Application of linear-array microtremor surveys for rock mass classification in urban tunnel design

Young Ho Cha   Jong Suk Kang   Churl-Hyun Jo

ABSTRACT

Urban conditions, such as existing underground facilities and ambient noise due to cultural activity, restrict the general application of conventional geophysical techniques. At a tunnelling site in an urban area along an existing railroad, we used the refraction microtremor (REMI) technique (Louie, 2001) as an alternative way to get geotechnical information. The REMI method uses ambient noise recorded by standard refraction equipment and a linear geophone array to derive a shear-wave velocity profile. In the inversion procedure, the Rayleigh wave dispersion curve is picked from a wavefield transformation, and iteratively modelled to get the S-wave velocity structure.

The REMI survey was carried out along the line of the planned railway tunnel. At this site vibrations from trains and cars provided strong seismic sources that allowed REMI to be very effective. The objective of the survey was to evaluate the rock mass rating (RMR), using shear-wave velocity information from REMI. First, the relation between uniaxial compressive strength, which is a component of the RMR, and shear-wave velocity from laboratory tests was studied to learn whether shear-wave velocity and RMR are closely related. Then Suspension PS (SPS) logging was performed in selected boreholes along the profile, in order to draw out the quantitative relation between the shear-wave velocity from SPS logging and the RMR determined from inspection of core from the same boreholes. In these tests, shear-wave velocity showed fairly good correlation with RMR. A good relation between shear-wave velocity from REMI and RMR could be obtained, so it is possible to estimate the RMR of the entire profile for use in design of the underground tunnel.

INTRODUCTION

A railway construction project for high speed trains travelling faster than 300 km/h, the so-called KTX (Korea Train eXpress), has been in progress since 1990 in Korea. The Seoul-Busan and Seoul-Mokpo KTX lines have been the first to start services, in April 2004, using newly constructed and partly modified existing railways. The next stage is the construction of a new railway for KTX from Taegu to Busan. The new railway is planned to run beneath the existing railway in Busan City (the second largest city in Korea) along a tunnel about 50 m deep and 5.7 km long. The main objective of our project was to determine basic information that would assist in designing the tunnel, by conducting geophysical surveys.

Figure 1(a) shows the planned route of the new railway, located under the existing railway. Many structures such as houses,
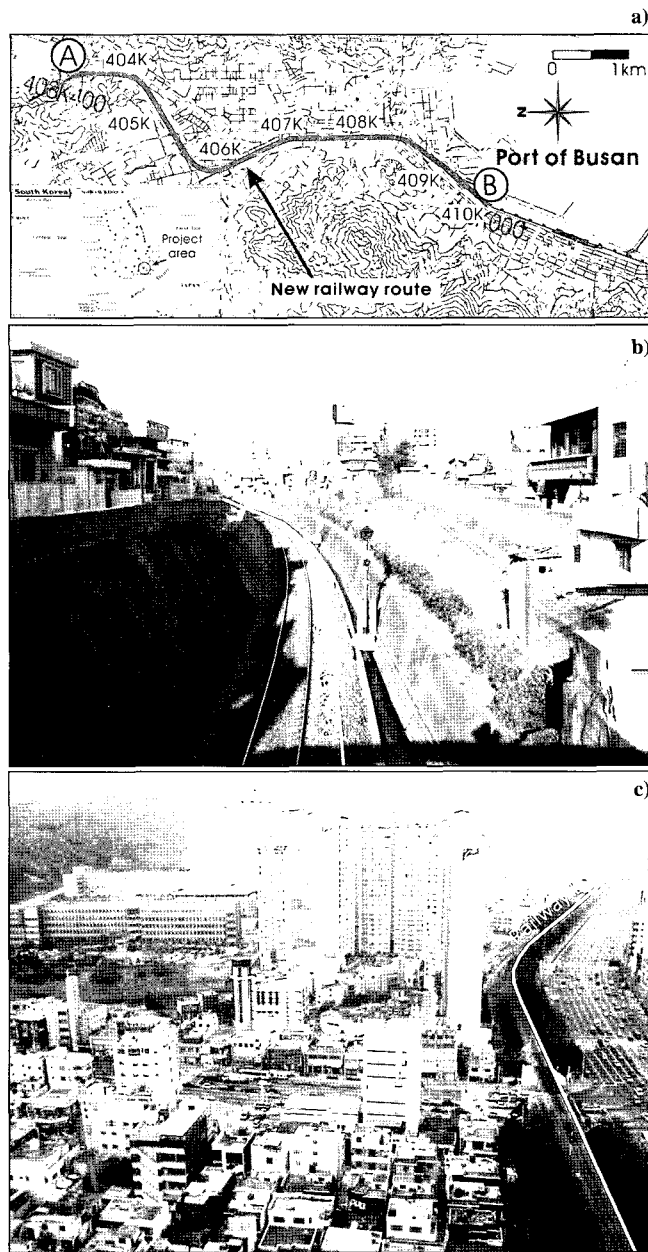
Fig. 1. a) Location map of the new KTX railway; (b) and (c) show photographic views of the site.

