to the spacing of current electrodes, varies between 1/3 to 1/8. The main factors influencing the depth of penetration are the number of subsurface layers, their specific resistivity and their individual thicknesses, in addition to the spacing of the current electrodes.

INTRODUCTION

The exploration geophysicist when conducting a geophysical exploration programme is often asked the question what the depth of penetration of his investigation techniques is before he has conducted any surveys. This question assumes particular importance in shallow engineering geological investigations, where investigations up to a particular depth or horizon below the ground's surface are required. This question is also important when field conditions are such that the length of the geophysical profile, whether refraction seismic or d.c. geoelectrical sounding is restricted because of the lack of space.

Refraction seismic studies and d.c. geoelectrical soundings were conducted by the author for shallow engineering geological investigations in the vicinity of the Ruhr-University, Bochum, Federal Republic of Germany (Rafek, 1984). The results of these investigations are used here to highlight some aspects of the problem in the estimation of the depth of penetration when conducting refraction seismic surveys and geoelectrical soundings. The general geology of the study area as well as the location of the survey sites is shown in Figure 1.

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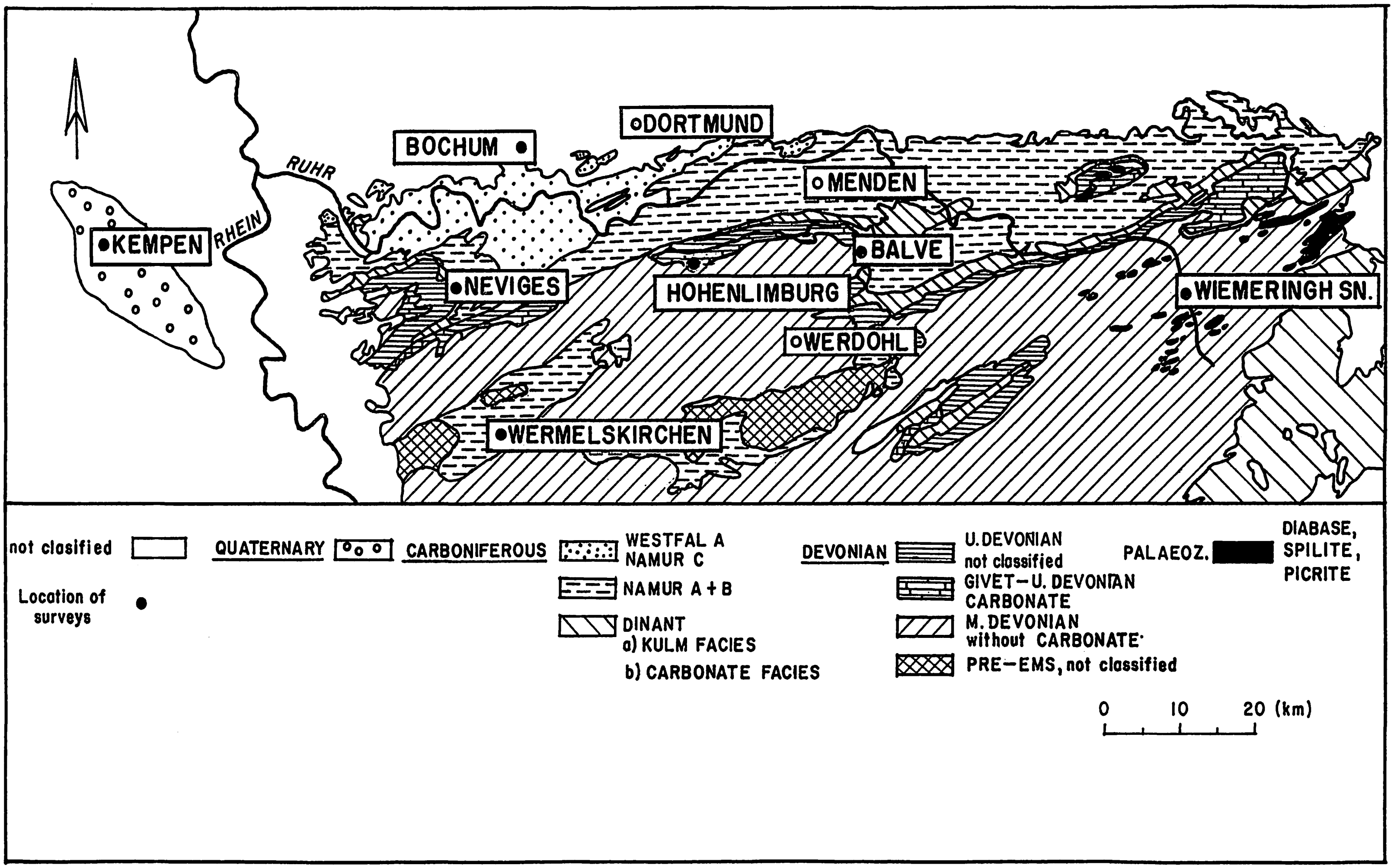

