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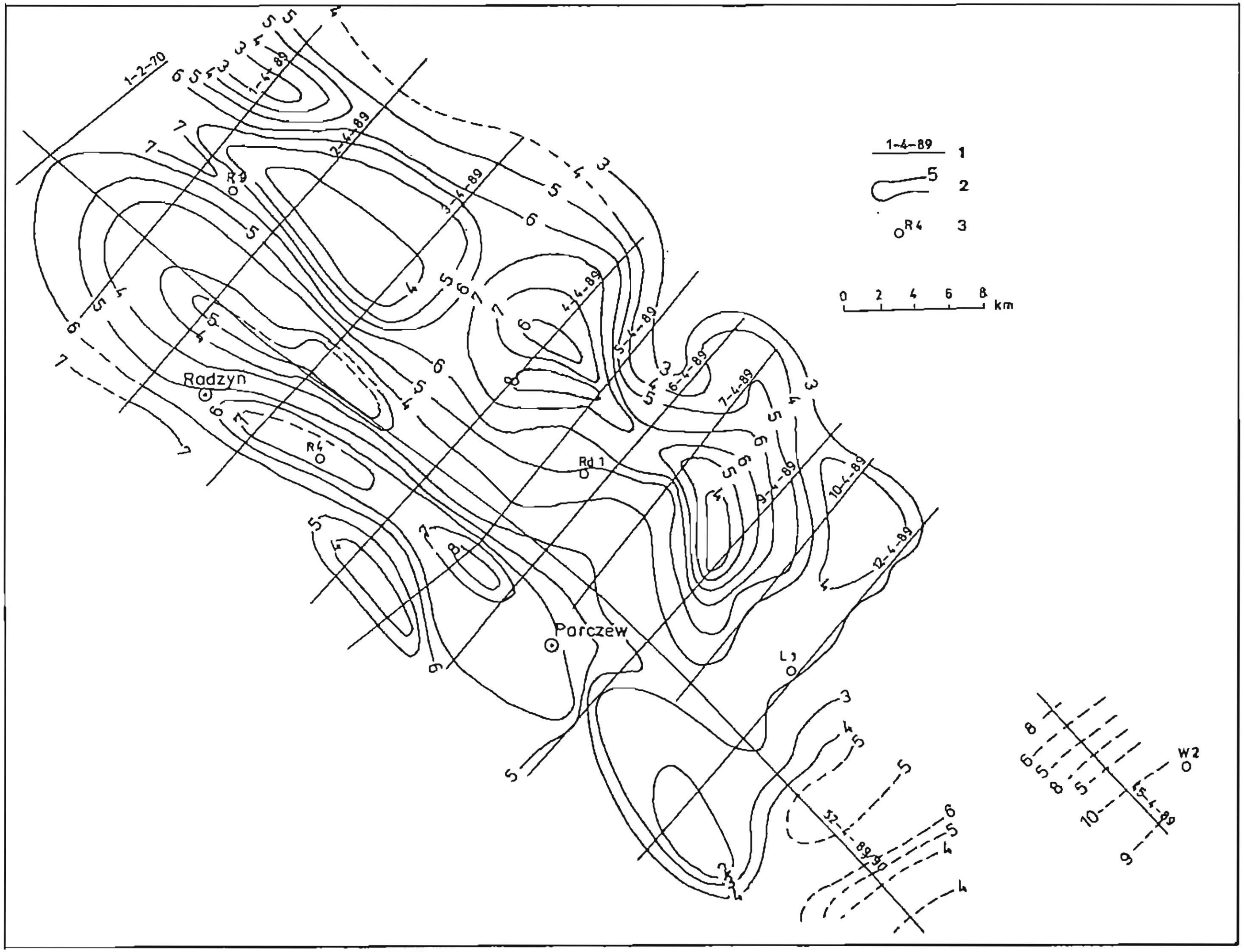
Making use of the low velocity zone (LVZ) in hydrogeology and engineering geology

Analysis of the results of low velocity zone (LVZ) measurements indicates that they can be used in both hydrogeology and engineering geology. The results of LVZ measurements allow calculation to be made of the aeration zone, wave velocity within the zone and its base, as well as water table configuration.

INTRODUCTION

A reflection method, depending on the purpose of the investigation, consists in recording waves of variable frequency range. Currently available instrumentation allows measurements of the high frequency range, that contribute to the use of the method for defining the structure of near-surface formations and determining their strength parameters. However, due to the high cost of seismic surveying, it is replaced by cheaper, though less accurate, geophysical methods. Keeping this in mind it seems reasonable to analyse whether some data acquired using the seismic method in the course of hydrocarbon exploration can be considered applicable to solving some tasks in the area of hydrogeology and engineering geology. This data, contained in geophysical reports and basic materials stored in archives, deals with near-surface formations, and no high expenses are needed to make use of them.

