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Seismic Refraction Survey to Investigate Shallow Sediments of Wadi Thuwal, North of Jeddah, KSA

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Abstract. A seismic refraction survey was conducted along 32 seismic profiles, to study the near-surface sediments and to delineate the level of the water table in Wadi Thuwal area, which is located 110 km to the north of Jeddah, KSA. Processing and interpretation of seismic data established a 2D-geo-seismic model consisting mainly of three layers: a surface wadi fill layer (sand and silt) with low average seismic velocity of 420 m/s, dry to water-saturated sand, clay and conglomerate with moderate average velocity of 1150 m/s, and a reefal limestone bedrock with high average velocity of 2710 m/s. Seismic velocities (V) of the delineated seismic layers were analyzed. Consequently, a linear relationship between seismic velocities and depth ($Z = 2.134 - 0.0085\ V$) was found, suggesting that there exists of a uniform seismic gradient across these seismic layers. A zone of lower bedrock velocity (1700 m/s) was outlined at the eastern part of the study area, adjacent to Harrat Thuwal, indicating a highly weathered fractured limestone. There is a gradual increase in the bedrock seismic velocity and depth from east to west and to north. Published velocity-rippability relations were used to confirm that the bedrock of the western part of the area would require blasting for excavation. It was difficult to determine water table depth because the high bedrock seismic velocity has, in some localities, masked the signature of the relatively lower seismic velocity indicative to the water table.

Keywords. Seismic, Wadi Thuwal, ray-tracing.

Introduction

This study presents the seismic refraction survey carried out at the promising Wadi Thuwal area, located about 110 km to the north of Jeddah and to the southeast of the newly established King Abdullah University for Science and Technology. The survey was started in Sept. 2007 and completed in Dec. 2008. Seismic refraction was conducted as a part of an aggregation of integrated geophysical surveys (magnetic, electric resistivity and time-domain electromagnetic (TDEM)), in order to investigate the nature of subsurface sediments and the groundwater potentiality and quality in Wadi Thuwal area. The main purpose of performing the seismic refraction survey at Wadi Thuwal area was to assess the near-surface sediments, outline bedrock topography and its relative strength, and to determine water table depth to evaluate the prevailing hydrogeologic conditions of the area.

The seismic refraction technique was used in the present study because, during the last four decades, it had widespread application in the delineation of shallow subsurface structures and in mapping bedrock topography and fractures, which ought to control the groundwater potentiality and its flow. Moreover, in areas characterized by complex geological structures, the seismic refraction technique has played a very important role in building up a precise geological model of the subsurface, because it provides inclusive coverage over the exploration area. Many workers have utilized seismic refraction technique to characterize bedrock in delineating subsurface structures for engineering purposes and in hydrogeologic studies. Among those are Redpath (1973); Dutta (1984); Palmer (2001); Bennett (1999); El-Behiry (1994, 1997 & 1999); Deen *et al.* (2000); El-Behiry *et al.* (1992, 1994); VGS (2003); Venkateswara *et al*. (2004); El-Behiry and El-Difrawy (2005); Rucker (2000); Sirles *et al.* (2006); Mokhtar and El-Behiry (2007); Christopher *et al.* (2008); and others.

Geology and Geomorphology of Wadi Thuwal

Wadi Thuwal area is bounded by latitudes 22° 10′ 00" and 22° 16′ 53.54" N and longitudes 39° 06′ 40" and 39° 16′ 20" E and lies just to the west of the Arabian Shield of Saudi Arabia and constitutes a part of the Red Sea coast (Fig. 1). Geologic mapping of the study area was essentially based on new data collected from the interpretation of satellite images and detailed field work carried out by Abdelwahed (2009) in addition to the previous work done by Ramsay (1986) and Johnson (2006). The geomorphology of the study area is represented by a wide coastal plain that covers most of the area and a basalt (Harrat Thuwal) plateau occupying its northeastern part (Fig. 2). The coastal plain is almost flat of a general northwest gentle slope. It is traversed by simple systems of drainage lines that mostly fade out in the central part of the area. The main channel runs from the southeast (the upstream) to the northwest (downstream) close to the basalt plateau, which is a fault controlled mass extending along a NW-SE direction. The general stratigraphic column of the study area and its surroundings is presented in Table 1.

Based on field investigations, the main rock units exposed in the study area are the Cenozoic sedimentary and volcanic rocks, which are represented by the Oligocene-Miocene sediments (Shumaysi Formation), the Quaternary Basalt (Harrat Thuwal), and the Holocene Wadi deposits. The exposures of the former two units constitute plateau landforms and their distribution is largely controlled by normal faulting.