apartments, buildings, roads and so on are located on both sides of the existing railway (Figure 1(b) and Figure 1(c)). As one can see, the high level of prevalent noise (vehicles, factory, and so on) and the narrow space restrictions make the use of conventional geophysical techniques like seismic refraction, reflection, and resistivity inapplicable.

On the other hand, such conditions are well suited to the use of the refraction microtremor (REMI) technique (Louie, 2001). REMI is a kind of microseismic survey (Aki, 1957; Okada, 2003)

that uses the Rayleigh wave component of ambient noise (passive sources) to obtain a shear-wave velocity profile. Therefore, cultural noise including the vibrations from the trains and cars on railways and roads, located parallel or perpendicular to the new railway route, became useful rather than a hindrance.

In this paper, the relationship between shear-wave velocity and RMR is studied, using laboratory tests and borehole logging. From these results, it can be seen that shear-wave velocity and RMR are closely related. A relationship between shear-wave velocity from REMI and RMR is inferred. The RMR of the entire profile for the planned underground tunnel is estimated from this relationship.

SITE DESCRIPTION

As mentioned above, the new railway will lie beneath the existing railway located in Busan City. Figure 1(a) shows the route of the new railway through the city. A geological cross-section (A-B) in Figure 2 was made from old maps, satellite images, and drilling logs. An alluvium layer that is 10–20 m thick overlies the bedrock. The bedrock seems to be composed of different kinds of granite (granite and felsite), and volcanic rocks (dacitic tuff, andesitic tuff, and andesite) in some regions. The geological conditions could be summarised as: granite or andesite bedrock, with volcanic intrusions, under 10–20 m thick alluvium. There are also several fault zones (the thick red lines in Figure 2).

THEORY AND METHOD

There are several methods that can provide shear-wave velocity from microtremors (Aki, 1957; Louie, 2001; Okada, 2003). It is impractical to use the circular or two-dimensional array (Okada, 2003; Roberts and Asten, 2004; Roberts and Asten, 2005; Hayashi et al., 2004) in our case because the site is spatially restricted (Figure 1(b) and Figure 1(c)). Therefore, we decided to apply the REMI technique, which uses microtremors recorded with a linear array (Louie, 2001). At this project site, abundant microtremors were generated by vehicles on the roads parallel or perpendicular to the route, and by the train on the existing railway that is parallel to the route of the new railway.

Louie (2001) proposed the refraction microtremor method that can provide shear-wave velocity to 100 metres depth, using conventional refraction equipment and a linear geophone array (Rucker et al., 2003; Pullammanappallil et al., 2003; Louie et al., 2002). In the inversion procedure, a Rayleigh-wave dispersion curve is picked in the wavefield-transformed domain, and the subsurface shear-wave velocity profile can be determined by a processing procedure similar to that used for the multi-channel analysis of surface waves (MASW; Park et al., 1999).

REMI processing involves three steps: velocity spectral analysis, Rayleigh wave phase-velocity dispersion picking, and shear-wave velocity modelling.

Step 1: p-τ transformation (the slant stack operation; Thorson and Claerbout, 1985) of vertical particle velocity, and transformation from p-τ to p-f domain by Fourier transformation.

Step 2: Velocity spectral analysis and Rayleigh wave phase-velocity dispersion picking. The lower limit of the apparent phase velocities are assumed to be the true phase velocities (Louie, 2001). This assumption in step 2 is the key point of the REMI technique using a linear one-dimensional array.

Step 3: Shear velocity modelling. The REMI uses a forward-modelling code adapted from Saito (1979, 1988) that interactively matches the normal-mode dispersion data picked in the p-f domain. The modelling algorithm iterates on phase velocity at each frequency and can model velocity reversals with depth.