It seems worth considering to what extent data from archives can be useful in hydrogeological studies and site investigation. This question will be analysed based on LVZ measurements taken in the Polesie Lubelskie area (J. Brauer, W. Kulig, 1991).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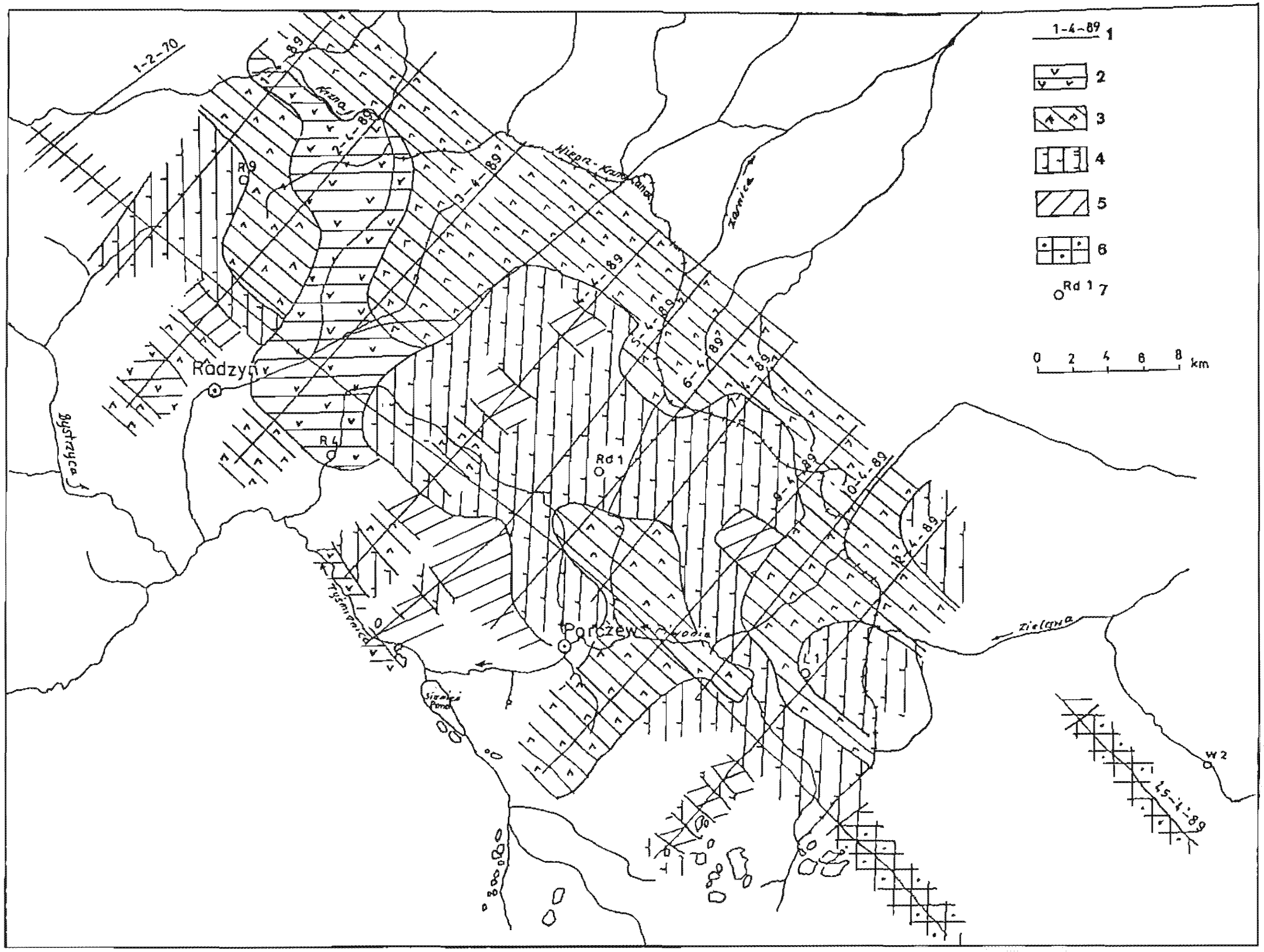
RELATIONSHIP BETWEEN THE LVZ AND THE AERATION ZONE

Due to the necessity of exact calculation of static corrections, the LVZ is always subject to careful study. The LVZ measurements are taken along seismic profiles, at a distance of each 1.5–2.0 km on the average or less if the land relief is diverse. It should be noted here that the seismic profiles are sited to some extent in a regular arrangement; it is almost a rule that their courses are far away from villages and towns, i.e. within an area where wells are missing, thus not giving any information on groundwater conditions. It should be remembered that the results of LVZ measurements allow determination of this zone's thickness and the elastic wave velocity within both the zone and the underlying formation. In seismic science, it is common to presume that the LVZ is composed of a near-surface formation complex, in which the velocity of the longitudinal wave propagation is less than 1000–1200 m/s. From a lithologic point of view, the zone can be made up of dry formations. Cohesive soils such as (for example) sands, gravels, sandy clays, peats, loess, weathering wastes, and the like are most common. In the event that near-surface formations are water-saturated, their physical parameters, including the velocity of the wave propagation, are subject to essential changes. This is the fact which simplifies the determination of the boundary between dry and water-saturated formations even if the lithology of both is similar. Thus, it can be concluded that the accuracy of determination of the LVZ base (equivalent to the total thickness) in the granular formations shall be dependent on the number of measurements taken in the course of the seismic survey. As mentioned before, the measurements are practically equally distributed over the area and are always more frequent than boreholes and wells in the same area.