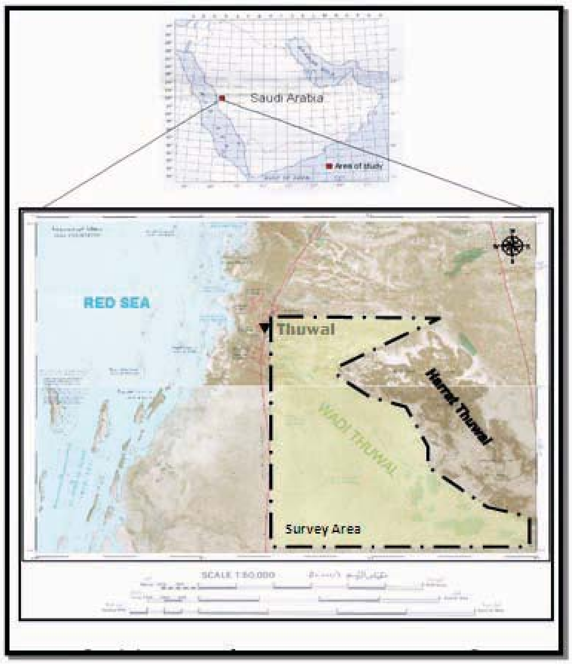

Fig. 1. Location map of Wadi Thuwal and the outline of the survey area.

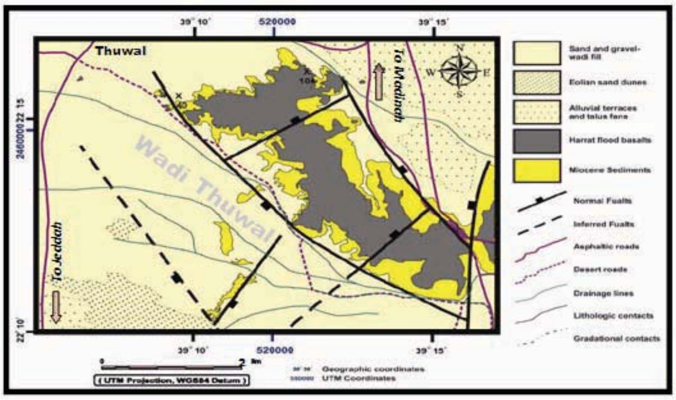

Fig. 2. Geologic map of Wadi Thuwal area (Al-Garni *et al.*, 2009).

Table 1. General stratigraphic column of Wadi Thuwal area and neighborhood.

Cenozoic sedimentary and volcanic rocks	**6- The Holocene Wadi deposits.**	
	5- The Quaternary Basalt (*Harrat Thuwal and Harrat Khulaysiyah*).	
	4- The Oligocene-Miocene Sediments. (*Shumaysi Formation*).	***Nonconformity***
Precambrian basement rocks	3- Younger dykes.	
	2- Kamil Suit. (mainly tonalites)	
	1- Samran Group. (*metavolcanics, metavolcaniclastics and metasediments*).	

The Oligocene-Miocene Sediments (Shumaysi Formation) in Wadi Thuwal area are frequently masked under a cover of basaltic boulders weathered out from the Harrat volcanics. Good exposures could however be recognized at three locations (Abdelwahed, 2009): (a) At the extreme southeastern part of the study area, to the west of Al Madinah road; where there exists about 15 m thick exposure of alternating red and green clays alternating with sandstones; (b) at the northern part along quarry faces cut below the wadi level in the downthrown block of the master normal fault that controls Harrat Thuwal from its western side, is represented by a 10 m thick alternating layers of red clays and conglomerates; and (c) at the central and southern parts along the coastal plain as low lying reefal limestone exposures.

The coastal plain of Wadi Thuwal area is formed by the Holocene sediments that cover most of its surface area. These sediments are represented by three varieties (Fig. 2); namely sand and gravel wadi fill, eolian sand dunes that mainly occur in the southern parts, and alluvial terraces which could be mapped at the extreme southwestern parts along a quarry face, cut below the wadi level. The sandy wadi fill forms most of the coastal plain of the study area.

Seismic Refraction Measurements (survey design and field procedures)

A total of 32 seismic refraction profiles, with total line-meters of about 15.5 km, were performed at the study area of Wadi Thuwal (Fig. 3). The locations and extensions of the conducted seismic profiles were essentially controlled by the abundance of aeolian sand dunes, exhaustive net of man-made sand barriers (Ogum), and huge excavations of old quarries, which occupy many parts of the area. However, three main factors were taken into account when positioning the seismic lines and during the course of field data acquisition; these are:

1- The performed seismic lines were, up to the extent possible, positioned at the locations of other geophysical surveys conducted in the area, to allow integration of their findings, with ours.

2- The seismic lines were mostly performed traversing the main course of Wadi Thuwal and its tributaries. This is to delineate the extensions of these channels, which consequently may help in assessing groundwater potentiality in the area.

3- Specifically, the seismic refraction line # L-1 was performed at the excavation base of a quarry at the extreme southwestern part of the area in order to reach greater probing depth.

4- The seismic lines were positioned such that to further investigate geologic structures revealed by geologic and magnetic studies.