We used a series of 110-metre refraction microtremor arrays consisting of 12 vertical geophones with 4.5 Hz natural frequency, and a seismic recorder with 24-bit resolution. We acquired 10–20 records each 15 seconds in length at each location, and used SeisOpt® ReMi™ software package (®Optim LLC, 2004) for data analysis. The shear-wave velocity profiles derived at each location were then put together to create a two-dimensional shear-wave velocity cross-section.

RESULTS

A relationship or correlation between shear-wave velocity and rock mass rating (RMR) of the recovered core must be inferred, for use in estimating RMR from shear-wave velocity. Rock Mass Rating is a very important geotechnical factor that is used to determine the design of supports in the underground tunnel. RMR has values ranging from 0 to 100 and is based on five parameters for classifying geomechanics, including rock strength, rock quality designation (RQD), joint spacing, joint condition, and groundwater conditions (Bieniawski, 1976).

First, we checked the relationship between shear-wave velocity and uniaxial compressive rock strength in laboratory tests. Then, we deduced the relationship between shear-wave velocity from Suspension-PS (SPS) logging and the RMR in the same borehole. The relationship between shear-wave velocity and RMR from laboratory tests and between shear-wave velocity from SPS logging and RMR would allow us to use the shear-wave velocity to
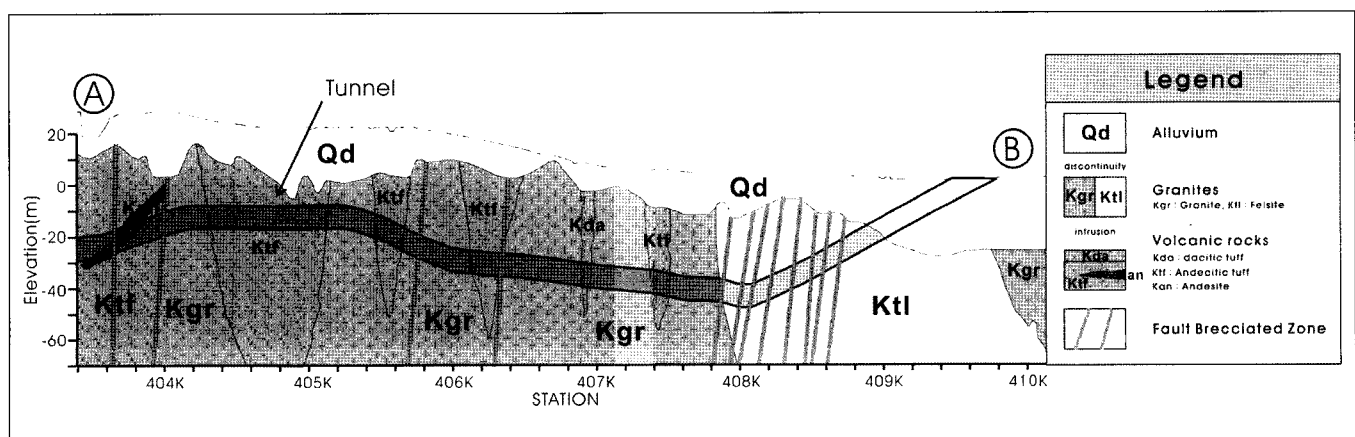

Fig. 2. A geological cross-section (A-B in Figure 1(a)) along the planned railway tunnel line.

estimate RMR. Finally, we applied the relationship between shear-wave velocity from REMI and RMR to get estimate RMR along the entire profile, including regions of interest.

Shear velocity versus uniaxial compressive strength – Laboratory test

In order to use shear-wave velocity for RMR estimation, we must know whether shear-wave velocity and RMR are related. It is difficult to compare shear-wave velocity directly with RMR, because RMR is a value applicable to some region of core recovered, and is composed of several factors, while the shear velocity is closely related to porosity, rock properties, pore fluids and other rock parameters. However, we simply compared shear-wave velocity measured in a laboratory test of a rock specimen with the measured uniaxial strength that is a component of RMR for the same specimen. Figure 3 shows plots of uniaxial compressive strength versus P and S-wave velocity. It is difficult to infer a relation between velocity and strength because of the small number of samples, but Figure 3 shows that velocity and strength are positively correlated. From these results, it can be deduced that shear velocity and rock strength are closely related.