The following section of this paper is based on the results presented in the previously mentioned report (J. Brauer, W. Kulig, 1991) and focuses on the LVZ thickness and longitudinal wave propagation within this zone. A total of 204 measurements of the LVZ were taken in all profiles along a total length of 302 km. They were taken at a distance of 1.5 km each. Calculated thicknesses of the zone were plotted on a sketch presented in Figure 1. The LVZ thicknesses as given on the sketch are related to the ground surface. Isolines of LVZ thickness are plotted at each 1 m of vertical distance. This may be questionable since the LVZ thickness should be expected to change with respect to the depth to the groundwater body, the fluctuation of which is dependent on the amount of rain, which fell with variable intensity in the course of the seismic survey. Such data is missing in the geological report; accordingly, it is difficult to analyse the water table fluctuation versus the rain depth. It should be noticed that despite the fact that the measurements were carried out in a period of a dozen months or so, the values acquired of the zone thickness are similar at the points of intersection between different profiles.

There are some cases of misleading data that did not fit the general situation and could not be used as the basis for plotting the sketch. For example, in the SW segment of profile

Fig. 1. Sketch of the thickness of the low velocity zone
1 — seismic profiles; 2 — isopachs; 3 — boreholes
Szkic miąższości strefy małych prędkości
1 — profile sejsmiczne; 2 — izopachyty; 3 — otwory wiertnicze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15-4-89
Krzna
Wieprz-Krzna kanał
Żarnica
Bystrzyca
Tyśmienica
Zielawa
Piwonia
Radzyn
Porczew
R9
R4
Rd 1
W2
Sitaczy Pond

5-4-89, the LVZ thickness was found to be 9 m while in nearby spots and on profile 4-4-89 it was only 4–5 m; the latter was plotted on the sketch. Similarly, a thickness of 4 m in the NW segment of profile 52-4-89/90 was excluded as not true. Important to note here is the fact that measurements were taken the same day, so water table fluctuation could not be considered a reason for such a large difference. A number of reasons may be causing such differences in LVZ thickness; however, their marginal nature is beyond the scope of this paper.

As variation of the LVZ thickness is low (from 2 to 9 m only), adoption of another vertical distance between the isopachs would be difficult to present on the sketch.

The isopach arrangement indicates a complicated situation with respect to LVZ thickness (Fig. 1). Based on the general situation presented, two distinct sectors can be distinguished in the survey area. On profiles 1-4-89 through 10-4-89 the predominant direction of isolines is NW–SE, with some exception in the southwestern segment of profile 12-4-89. Against this general background of NW–SE isopachs, a number of forms can be observed related to a local increase or decrease in the LVZ thickness.

Local variations in the LVZ thickness north of profile 52-4-89/90 are isometric in shape, while nearby and southwards of this profile they are more elongated and their surface area is less. The number of data from the area east of profile 12-4-89 concerning LVZ thickness and contained in the geophysical report (J. Brauer, W. Kulig, 1991) is insufficient to plot the sketch. Nevertheless, the direction of isopachs on profiles 45-4-89 and 52-4-89/90 as presented in the report seems to be very likely.