A schematic drawing is presented (Fig. 4) to illustrate the applied seismic refraction field layout, and Table 2 lists survey parameters and geometries. These parameters are the most commonly applied for seismic refraction surveys for groundwater, engineering and environmental applications (Lankston, 1997). In refraction surveys, depth of investigation is related both to the length of the surface spread of geophones and source points, and the expected subsurface velocities. Since bedrock in the survey area probably consists of relatively high velocity material (assumed greater than 2500 m/s), the first geophone to "receive" refraction signal from that layer would be at a distance of 3 to 4 times the expected depth. A conservative estimate of maximum probing depth of investigation is made accordingly as the total spread length is divided by 3 (Moony, 1980). In the present study, the spread length was designed as such that a high S/N ratio is obtained and an average minimum probing depth of about 50 m is achieved. This depth is adequate to delineate fully the topography of high seismic velocity elements of the bedrock. Figure (5) shows the equipment layout and field operation during the data acquisition in Wadi Thuwal area. The good quality of first break times for both near and far traces is evident from the seismic records presented in Fig. (6). Sometimes, however, first break times become less distinctive with increasing distance from shot due to lower S/N ratio. In this case, event timing becomes legitimate for the long offset shots because the objective is to obtain arrivals for phantoming to the near shots.

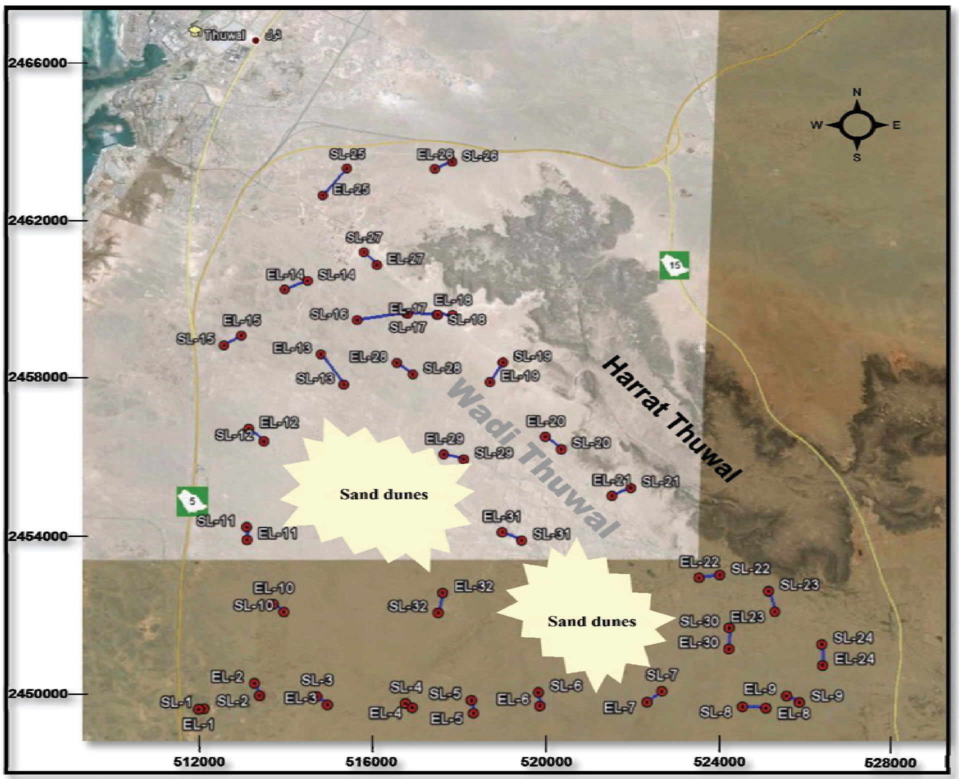

Fig. 3. **Satellite image of Wadi Thuwal area showing the location, distribution and orientation of the performed seismic refraction lines. ("S" denotes start of line and "E" denotes end of line).**

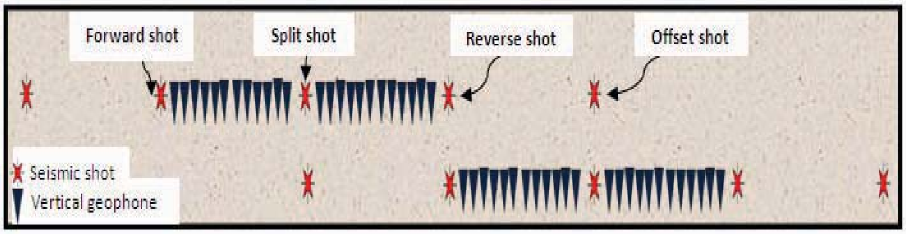

Fig. 4. Schematic plan of field seismic refraction survey layout, Wadi Thuwal area.

