ECOHYDROLOGY
ASIA - PACIFIC
REGION

GROUNDWATER ASSESSMENT AND MODELING UTILIZING REFRACTION SEISMIC SURVEYS

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Proceedings of
Asia-Pacific Workshop
on Ecohydrology,
Indonesia, 2001

ABSTRACT

A series of refraction seismic surveys has been conducted over alluvial deposits in Rapid City, South Dakota, to determine the thickness of saturated aquifer. The results indicate the presence of three rock strata consist of: (1) Unsaturated alluvium at the very top, which yielded average seismic velocity of 215 m/s and thickness ranging from 1.3 m to 2.7 m; (2) Saturated alluvium, which had seismic velocity of 1200 m/s to 1765 m/s and thickness ranging from 7.2 m to 11.0 m; and (3) Impermeable red shale of Spearfish Formation, which yielded seismic velocity of 2300 m/s. The contact between the alluvium and the Spearfish Formation is undulatory, representing the old Rapid Creek erosional surface, along which several major paleochannels were recognized adjacent to the current Rapid Creek channel.

Data from seismic surveys were also used to asses groundwater resources and to model groundwater flow for best possible withdrawal methods. The results showed that a pumping well penetrated to the bottom of the aquifer was able to discharge more than 54,000 lt/hr or 3,200,000 lt/day, and recharge from adjacent Rapid Creek could return the water table to nearly its original position within a few hours. Assuming that water from the Rapid Creek can sufficiently recharge the aquifer throughout the area of study, Rapid Creek alluvium aquifer can provide all local water demands.

Key words: groundwater; seismic survey

1. INTRODUCTION

Rapid City is a community with a population of 60,000, located in the east flank of the Black Hills uplift, South Dakota. The community consumed approximately 48 million liters of water daily, which were withdrawn from several venues such as alluvium aquifer, deep pumping wells, and water directly pumped from adjacent creek. More than half of the water supply (26 million liters) came from Rapid Creek alluvium aquifer, collected through several collection galleries, buried at depths between 3 m and 4 m. The use of collection galleries has been the preferred choice, because of their economical advantage. The operation and maintenance of the galleries cost only $ 1.50 per million liters of water, whereas pumping water directly from Rapid Creek costs about $ 13.00 to produce the same amount of water. Due to their economical advantage and expected increase in water demand in the future, the use of collection galleries could be expanded to serve the need of Rapid City's water supply.

The interest in this project arose, because little information is available on the properties and extent of the aquifer. This survey attempts to investigate and asses the aquifer properties such as, depth and thickness, lateral extent, permeability, and specific capacity. Depth, thickness, and lateral extent were investigated utilizing refraction seismic, whereas permeability and specific capacity were investigated by conducting pumping tests and computer modeling.

2. GEOLOGICAL SETTING

The area of study is located in the eastern flank of the Black Hills uplift, at the bottom of a long and narrow depression known as the Red Valley, which is underlain by a sequence of Triassic sedimentary rocks, mainly consist of red, silty shale, and in some places gypsum. In the vicinity of Rapid City, where this study was conducted, the shale is overlain by alluvium deposits of Rapid Creek flood plain (Figure 1). The plain is nearly flat and mostly covered by grass fields, trees, and sidewalk as parts of city parks system.

The alluvium deposits are a mix of dark brown silty clay with silt, sand, and gravel. At the very top is lean sandy clay, underlain by a thin layer of clayey gravel. At the bottom is a layer unconsolidated to moderately consolidated sandy gravel, which consists of well-rounded rocks of older formations from the center of the Black Hills uplift, such as quartz, quartzite, chert, and limestone. This layer generally has excellent porosity of up to 30% and forms much of the alluvium aquifer.

3. REFRACTION SEISMIC SURVEYS AND RESULTS

Refraction seismic surveys were conducted using a 12-channel seismograph, EG & G Geometrics model ES-1210, with 14 hertz geophones as receivers. Both sledge hammer and seisgun were used for energy source. A total of 15 seismic lines were completed, equal to a cumulative length of more than 3000 meters, mostly at directions perpendicular to the Rapid Creek axis. Each line was shot twice, forward and reverse directions, for the correction and detection of dipping layers. Data processing of seismic data to determine seismic velocities and thickness were done using computer programs written in FORTRAN, namely SIPT1, published by US Geological Survey (Scott, 1978). The programs utilize a delay-time method combined with a ray-tracing technique to smooth out depth calculations. This combined method was very useful in dealing with undulatory refractors commonly found throughout the area of study and have greatly enhanced the quality of seismic interpretations.