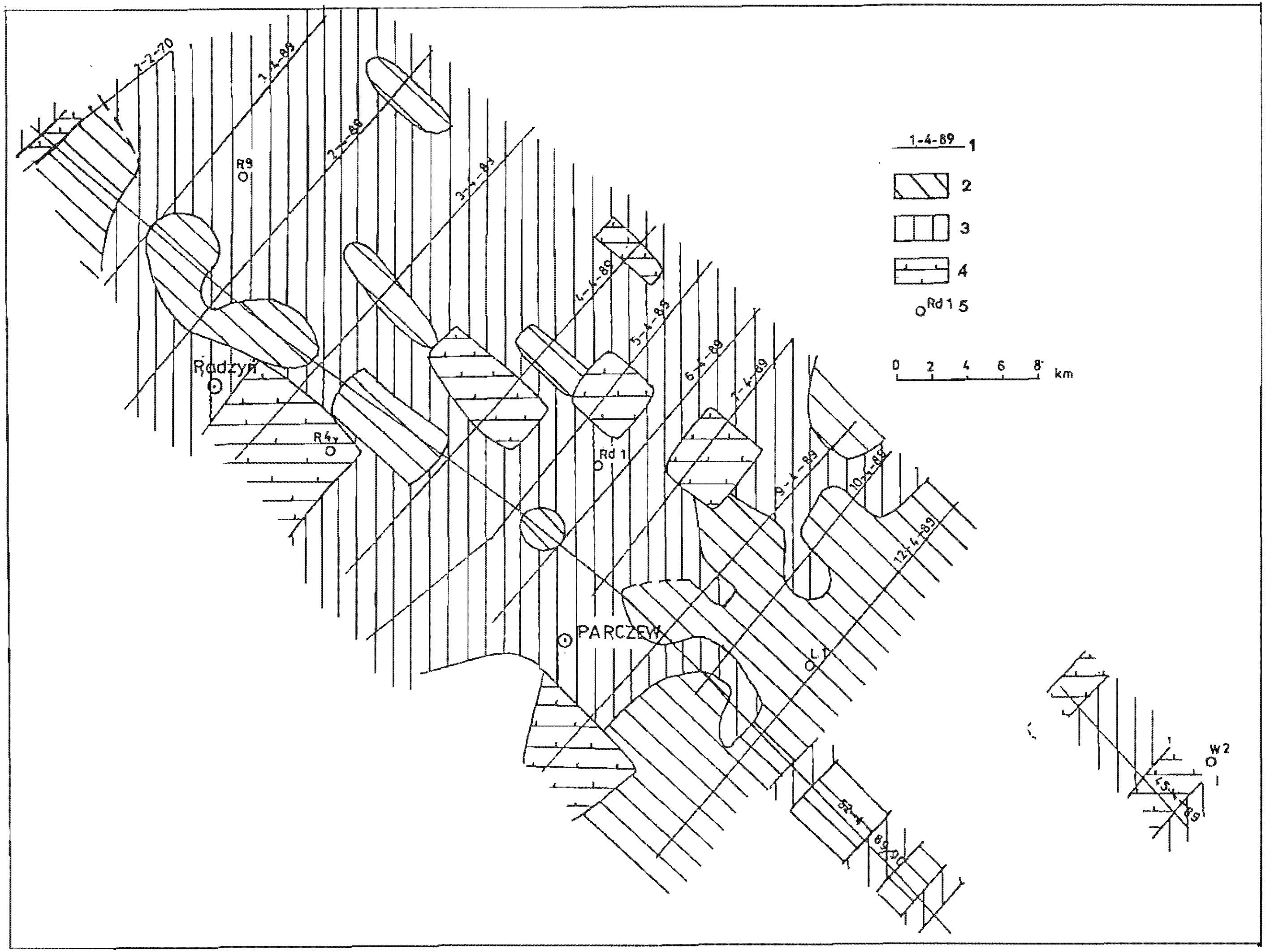
It is reasonable, when analysing LVZ thickness, to define its possible relationship with elevations of land surface as indicated in Figure 2. The sketch was compiled in a slighty simplified way, with five groups of land elevations distinguished. The course of the boundaries between particular elevation groups was delimited mid-way between the nearby profiles or the LVZ measurement points. It may happen that the elevations on the sketch are different from those taken from a topographic map if distances between the profiles are large. Comparison of sketches (Figs. 1 and 2) indicates that there is a small range in zone thickness — extreme value is equal to 8 m while 2–3 m is most common. On the other hand, the land elevations are more diverse and 50 m is the range of elevations, though in most of the area it does not exceed 10 m. Only this fact indicates it is difficult to find a relationship between the LVZ thickness and the land elevations. Nevertheless, a correspondence can be observed on the sketches. For instance, thickness in the range of 4–8 m predominates in the southeastern segment of profile 52-4-89/90 and all of profile 45-4-89, and this fact is followed by the highest elevations over the entire survey area. It is characteristic that the boundary between the highest and the lowest land elevations within the remaining area takes the SW–NE direction. This direction is very close to the direction of the LVZ isopachs and similarly it is parallel to the Hanna Fault. This is the basis for the conclusion that the Hanna

Fig. 2. Sketch of the land elevation

1 — seismic profiles; areas elevated: 2 — less than 150 m a.s.l., 3 — from 150 to 155 m a.s.l., 4 — from 155 to 160 m a.s.l., 5 — from 160 to 165 m a.s.l., 6 — from 165 to 196 m a.s.l.; 7 — boreholes

Szkic wysokości powierzchni terenu

1 — profile sejsmiczne; obszary o wysokości: 2 — poniżej 150 m n.p.m., 3 — od 150 do 155 m n.p.m., 4 — od 155 do 160 m n.p.m., 5 — od 160 do 165 m n.p.m., 6 — od 165 do 196 m n.p.m.; 7 — otwory wiertnicze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15-4-89
R9
R4
Rd 1
L 1
W 2
Radzyń
PARCZEW

Fault might affect both the isopach distribution and the land surface relief in this part of the survey area.

Correlation between the direction of the LVZ isopachs and the boundaries of particular land elevation groups can also be observed in other parts of the survey area including those on the northeastern segments of almost all seismic profiles. There is a change in the isopach direction on profiles 5-4-89 and 6-4-89 which is also followed by shifting of the elevation boundary toward the SW. Similarly, some agreement is reached between the boundary of the land elevation division and the isopach distribution between profiles 3-4-89 and 4-4-89 in the area north-east of profile 52-4-89/90. The course of LVZ isopachs approximates the boundaries of the land elevation division which is also clearly visible in other fragments of the area under consideration, for example, in the area of intersection between profiles 7-4-89 and 52-4-89/90. However, it is difficult to say that agreement was reached everywhere between the directions of the isopach course and the boundaries of the elevation division. There are different reasons for such a situation, including (for example) variations of lithology and physical properties of the near-surface deposits as well as the effect of other factors, including tectonics, on the water table configuration. The near-surface deposits were broadly discussed in T. Krynicki's work (1995). It is a characteristic fact that despite variations in the lithology of the surficial deposits the velocities of longitudinal wave propagation are close to each other and, in general, are low (Fig. 3). The velocities seem to primarily reflect the physical conditions of the deposits. Because they are unsaturated, they can be considered as having a similar porosity. It should be remembered that the velocities of wave propagation are in close relation to the porosity: the lower the velocity, the better the porosity.