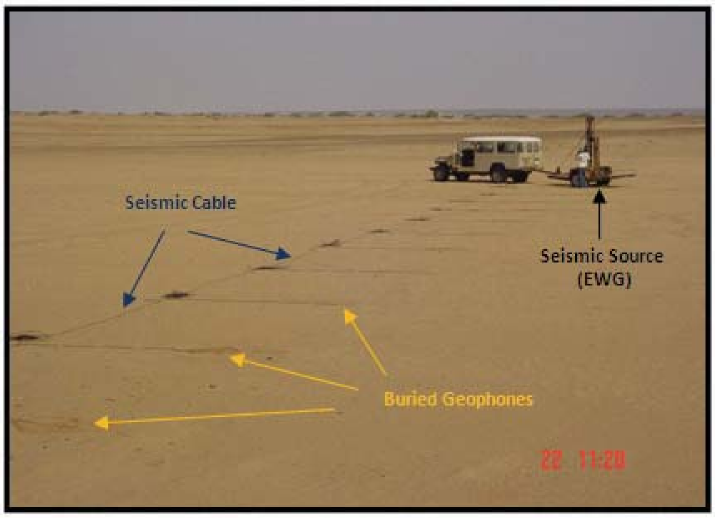

Fig. 5. Seismic field layout and operation in Wadi Thuwal area.

Table 2. Seismic survey parameters, Wadi Thuwal area.

Seismic Parameters	Specifications
Inter-geophone spacing	5.0 m
Shot-1st-geophone spacing	2.5 m
Number of geophones per spread	24 geophones
Offset shot-near geophone distance	30 – 60 m
Number of shots per spread	5 – 7 shots
Min. number of spreads per seismic line	2
Max. number of spreads per seismic line	9
Min. length of seismic line	120 m (L-1 in excavation pit) + 60 m offset
Max. length of seismic line	1080 m (L-16) + 120 m offset
Total number of fired seismic shots	534 shots
Expected probing depth	50-60 m
Total line-meters of performed seismic lines	15,480.0 meters

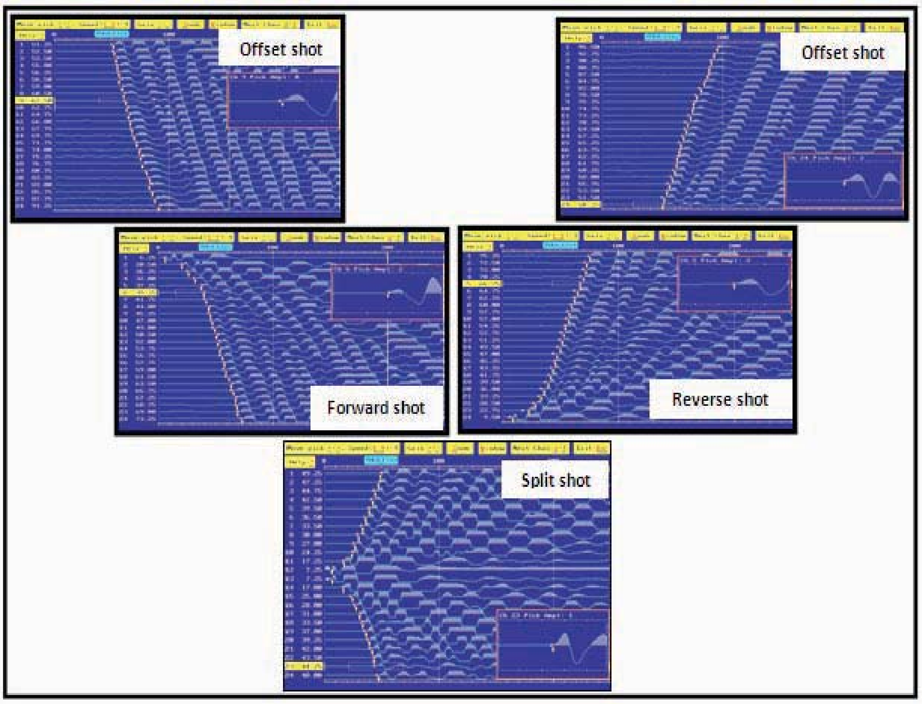

Fig. 6: Examples of field seismograms of different seismic shots along one spread.

Seismic Refraction Data Processing and Analysis

The refraction seismic data were processed and interpreted using the widely used SIP (V.4.1) set of computer programs from Rimrock Geophysics Inc. (Rimrock Geophysics, 2003). The processing and interpretation sequence consisted of picking the first breaks, creation of data files for the interpretation program through modeling and iterative ray-tracing techniques. After ensuring that good quality seismic signals were recorded in the field, the first step in processing was to pick the first-break times and plot the travel-time curve for each shot. These travel time data were then verified for both reciprocity and parallelism. Inspection of the observed travel time curves revealed the following remarks: (1) In general, they suggest essentially a three layer subsurface medium. (2) Although the man-made sand barriers (Ogum) were everywhere in the study area, a great consideration was given to avoid them. Some lines have crossed these barriers. This results in recording some anomalous travel times (Fig. 7a) that could be manually smoothed later prior to further processing of the data. (3) Total arrival times vary from one spread to another along the same seismic line (Fig. 7b). This gives direct indication to lateral inhomogeneities in the attitude of the medium and/or its refracting nature.