Shear velocity from SPS logging versus RMR

SPS logging data were available at five boreholes, and we compared the RMR at each borehole with P-wave and S-wave velocity from SPS logging. Figure 4 shows the linear relationships between them. We can deduce that RMR and shear-wave velocity

are well correlated, and that RMR between boreholes can be estimated from shear-wave velocity.

Shear velocity from REMI versus RMR

REMI data was collected with a series of 110-metre-long arrays with 10-metre spacing between 4.5 Hz geophones. An example is shown in Figure 5(a). After acquiring each set of REMI data, the array was moved up 40 metres, so that each REMI array has a 70-metre zone of overlap with both the previous and the next array. This overlap between arrays may degrade the lateral resolution of shear-wave velocity structure and cause the lateral averaging of shear-wave velocity structure.

A shear-wave velocity profile was derived for each array and an example is shown in Figure 5(d). This velocity profile represents the shear velocity at the midpoint of an array. 134 velocity profiles were obtained along the entire railway tunnel route. Most profiles were obtained with linear arrays that were parallel to the route, but some tens of profiles were obtained using a linear array perpendicular to the route, because of obstacles, such as cross roads, to laying out an array in the parallel direction.

Figure 5(a) shows a raw 15-second record for REMI analysis. Figure 5(b) shows the Rayleigh wave spectrum obtained by a p-f transformation of the wavefield. From the spectrum, we pick the Rayleigh wave dispersion curve (the dots in Figure 5(b)). As mentioned earlier, the picked points are the lower limit of phase velocity of meaningful Rayleigh waves. A shear-wave depth
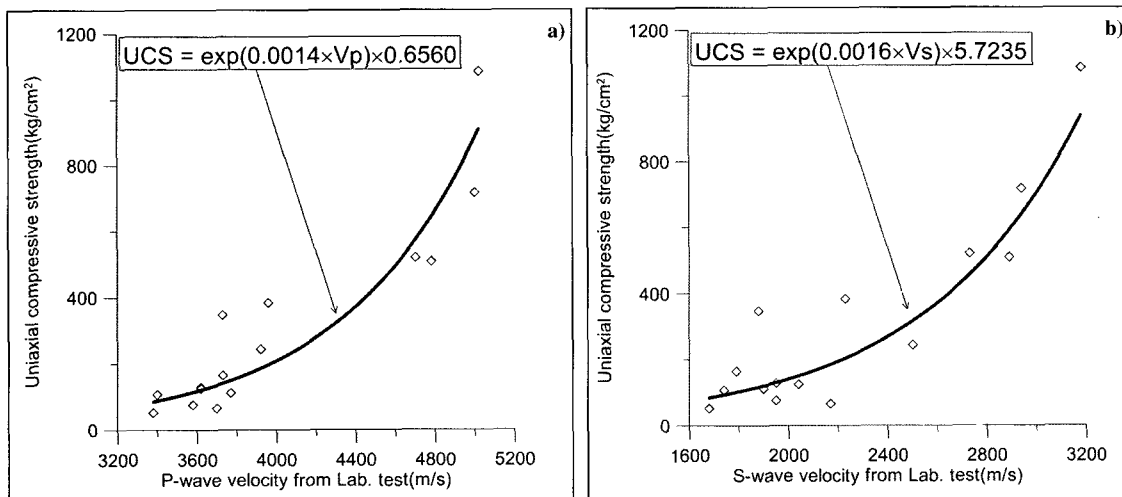