For this reason, maps or sketches showing the velocity distribution within the low velocity zone may indirectly be used for determining infiltration conditions for rain water. As can be seen from the velocity distribution in Figure 3, the most favourable velocities, not more than 300 m/s though poorly differentiated, can be found in profiles 10-4-89 and 12-4-89 and in segments of profiles 9-4-89 and 52-4-89/90. No doubt, these velocities are very low and can be connected with a high percolation potential of rain water. Such low velocities were measured on the entire 12-4-89 profile or in the area where a large percent of the near-surface deposits are composed of clays and sands, with poor participation of peat. The presence of peat could clarify the low velocities; however, the velocities are too low on the part of the profile running through the area of sand and, in particular, clay occurrence. It seems reasonable to assume that a decrease of the velocity is caused by the peaty formations that accompany the water-logged areas.

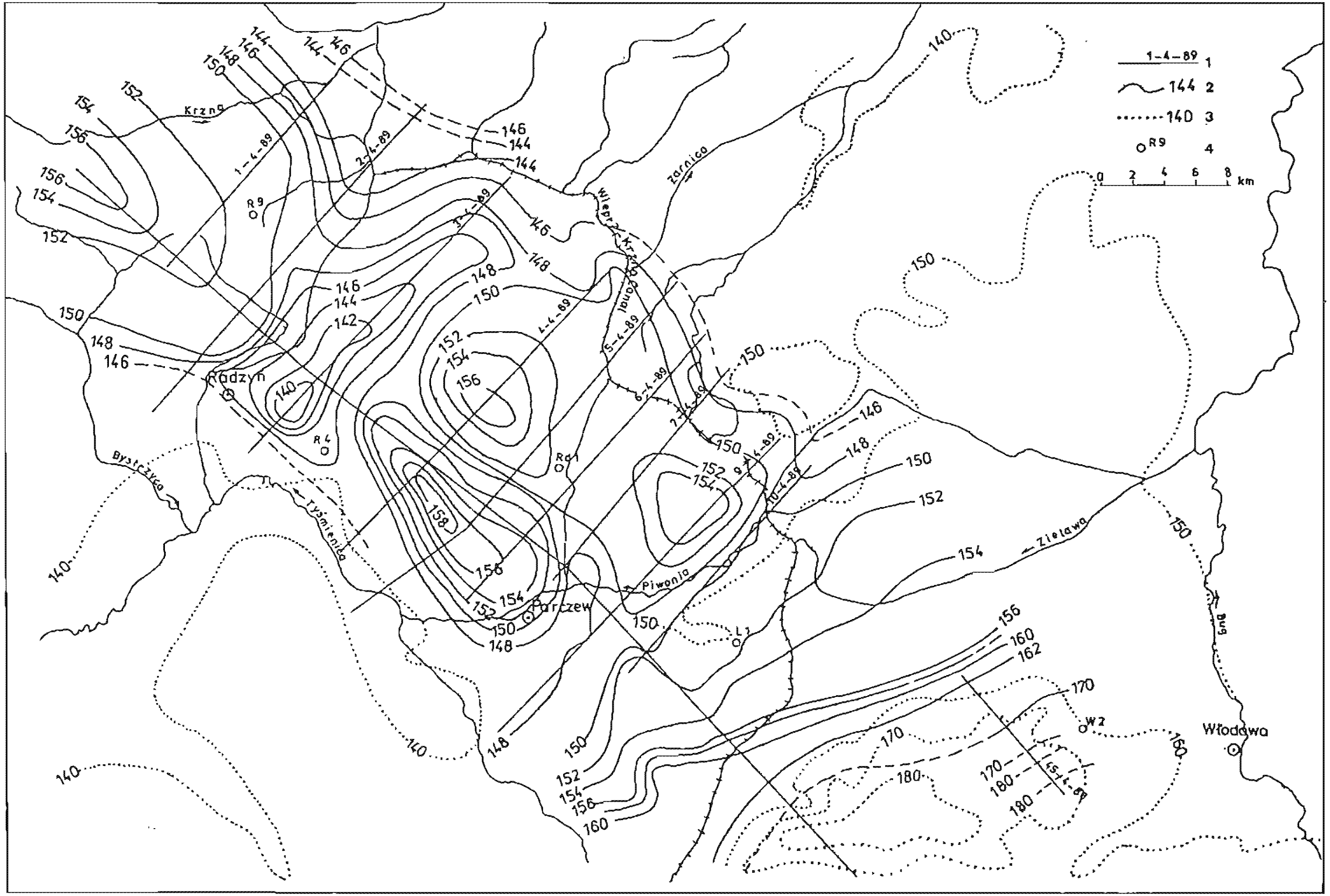
However, in the morphologically lowest area, where the land elevations do not exceed 150 m a.s.l., higher velocities (more than 300 m/s) were also recorded. Such is the case on

Fig. 3. Distribution of the longitudinal wave velocities within the low velocity zone

1 — seismic profiles; areas with velocities: 2 — up to 300 m/s, 3 — from 300 to 400 m/s, 4 — more than 400 m/s; 5 — boreholes

Rozkład prędkości fal podłużnych w strefie małych prędkości

1 — profile sejsmiczne; obszary z prędkościami: 2 — do 300 m/s, 3 — od 300 do 400 m/s, 4 — powyżej 400 m/s; 5 — otwory wiertnicze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a segment of profile 2-4-89, the location of which is approx. 7 km north-east of the intersection with profile 52-4-89/90. The velocities exceeding 400 m/s are of secondary importance and most likely are caused by an increased silting-up of the surficial deposits.