The second step in processing the seismic refraction data was to assign layer numbers to travel time segments of different slopes taking into account the principles of reciprocity and parallelism. It has provided information on the number of encountered seismic velocity layers and, hence, allowed tracking velocities along the seismic line.

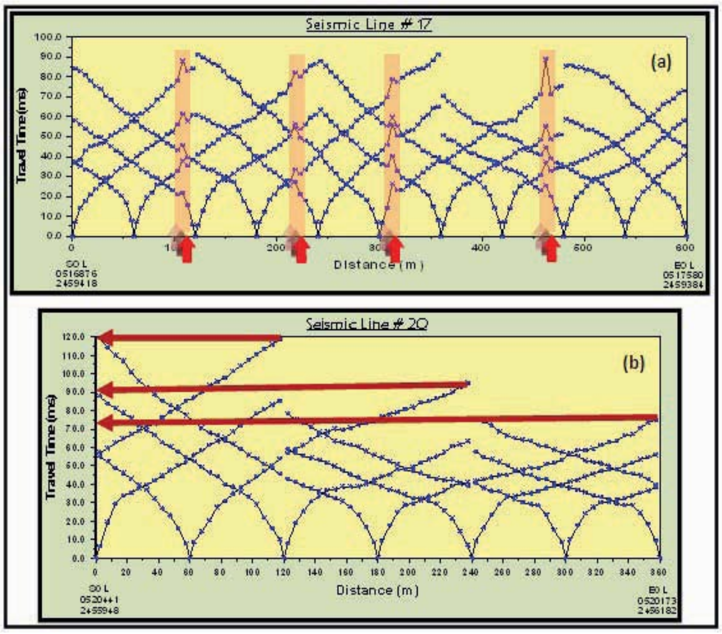

Fig. 7. (a) Anomalous travel time data. Sharp increase in arrival times, shown by arrows, is due to location of some geophones on sand barriers (Ogum). (b) Lateral changes in reciprocal times that may indicate to lateral refractor inhomogeneities.

The third step in the processing scheme was to follow the phantoming procedure in order to achieve complete travel time coverage of the same refractor along the total length of the spread. The process of phantoming is applied to obtain first break-type arrivals of refractions in the offset distance zone between the shot point and the crossover point. The time shifted arrivals are called phantom arrivals (Redpath, 1973). By using multiple shots per spread during field operations and by phantoming the data, first-break type arrival times can be obtained for each geophone position along the line. In the zone of overlap, the travel time curves are parallel indicating to head wave arrivals from the same refractor in both shots. Because the two curves are parallel, the time difference between the two curves is the same at each geophone point. Therefore, the apparent velocities that would be determined from the travel time graphs are based on rays that have emerged from different parts of the refractor.

Calculation of Seismic Velocities and Refractor Depths

Several routines are used for selection of the proper velocities. For the direct arrivals through the first layer, the velocity is computed by dividing the distances from each shot point to each geophone by the corresponding arrival times. These individual velocities are averaged for each shot point, and a weighted average is computed. For layers beneath the first layer, velocities are computed by two methods: 1) Regression, in which a straight line is fit by least squares to the arrival times representing the velocity layer and average velocities are computed by taking the reciprocals of the weighted average of the slopes of the regression lines, and 2) the Hobson-Overton method (Scott, 1973), wherein velocities are computed if there are reciprocal arrival from two opposite shot points at two or more geophones. Final velocities used in the inversion process are computed by taking an average of the two methods.

Seismic refraction method gives information about the subsurface in terms of seismic velocities because seismic velocities are directly related to the quality and strength of the medium. Therefore, qualitative seismic velocity classification can be used for identifying the subsurface stratigraphy in terms of different rock units, such as soil, weathered, or hard rock layer (Venkateswara *et al*., 2004). Furthermore, seismic velocities in various rock materials can be related to the ability of specific size and power bulldozers to excavate them by ripping. This means that seismic velocities obtained from time-distance plots can characterize rippability (Caterpillar, 2000). Table 3 gives a compiled relation among seismic velocities, rock types, and rippability. This classification is used as a guide in the present study to characterize the bedrock of Wadi Thuwal area.

Table 3. Compiled relationship among rock types, seismic velocities, and rippability. (compiled from Venkateswara et al., 2004; and Caterpillar, 2000).