Fig. 3. Relationship between uniaxial compressive strength and seismic velocity from laboratory tests: a) P-wave velocity; b) S-wave velocity.
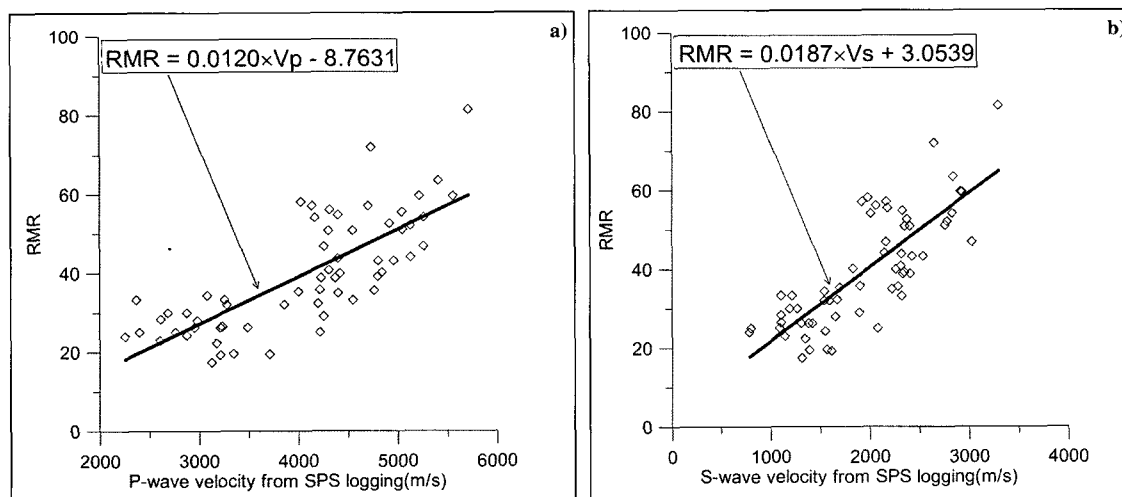

Fig. 4. Relationship between RMR and seismic velocity from SPS logging: a) P-wave velocity; b) S-wave velocity.
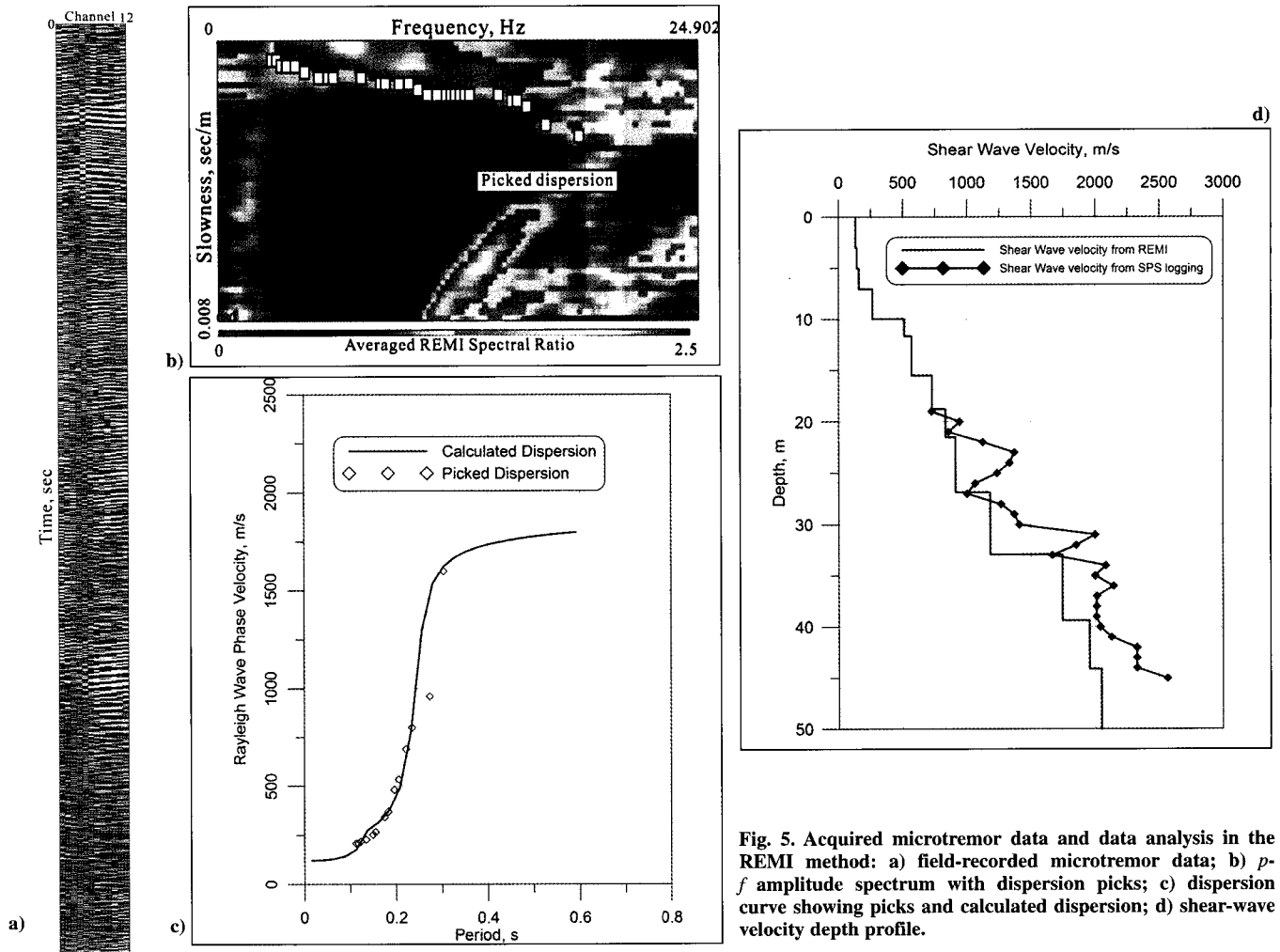
Fig. 5. Acquired microtremor data and data analysis in the REMI method: a) field-recorded microtremor data; b) p-f amplitude spectrum with dispersion picks; c) dispersion curve showing picks and calculated dispersion; d) shear-wave velocity depth profile.