Some difficulties emerge when trying to find correlation, based only on LVZ measurements, between the lithology of near-surface deposits and the velocities of longitudinal wave propagation. However, the rather low velocities indicate that the zone is built up of dry deposits here, i.e. occurring above the water table. Therefore, the LVZ bottom can be identified with the bottom of aeration zone which is a subject of interest to hydrogeologists. Then, the LVZ thickness as presented in Figure 1 simultaneously constitutes the thickness of the aeration zone.

THE BOTTOM OF THE AERATION ZONE AND THE WATER TABLE

The accuracy of defining the thickness of the aeration zone (consequently, its bottom) using the seismic method is high and even exceeds the achievements of the vertical electrical sounding method that is common in hydrogeological investigations.

However, it is important to the hydrogeologist to define the depth to the water table. This depth cannot always be defined unequivocally from LVZ measurements only. This is due to the fact that the velocities of wave propagation are similar in saturated sands and wet clays or clays occurring below the water table. It is further noticed that seismic specialists involved in investigation of sedimentary rock complexes are not interested in differentiating saturated sands from wet clays, since a similar energetic effect is produced in both deposits when initiating the elastic waves using explosives. For this reason, and despite a huge amount of data acquired (some data already lost irretrievably), the issue of distinguishing lithologic beds within near-surface deposits has not yet been solved by any synthetic work.

With reference to data on the velocities of wave propagation, a conclusion can be drawn that in the sand profile the increase of velocity at the bottom of the aeration zone is induced, above all, by the presence of groundwater (which can be easily and accurately defined). If there are wet clays or clays below the aeration zone, then their top may mistakenly be identified as the water table. No doubt, under such circumstances the vertical electrical sounding method may be useful assuming that water mineralization is low.

The surface deposits in the survey area are composed of sands and clays (also, sandy clays); of secondary importance are clays, marls, and limestones. Carbonate deposits in the northeastern segment of profiles 9-4-89, 10-4-89, and 12-4-89 are covered with thin Quaternary cover, and sometimes with only a surface soil, scores of centimetres thick. It is worth noting that within solid formations including marls and limestones the water table

Fig. 4. Sketch of water table configuration

1 — seismic profiles; 2 — water table contours, in metres above sea level; 3 — water table contours according to a hydrogeological map scaled 1:200 000; 4 — boreholes

Szkic ukształtowania zwierciadła wód gruntowych

1 — profile sejsmiczne; 2 — hydroizohipsy w m n.p.m.; 3 — hydroizohipsy przeniesione z mapy hydrogeologicznej w skali 1:200 000; 4 — otwory wiertnicze

does not form a continuous, uniform plane unless a well fissured system is developed. It is possible to indirectly conclude the degree of fissuring based on the value of wave velocity. These relations will be discussed later. It should be noticed instead, that in the area under consideration the velocity of wave propagation through the carbonate rocks occurring beneath the aeration zone are relatively low. This may be a manifestation of a well developed fissure system and may suggest that one uniform and continuous water table will develop within the topmost part of the marl and limestone sequence.

The groundwater data from a number of dug and drilled wells, in principle irregularly located in more important localities, exhibits some differences in depths to the water table even in the same locality. The differences are not large; they are equal to several metres at most, and may be dependent on the water table fluctuation in particular years or seasons of the year when a well was completed. Driller's data on the depth to the first groundwater body is close to the thickness of the zone of aeration as concluded from the LVZ measurements. In addition, the water table contours on the hydrogeological map scaled 1:200 000 superimposed on the sketch showing the isolines (in metres above sea level) of the bottom of the aeration zone are to a large extent consistent as to their value and direction (Fig. 4).

One can wonder whether the aforementioned circumstances are sufficient to relate the isolines of the bottom of the aeration zone with the water table contours representing the elevation of this water table body. Most likely, some discord should be taken into consideration since the LVZ measurements were taken a couple of years ago. Even admitting some errors in determination of the water table in clays and carbonate formations on the basis of only LVZ measurements, was accepted here that the depth to the bottom of the aeration zone can be identified with the depth of the water table from the ground surface. Thus, it might be a common groundwater body with water table conditions, which is separated from the land surface by the zone of aeration.

CONFIGURATION OF THE WATER TABLE

The sketch shown in Figure 4 is based on the LVZ measurements that are contained in J. Brauer and W. Kulig's report (1991); exluded is data from the same area and its environs acquired in other years. For better presentation of the water table configuration a 2-metre vertical distance was selected for the water table contours; this vertical distance is less than that applied when a hydrogeological map on the scale of 1:200 000 was compiled.

From consideration of general arrangement of water table contours in the horizontal profile, three distinct regions can be distinguished in the survey area:

— western region — extending more or less to profile 2-4-89;
— central region — between profiles 2-4-89 and 10-4-89;
— eastern region.

The water table contours in the first two regions and part of the eastern region are between 146 and 156 m a.s.l. Elevation of the water table changes irregularly. For example, there are very low gradients on the entire lenght of profiles 10-4-89 and 12-4-89 and a long segment of profile 1-4-89. On the contrary, an increase of the water table gradient and a change in the course of the water table contours appear in the vicinity of profile 3-4-89.