Subsurface strata	Seismic Velocity (m/s)	Rippability
Soil layer (all types)	**< 1100**	***Easily ripped***
Pebbles/boulder mixed layer	**1050-1600**	***Moderately difficult***
Weathered rock layer	**1600-2500**	***Difficult ripping/light blasting***
Hard to massive rock	**>2500**	***Blasting required***

The interpretation program applied in the present study uses the delay-time method (Redpath, 1973) to obtain a first-approximation depth model, which is then trimmed up by a series of ray-tracing and model adjustment iterations, to minimize discrepancies between the picked arrival times and corresponding times traced through a 2.5-dimensional model. Arrival times at two geophones, separated by some variable XY-distance, are used in refractor velocity analyses and time-depth calculations. Using the principles of migration and iterative ray-tracing (Iversen *et al.,* 1996), forward and reverse seismic rays emerge from essentially the same point on the refractor, thus requiring the refractor to be plane over only a small distance. The ray-tracing procedure tests and corrects the estimated migrated positions of points representing the locations of ray entry and emergence, on the refracting horizon taking into account its dip at those points, thus, enabling accurate representation of steeply dipping horizons.

Results and Discussions

Figure (8) shows selected examples for the calculated two-dimensional seismic-depth models with annotated average velocities for each layer. The evident irregularities in the mapped refractors may be due to the presence of conglomerates and small tributaries in the wadi. The calculated seismic model established from the present study shows three layers; these are, from top to bottom:

1- A surface layer having low seismic velocity ranging between 310 and 650 m/s and corresponding to wadi fill deposits of loose sand and silt. The average thickness of this layer is about 3.5 m which attains a maximum thickness of about 6.5 m at the southern and northern parts of the study area (Fig. 9).

2- A second layer with moderate seismic velocities that range between 710 and 1855 m/s. The lower velocities correspond to dry alluvial deposits (sand and silt), whereas the higher velocities correspond to water-saturated sand, clay, and conglomerates. The thickness of this layer varies greatly throughout the study area. The average thickness of this layer is about 6.5 m and it attains a maximum thickness of about 20 m at the northern part of the area (Fig. 9).

3- Bedrock with relatively high seismic velocities that range between 1765 and 4865 m/s. The lower velocities of this layer correspond to weathered limestone, whereas the higher velocities correspond to intact reefal limestone. The surface of the bedrock has rough topography with general slope from east to west (Fig. 9). The average depth of the bedrock ranges between about 9 m at the southeastern part of the area and increases gradually to the west and to the north, where it reaches about 11 m and 24 m, respectively. The high seismic velocities of the consolidated bedrock mask sometimes the signature of the relatively lower seismic velocity of the water- saturated layers. Consequently, it is difficult to determine the exact depth to the water table, as the level would be controlled by the attitude of the bedrock.

A layer with limited areal extent could only be outlined in four seismic lines (L-3, L-5, L-14, and L-25), sandwiched between the second layer and the bedrock. The calculated seismic velocities of this middle layer range between 1960 and 2680 m/s. A maximum thickness of about 20 m for this layer is found in the seismic model of seismic line # 25 at the far northern part of the area. This layer consists of clay and conglomerates.

Since one of the main targets of the present study is to investigate the bedrock conditions, a contour map (Fig. 10) is constructed showing the areal distribution of bedrock velocity in Wadi Thuwal area. A general increase in bedrock velocity is observed from east to west. The relatively lower velocities to the east are due to faulting near the Harrat Thuwal and associated higher weathering effect. It is also evident that the revealed relative velocity maximums, marked as A, B, and C, coincide with the three outcrops of the Shumaysi Formation. Also, the noted 2500 m/s-contour line that separates the eastern less-consolidated bedrock from intact western coastal one means that the bedrock of the coastal area of Wadi Thuwal will be difficult to rip and, in most cases, will require blasting for excavations. Furthermore, a linear relation (Z=2.134-0.0085 V) (Fig. 11) is obtained between the calculated seismic velocities and depths for the delineated seismic layers. Such linear relationship suggests constant velocity gradient in spite of the dispersion of seismic velocities that increases with depth (Fig. 11a). The wide range in bedrock seismic velocities (from 1765 to 4865 m/s) indicates to the marked inhomogeneities in the strength of the bedrock in the study area.