Prior to these surveys little was known about the seismic velocities of the Spearfish Formation and the alluvium aquifer in the area of study. Preliminary seismic surveys were therefore necessary to determine their in situ properties. To achieve this, seismic velocity of Spearfish Formation were measured directly on its outcrops and it yielded seismic velocity of 690 m/s for weathered shale, and 2300 m/s for the fresh one. Throughout the Black Hills shale lithology is relatively homogenous, and their seismic properties are expected to be homogenous as well. It is assumed that the above seismic properties represent typical properties of shale in the region, and will be used as a reference for shale seismic velocity in this study whenever uncertainty arises. The use of velocity reference was important, because results from refraction surveys varied considerably from one place to another due to field irregularities.

Under ideal conditions, where layer interfaces are flat and horizontal, seismic velocities of each layer can be determined from travel-time curves using conventional method:

$$V_i = \frac{dx}{DT} \qquad (1)$$

Where

Vi seismic velocity of the i^{th} layer

dx horizontal differential

dT travel time differential.

The geological conditions in the area of study, however, is far from being ideal, where the layers are neither smooth nor harizontal. To overcome the effects of these irregularities, we implement linear regression method to determined dx/dT slope by considering travel times from both ends of the seismic lines (forward and reverse shots). This method can be conveniently formulated as:

$$V = \frac{\square\,[X1_i - X2_i]2 - [(X1_i - X2_i)]/n}{\square[X1_i - X2_i][T1_i - T2_i] - [\square\square(X1_i - X2_i)][\square(T1_i - T2_i)]/n} \qquad (2)$$

where

$X1_i$ distances between the i^{th} geophone and the forward shot point

$X2_i$ distances between the i^{th} geophone and the reverse shot point

$T1_i$ arrival times at the i^{th} geophone from forward shot point

$T2_i$ arrival times at the i^{th} geophone from reverse shot point.

Results of velocity calculations using equation 2 are presented in Table 1. Seismic velocities of near surface, unsaturated alluvium deposits were generally simpler to determine. Their average seismic velocities (V_1) of 360 m/s. Lower velocities are usually associated with porous soils, and the higher ones are associated with gravel. In some localities, where soils were more heavily weathered V_1 is often lower than 210 m/s. For saturated alluvium, seismic velocities range between 1100 m/s and 1760 m/s, but most of them were between 1350 m/s and 1500 m/s, with an average velocity of 1430 m/s. The existence of weathered red shale below the unsaturated alluvium is unclear. However, observations on older erosion surface show sharp contacts between the overlying alluvium deposits and the underlying shale. In this study it is also assumed that no such layer exists.

Seismic velocities of shales vary considerbaly throughout the area of study due to highly undulatory surface along the bedrock surface, which were difficult to resolve using refraction method. In some locations the calculated velocities were lower than 2100 m/s, and cause inaccurate depth estimates. In order to obtain better depth estimates, all seismic velocities of shales lower than 2100 m/s were substituted by the standard shale seismic velocity of 2300 m/s. This procedure significantly improved the accuracy of depth computations.

Water table depths and layer thickness determine from seismic surveys were in a good agreement with field observations through monitoring wells available in the area of study (Figure 2), where seismic velocity discontinuities generally were located adjacent to lithologic boundaries. At the very top, water table determined from seismic surveys were slightly lower than well observations. These differences were suspected due to patchy low velocity zones related to weathered