Figure 1 : General geology of study area and location of surveys

The study area is located in the northern part of the "Rheinischen Schiefergebirge", with the exception of the site at Kempen. About 80% of this region consists of Devonian beds, with lower Devonian slates and sandstones predominating. Upper Middle Devonian massive limestone are exposed in the northern part of this region and constitute an important raw material for the building as well as iron and steel industry. The Carboniferous beds comprise of the coal-barren Dinant and coal- bearing upper Carboniferous "Ruhrkarbon". The region around Kempen is composed of Quaternary sediments of the Rhein overlying Tertiary beds.

REFRACTION SEISMIC SURVEYS

The depth of penetration of the refraction seismic method depends, among other factors, on the length of the seismic profile. This factor becomes particularly important when field conditions restrict the length of the seismic profile. Other factors which also influence the depth of penetration are the true p-wave velocities in the different layers present, as well as their individual layer thickness.

A number of estimates for the depth of penetration are known when using the refraction seismic method. Bullock (1978) estimates the depth of penetration to be 1/5 of the length of the seismic profile. However no explanation is given as to how this value is obtained.

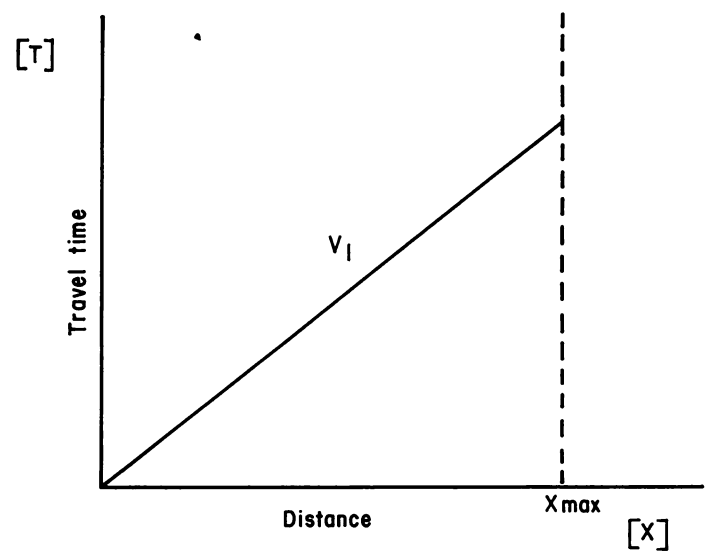

Fig. 2: Travel time diagram for estimation of minimum depth for a two-layer case (after Mooney, 1976).

Mooney (1976) suggests a method to determine a minimum depth for a two-layer case (p. 8-6, 8-7) and a three-layer case (p. 9-9, 9-10) from the length of the profile. In such a case, the depth of the second layer for example in a two-layer case is estimated in the following way (Figure 2): from the travel time curve, where only the velocity, V_1 of the first layer is measured, it is assumed that the V_2 branch of the travel time curve starts after Xmax, where V_2 is the velocity in the second layer. Thus using Xmax as the cross-over distance and an estimated velocity in the second layer (V_2), the depth of the second layer can be determined. As a rule of thumb, basing on this consideration, the depth of penetration is found to be 1/3 of the length of the profile. For a three-layer case, the same method can be applied to estimate the depth of a third layer which has not been detected. In such a case, the rule of thumb that the depth of penetration is 1/3 of the length of the seismic profile results in a conservative estimate of the depth of penetration.