Larger water table gradients are observed in the central region, south of profile 52-4-89/90. Only in this region are there some water table elevations that do not fit the general arrangement of the water table contours. Similarly, other seismic data was excluded from the sketch along the southeastern segment of profile 52-4-89/90 and all of profile 45-4-89. Abrupt variations in the water table elevations may be caused by different factors among which the importance of a tectonic factor seems to be most likely.

When comparing values of the water table contours plotted according to the seismic data with those plotted from hydrogeological data (where it was possible, of course) a conclusion was drawn that both are close to each other. The course of the water table contours is also consistent. However, with respect to data acquired on the configuration of the water table, the LVZ measurements appear to be more important than those acquired from the hydrogeological study. The results of the hydrogeological study are more detailed only in the vicinity of profile 45-4-89 and the terminal segment of profile 52-4-89/90. Long distance between analysed seismic profiles is the reason for this situation.

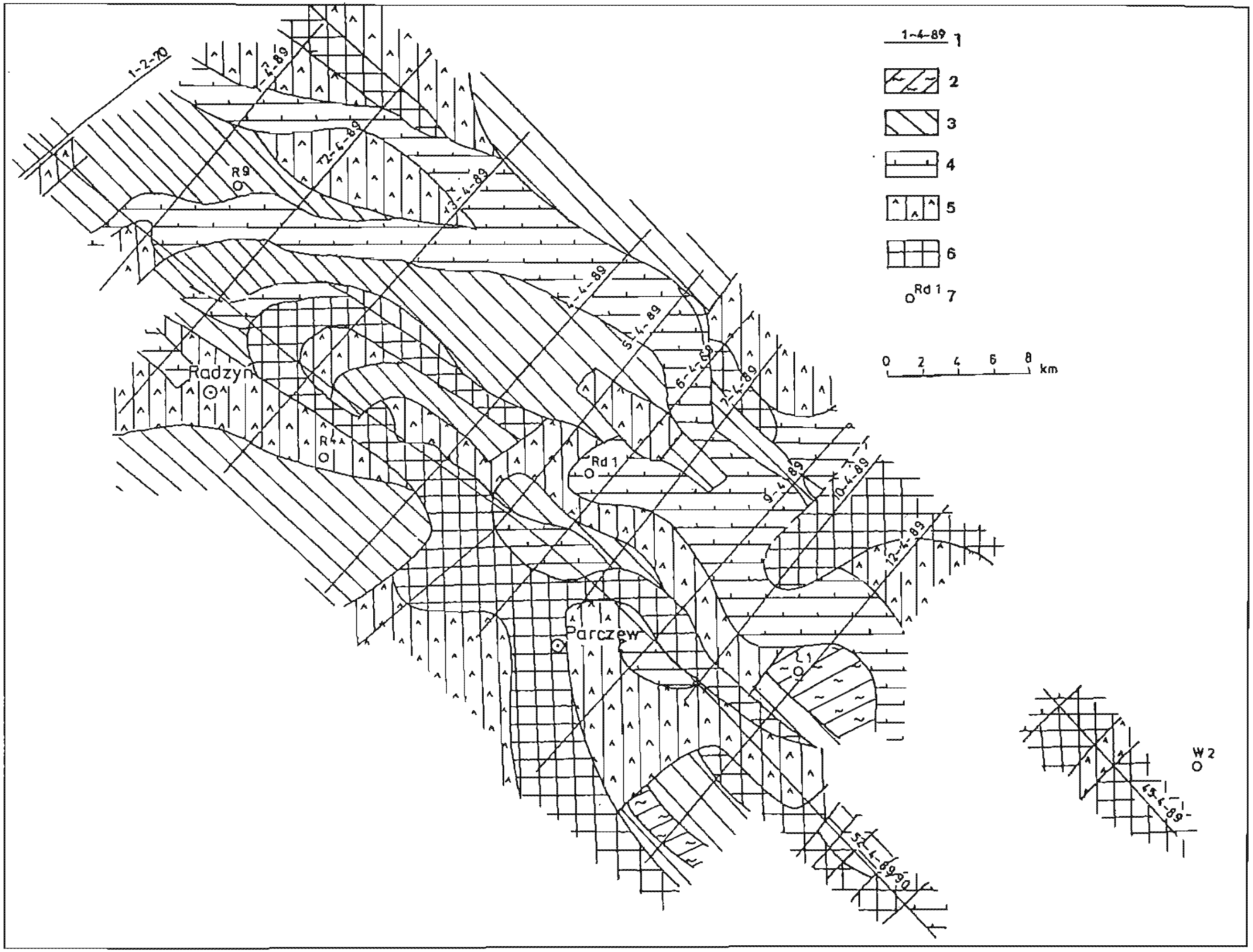
VELOCITY OF ELASTIC WAVE PROPAGATION THROUGH THE FORMATION BENEATH THE AERATION ZONE

Figure 5 shows the distribution of the wave propagation velocity through the formation occurring beneath the aeration zone. Some groups of velocities containing common variations in the velocity at each 100 m/s were drawn on the sketch to increase its legibility. A velocity group in the range of 1700–1720 m/s is an exceptional case; such are the velocities recorded on all profiles in the NW–SE direction.