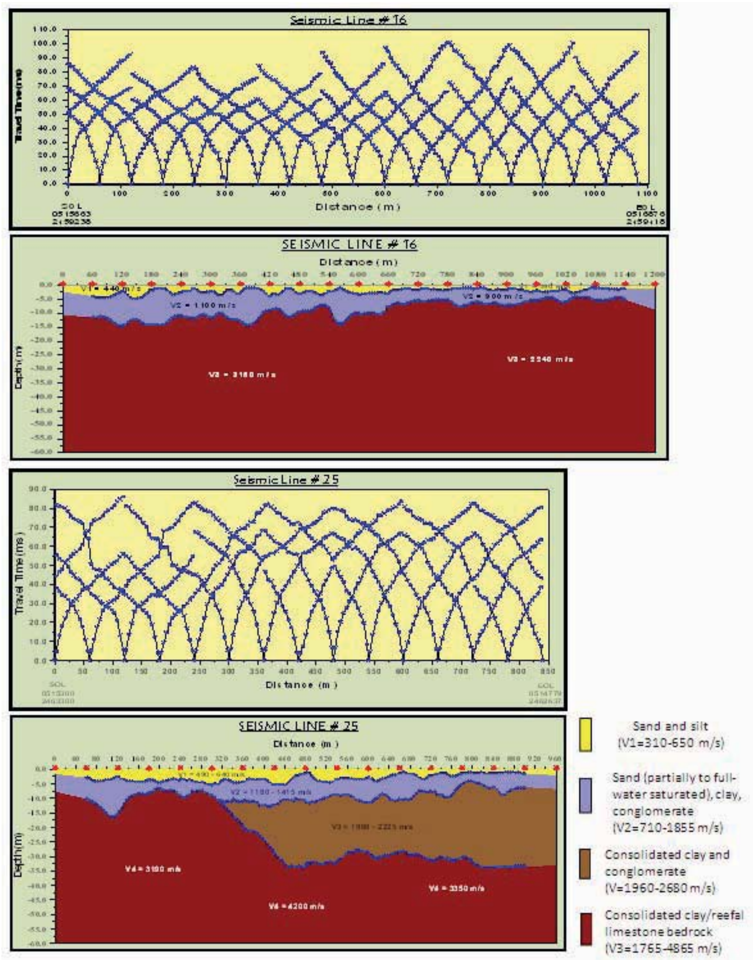

Fig. 8. Selected observed travel times and calculated depth models, Wadi Thuwal area.

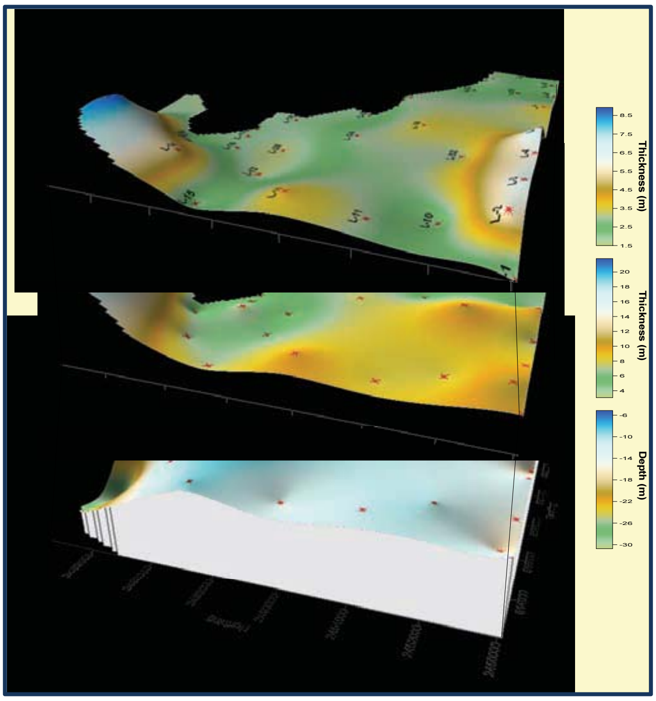

Fig. 9. 3D-presentation of the three delineated seismic layers in Wadi Thuwal area.

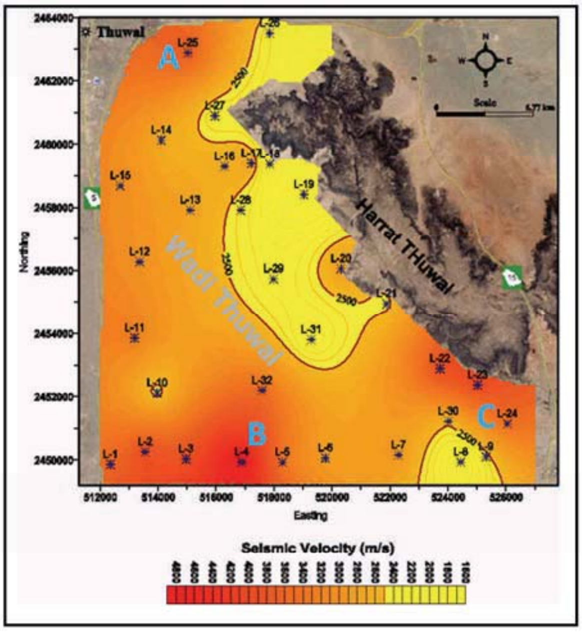

Fig. 10. Calculated seismic velocity of bedrock in Wadi Thuwal area.