For the surveys under discussion , the following empirical method was used to determine the depth of penetration and the depth factor. The purpose of this determination was also to check the validity of the mentioned rules of thumb. For a layer under consideration the distance Xa, which is five times the sample interval ΔX from the cross-over distance Xc was taken and divided by the calculated depth of this layer to give the depth factor. The distance Xa is considered as the profile length necessary for the detection of the layer under consideration. The distance Xa is also dependent on the sample internal ΔX. In this manner, the depth factor for each layer can be determined. Where the layers were dipping an average value for the depth factor was determined (Figure 3).

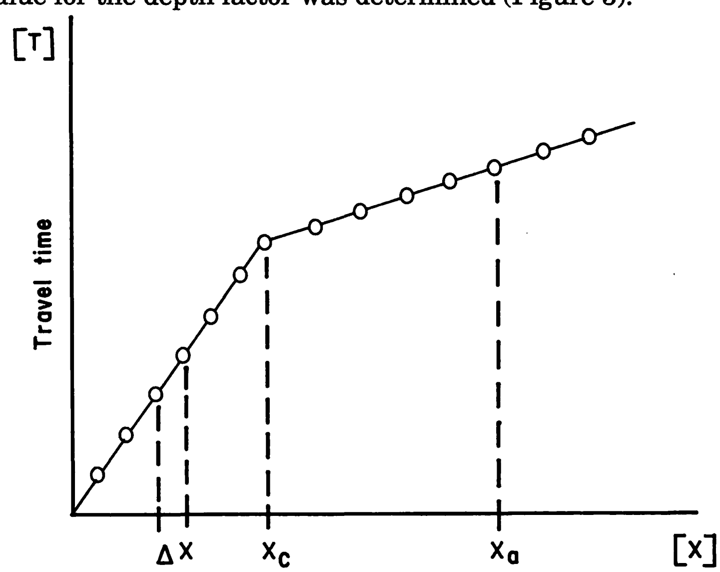

Fig. 3: Travel time diagram for the empirical determination of depth of penetration and depth factor.

The results of this consideration for selected field examples are shown in Table 1. As can be seen from this table, the ratio of the depth of penetration (d) to the profile length required for detection of the respective layer (Xa), the depth factor varies between 1/2 and 1/10. This consideration illustrates very clearly the difficulty in estimating the depth of penetration before refraction seismic studies are conducted. The depth of penetration is dependant on the length of the profile,

Table 1: Depth of penetration and depth factor of selected refraction seismic studies.

Profile	layer	Profile length Xa [m]	Depth of penetration d [m]	Depth factor [Xa/d]
Location: Ruhr valley, Bochum-Stiepel				
P1	2	17	5.0	1/3
	3	24	10.3	1/2
P5	2	16	3.3	1/5
	3	22	7.9	1/3
P7	2	16	4.7	1/3
	3	20	9.4	1/2
Location: Wiemeringhausen, Hochsauerland				
P2	2	10	2.0	1/5
	3	20	2.0	1/4
	4	36	10.9	1/3
Location: Steltenberg, Hohenlimburg				
Normal	2	6	1.0	1/6
Weathering Profile	3	25	6.6	1/4
Marl-limestone	2	6	0.6	1/10
boundary	3	28	2.8	1/10
Location: Weathering profile, Neviges				
Carbonate-rich	2	8	1.5	1/5
Siltstone (grey)	3	18	5.5	1/3
Carbonate-poor	2	7	1.0	1/7
Siltstone (brown)	3	18	3.0	1/6

D.C. GEOELECTRICAL SOUNDINGS

The depth of penetration, often also refered to as the depth of exploration of d.c. geoelectrical soundings can be considered as a controversial topic and has been dealt with by many authors. Roy and Elliot (1981) reviewed the definition of the depth of penetration given by various authors and discussed this topic with theoretical, experimental and field data. However they restricted their discussion only to curves of the maximum-minimum type (K, KH, H and HK) of d.c. resistivity soundings. These are curves characterised by a distinct turning point.