At a glance it is possible to conclude that the image on the sketch is diverse; also, any correlation of the velocity distribution is missing in the aeration zone (Fig. 3). Similar groups of velocity variations, in principle equal to 100 m/s, were applied when plotting both sketches. Thus, it can be concluded that the reasons why there is no correlation between the velocities are not connected with the way the sketches were compiled.

It should be mentioned that the velocities of the longitudinal wave propagation are in the range of 1500–2000 m/s through the saturated sands whereas 1700 to 2500 m/s in loams and clays. Such are the average velocities that have emerged from a huge number of measurements taken in different areas of Poland. In solid rocks such as limestones (for example), as well as those occurring beneath the groundwater table, the velocities are variable within a broad range from 2000 to 4500 m/s and depend on the degree of rock consolidation. Because the velocities are similar in granular formations and in weakly cohesive formations it is difficult to determine the lithology of formations beneath the aeration zone using the velocity parameter only. Nevertheless, in these cases the rule that the increase in the velocity of seismic wave propagation through the formations of similar lithology follows a decrease in porosity remains valid.

From among the zones of similar velocities, attention should be directed to that zone where the velocities are 1700–1720 m/s. Despite insignificant range of variation, this zone is the longest. Its width is variable, and eastward of profile 3-4-89 it is divided into narrow subzones. The constant velocities can be interpreted by the occurrence in this zone of a formation with a very uniform lithology.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10-4-89
12-4-89
15-4-89
52-4-89/90
R9
R4
Rd 1
W 2
Radzyn
Parczew

Some difficulties may appear when defining the lithology of deposits beneath the aeration zone based only on the velocities acquired from LVZ measurements. However, these velocities can be used to characterize their surface distribution and to identify zones of similar velocities. In this way some zones can be defined where formations of similar elastic parameters occur.

Based on the general distribution of the velocities in the survey area (Fig. 5), three regions could be distinguished:

— western, with its eastern boundary running between profiles 3-43-89 and 4-4-89;
— central, extending eastward up to profile 6-4-89;
— eastern, within the area with remaining profiles.

A SW–NE direction of the boundaries of similar-velocity zones dominates in the western region whereas NW–SE is a predominant direction within the eastern region. The boundaries of the similar-velocity zone are variable in the central region. There is a large variation of both the velocities and the boundaries of particular zones along profile 52-4-89. Frequent changes of velocity also appear along all of profile 12-4-89 and the southeastern segment of profile 52-4-89/90.

Once the distribution of the elastic wave velocity as presented in Figure 5 have been used to characterize the elastic properties of the formation beneath the aeration zone, then the boundaries of the velocity regions or distinguished zones can be expected to correlate to some extent with some subterranean factors, and above all with processes of hydrogeological nature that are influenced by tectonic manifestations. It is a broad question how the tectonics affect the hydrogeological conditions; this question awaits a separate discussion.

CONCLUSIONS

Data from the LVZ measurements inherent in seismic investigation may be helpful in investigating hydrogeological conditions. They allow determination of the thickness of the aeration zone and the velocities of elastic wave propagation to be made; they also allow assessment of the cohesiveness of soils.

The results of LVZ measurements contain information on the water table and the directions of groundwater flow, and the values of hydraulic gradients as well. Based on such data it is possible to prepare water table contour maps, in particular for unpopulated areas where hydrogeological data is scanty. The seismic data including the LVZ measurements should also be used for compilation of geological maps of the near-surface formations and hydrogeological maps as well. Also, cost of preparation of a site investigation report can

Fig. 5. Distribution of the longitudinal wave velocities within the formations beneath the aeration zone

1 — seismic profiles; velocity zones: 2 — less than 1600 m/s, 3 — from 1600 to 1690 m/s, 4 — from 1700 to 1720 m/s, 5 — from 1730 to 1800 m/s, 6 — more than 1800 m/s; 7 — boreholes

Rozkład prędkości fal podłużnych w utworach poniżej strefy aeracji

1 — profile sejsmiczne; strefy prędkości: 2 — poniżej 1600 m/s, 3 — od 1600 do 1690 m/s, 4 — od 1700 do 1720 m/s, 5 — od 1730 do 1800 m/s, 6 — powyżej 1800 m/s; 7 — otwory wiertnicze

be decreased in the event the information acquired in the course of the seismic investigation is reasonably utilised.

Obviously, both the velocity and the thickness maps prepared for the low velocity zone would be applicable in calculation of static corrections, particularly in the event that surface energy sources were employed.

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WYKORZYSTANIE POMIARÓW STREFY MAŁYCH PRĘDKOŚCI W HYDROGEOLOGII I GEOLOGII INŻYNIERSKIEJ

Streszczenie

Przedstawiono wyniki analizy pomiarów strefy małych prędkości wykonanych na Polesiu Lubelskim. Opracowano szkic miąższości strefy aeracji oraz szkic rozkładu prędkości rozchodzenia się w niej fal podłużnych. Prędkości w strefie aeracji są mało zróżnicowane. Szkic swobodnego zwierciadła wód gruntowych wskazuje na jego urozmaicone ukształtowanie. Na podstawie prędkości propagacji fal w utworach poniżej strefy aeracji wyodrębniono kilka stref, z których jedna o prędkości 1700–1720 m/s powinna być przedmiotem szczegółowych badań, w tym także hydrogeologicznych.