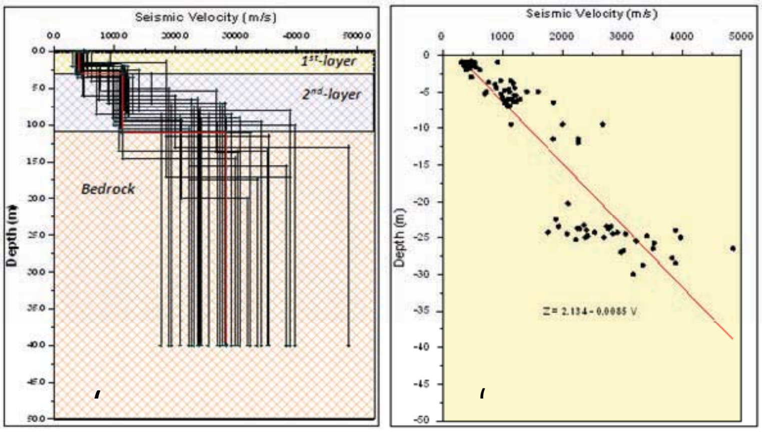

Fig. 11. Seismic velocity-depth relation for delineated strata, Wadi Thuwal area.

Conclusion

About 15.5 line kilometers of seismic refraction profiles were conducted in Wadi Thuwal area, which is located at 110 km north of Jeddah, KSA, in order to study the subsurface sediments, investigate the bedrock topography and its relative strength, and to delineate water table for hydrogeologic studies. The recorded seismic data were processed and interpreted in order to construct seismic models for geologic interpretation. Three seismic layers could be mapped; a surface layer corresponding to wadi fill deposits (average velocity V1av=420 m/s), dry to water-saturated sand, clay and conglomerate (V2av=1150 m/s), and reefal limestone bedrock (V3av=2710 m/s). Seismic velocities of the delineated seismic layers were analyzed. As a result, a linear relationship between seismic velocities and depth was found. The calculated lower bedrock velocity (1700 m/s) noted at the eastern part of the study area indicated to a highly weathered fractured limestone. There is a gradual increase in the bedrock seismic velocity and depth from east to west and to north. The northern part of Wadi Thuwal area showed an abrupt increase in the bedrock depth that may be due to faulting and weathering. A bedrock seismic velocity contour line of 2500 m/s was drawn separating the eastern less-consolidated bedrock from intact western coastal one. It divides, in fact, the bedrock of the coastal area of Wadi Thuwal, that is difficult to rip and in most cases will require blasting for excavations, from the easily to rip eastern part. The high seismic velocity of the consolidated bedrock has, in some locations, masked the signature of the relatively lower seismic velocity attributed to water table. Therefore, it was difficult to exactly determine the depth to the water table, as its level was also greatly controlled by the attitude of the bedrock.

Acknowledgments

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مسح سيزمي انكساري لدراسة الرسوبيات الضحلة بوادي ثول، شمال جدة، المملكة العربية السعودية

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المستخلص. تم إجراء مسح سيزمى انكساري، يتكون من ٣٢ بروفيل سيزمى لدراسة الرسوبيات الضحلة وتعيين مستوى المياه الجوفية بوادي ثول الواقع حوالي ١١٠ كم للشمال من مدينة جدة، المملكة العربية السعودية. نتج من التحليل المستفيض للبيانات السيزمية نموذجا عاما جيوسيزميا للمنطقة، يتكون من ثلاث طبقات سيزمية رئيسية هي: طبقة سطحية من رسوبيات الوادي (الرمل والسلت)، تتميز بسرعة سيزمية منخفضة مقدار متوسطها ٤٢٠ م/ث، يليها طبقة من الرمل والطفلة والزلط، تتميز بسرعة سيزمية متوسطة مقدار متوسطها ١١٥٠ م/ث. يقع الجزء العلوي من هذه الطبقة فوق مستوى المياه الجوفية وتمتد في العمق إلى ما دون مستوى المياه الجوفية. ويلي ذلك طبقة صخور الأساس (bedrock) والتي تتكون من حجر جيري وتتميز بسرعة سيزمية عالية مقدار متوسطها ٢٧١٠ م/ث.

وقد أوضح تحليل السرعات السيزمية للطبقات السيزمية وجود علاقة خطية بين السرعات السيزمية والعمق، مما يدل على التوزيع المتجانس للسرعات خلال الطبقات. التوزيع الأفقي للسرعة السيزمية والعمق لصخور الأساس توضحان زيادة مطردة من الشرق إلى الغرب وإلى الشمال مع وجود نطاق ذو سرعة سيزمية منخفضة

(١٧٠٠ م/ث) إلى الشرق بجانب حرة ثول، يدل على ضعف صخور الأساس بهذا النطاق. وتم استخدام العلاقات المنشورة بين السرعات السيزمية والقدرة على الحفر (rippability) في استنباط أن صخور الأساس تزيد مقاومتها للحفر كلما اتجهنا غربا.

لقد كان من الصعب تعيين مستوى المياه الجوفية بمنطقة الدراسة، لارتفاع السرعات السيزمية للصخور (الطبقة الثانية وصخور الأساس) أعلى من السرعة السيزمية المميزة للطبقات الحاملة للمياه الجوفية، مما أدى إلى حجب ما يدل عليها.