As the depth factor, Roy and Elliot defined D/L where D is the depth of the midpoint or midline (parallel to the earth's surface) of the target bed or body and L is the total electrode separation for which the apparent resistivity curve shows a maximum or a minimum in the case of resistive or conductive beds, respectively. In this consideration only the Schlumberger and Wenner electrode configurations were dealt with. From these considerations it can be seen that Roy and Elliot's definition can only be applied for determining the depth factor of intermediate layers, since the depth to the midpoint of such a layer is determinable and the sounding curve would have a distinct turning point. In their discussion, Roy and Elliot showed that the depth of penetration and the depth factor cannot be expressed in terms of a simple rule of thumb for possible combinations of specific resistivity, layer thicknesses and electrode separation.

For determining the depth of penetration and the depth factor of the conducted d.c. resistivity soundings, the author prefers the definition from Astier (1971; in Zigl, 1978). In this definition, the depth of penetration D to the top edge of the layer under consideration is taken instead of the depth to the middle of this layer, as in the case of Roy and Elliot's (1981) definition. This has the advantage that the lowermost layer whose thickness is considered as infinite can also be considered. Furthermore, Astier (1971) did not restrict his discussion to maximum-minimum curves but also considered other types of curves.

Table 2 shows the electrode separation, depth of penetration as well as the depth factor for selected resistivity soundings. As can be seen from this table, the depth factor varies between approximately 1/3 till 1/8. This result also shows that the most important factors which influence the depth of penetration are the number of layers present beneath the surface, their specific resistivity as well as their individual layer thicknesses.

It should be mentioned that the determination of the eletrode separation at which a layer under consideration is being registered, is influenced to a certain extent by the subjectivity of the person carrying out his determination. For a multi-layer sounding curve, it is difficult to determine the electrode separation at which a layer under consideration is being registered and is influencing the measured apparent resistivity. This is especially the case when the sounding curve does not have a clear maximum or minimum value. As a result of this, the calculated values of depth factor can be considered as semi-quantitative values.

Table 2: Depth of penetration and depth factor of selected d.c. resistivity soundings.

Sounding	Layer No	Electrode Separation L[m]	Depth of penetration, D[m]	Depth factor D/L
Location: Ruhr valley, Bochum-Stiepel				
TS1	5	50	8.5	1/6
TS 2	5	40	7.0	1/6
TS 3	4	50	7.0	1/7
TS 4	5	80	10.0	1/8
Location: Kempen, Lower Rhein				
S1	3	40	9.0	1/4
	6	200	27.0	1/7
S2	3	25	8.0	1/3
	4	100	33.0	1/3
S3	4	40	10.5	1/4
	6	150	25.5	1/6
S4	3	30	8.0	1/4
	5	150	29.0	1/5
S6	3	12	3.0	1/4
	6	150	29.0	1/5
S7.1	3	30	10.0	1/3
	6	150	24.5	1/6
S8	3	25	8.5	1/3
	5	150	26.0	1/6
S9	3	12	3.0	1/4
	6	120	28.0	1/4
S10	3	30	9.5	1/3
	5	120	25.0	1/5
Location: Steltenberg, Hohenlimburg				
Limestone profile	3	20	7.0	1/3
Marl profile	3	12	2.3	1/5
Wermelskirchen				
Siltstone profile	3	20	6.0	1/3

CONCLUSIONS

The difficulty in predicting the depth of penetration when using the refraction seismic technique and geoelectrical resistivity soundings has been illustrated here. For the exploration geophysicists, it would seem that carrying out test surveys before an extensive exploration programme could provide the necessary estimate of the depth of penetration in a particular survey area provided that within it there are no major changes in the geology.

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