Table 1. Seismic velocities and thickness of the corresponding layers

Location	SEISMIC VELOCITY (m/s)			THICKNESS (m)	
	V1	V2	V3	Layer 1	Layer 2
SP#1A	279	1576	2406	1.2	8.5
SP#1B	305	1495	2423	1.9	5.9
SP#2	259	1533	2326	1.0	9.8
SP#3	227	1535	1972	1.3	7.9
RP#1	200	1576	2181	0.9	5.7
RP#2	276	1807	2405	2.0	10.0
NGS#1A	181	1679	2164	1.1	7.8
NGS#1B	250	1385	1951	1.2	3.1
NGS#2A	319	1286	2076	1.5	10.5
NGS#2B	322	1378	1966	2.0	7.5
NGS#3A	270	1510	2612	1.2	8.4
NGS#3B	274	1234	1939	1.0	3.1
NGS#4A	358	1509	2195	1.8	4.2
NGS#4B	340	1652	2222	1.4	5.8
NGS#5	366	1286	2829	1.9	4.8
NGS#6	344	1285	1945	1.6	5.1
SGS#1	309	1064	1978	1.3	7.7
BP#1	344	1210	2071	1.3	3.8

soil on the surface, which caused a slight delay in arrival times. The next velocity discontinuity is correlated to the boundaries between alluvium and the underlying Spearfish Formation. The contact is undulatory, representing erosional surfaces of older Rapid Creek. Almost all deep channels are located adjacent to the current Rapid Creek, suggesting that channel locations have not changed much since the beginning of alluvium deposition.

4. PUMPING TEST AND GROUNDWATER MODELING

Pumping tests were conducted at three locations, *i.e.* Braeburn Park, Sioux Park, and Baken Park (Figure 1), all were located adjacent to the Rapid Creek. All wells were drilled penetrating into the bedrock, with saturated alluvium thickness of up to 16 feet. During pumping tests drawdown and recovery data were recorded and analyzed using conventional Theis method. Results of pumping tests show that the aquifer has a wide range of porosities and permeabilities, but at all locations it appears that the aquifer is hydraulically connected with Rapid Creek. Two locations were very promissing for future collection galleries, *i.e.* Braeburn and Sioux Parks, which were able to produce 2200 L/min and 820 L/min of water respectively (Table 2). Baken Park is considered unfavorable due to its low permeability caused by high clay content (only able to discharge 110 L/min) and bitter taste in the water.

Table 2. Aquifer properties of Rapid Creek alluvium deposits determined from three pumping tests.

Aquifer Properties	**Units**	**Baken Park**	**Braeburn Park**	**Sioux Park**
Discharge, Q	liter/min	110	2,250	830
Permeability, K	cm/s	0.012	0.173	0.075
Transmissivity, T	cm^2/s	0.000008	0.000122	0.000053
Hidr. conductivity, k	cm/s	0.0944	0.8024	0.4720
Saturated thickness, b	Meters	2.4	4.8	5.4
Storage coefficient, S		0.16	0.16	0.15
Specific capacity, Cs	cm^2/s	0.000043	0.00144	0.00049
Collection galleries ?		no	OK	OK

Utilizing the data sets of seismic, monitoring well, and pumping test observations, groundwater flow and discharge were modeled to investigate aquifer performance. Assuming the aquifer is homogenous and the rate of recharge from the adjacent Rapid Creek is constant, the discharge was modeled to resemble collection galleries, and variable discharge rates were tested. It is found that a 10-foot collection gallery in Sioux Park could produce 3 million liters of water within a period of 15 hours. In the stated period the maximum drawdown was 11 feet at the center of the collection gallery. After the pumping ceased, water table recovered to nearly its original position within 3 hours. Aquifer at Braeburn Park is expected to perform better because of more superior aquifer properties, and therefore was not modeled. Provided that the discharge of Rapid Creek is sufficiently continous, all water demand can be supplied by the alluvium aquifer by building a number of collection galleries in different locations within the area of study.

5. CONCLUSION

Seismic refraction method has been very useful as a tool for shallow subsurface investigation in the area of study. using the method, depths of aquifer discontinuities could be resolved fairly accurate to be used for groundwater assessment and modeling. Results of groundwater flow modeling suggests that the Rapid Creek alluvium aquifer is very promissing as a source of all Rapic City water supply.

Acknowledgment

Author wishes to thank Earl Green of South Dakota Geological Survey who provided the hardwares and crews to do these surveys. Darrel and Dave are appreciated for their assistance during those long and hot summer days. The assistance of Debra to finish several last lines are also acknowledged.

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