profile is then derived from the picked dispersion curve by iterative simulation (Figure 5(d)). Figure 5(c) shows the fit between the dispersion picks and the calculated dispersion curve generated by the final shear-wave velocity profile. Figure 5(d) shows the shear-wave velocity from this method, compared with SPS logging results at the same position. There is some difference between them. This is due to the different frequency bands of the two methods, the uncertainty of the dispersion picks, lateral averaging of velocities by the long array, and array overlap. It is well-known that P-wave velocities from laboratory tests on saturated core using an ultrasonic source are much faster than P-wave velocities from seismic refraction or crosshole tomography surveys using dynamite or sledge hammer sources; Batzle et al. (2001) shows the frequency dependence of velocity using ultrasonic techniques. In our case, SPS logging uses a source of several hundreds to thousands of Hertz, but REMI uses signals of less than 20 Hz. It

can be inferred that these differences in frequency between SPS logging and REMI are the cause of the difference in shear-wave velocity between the two methods, by analogy with the difference in P-wave velocities between laboratory tests and surface seismic methods.

Figure 6 shows the shear-wave velocity section of the whole area, obtained by putting together the individual shear-wave profiles derived using the REMI technique. Remarkable consistency is noticeable between the geometry of layers (alluvium, highly weathered rock, and moderately weathered rock) observed from drilling logs and the shear-wave velocity section derived from REMI method. The trend of the velocity curves is very similar. This agreement between the two methods means that the shear-wave velocity profile from REMI is a good representation of the actual shear-wave velocity structure.
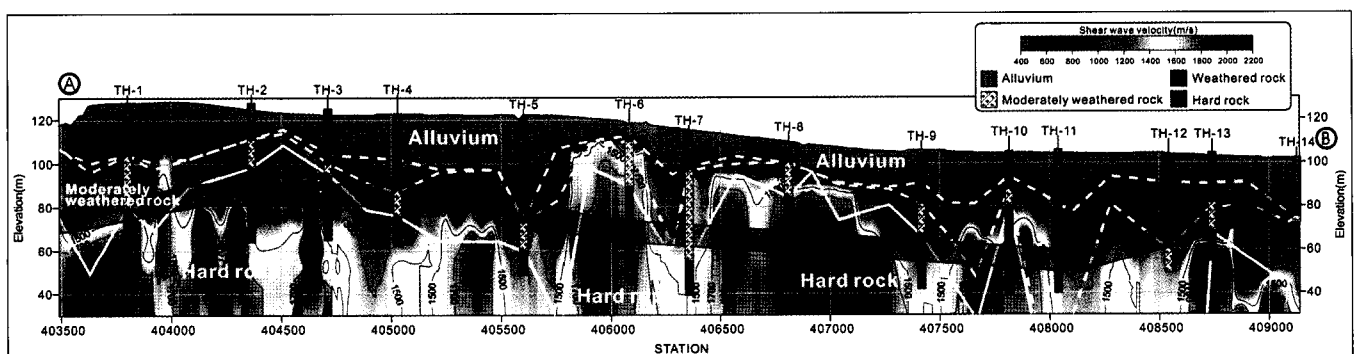

Fig. 6. The shear-wave velocity section determined from microtremor analysis, overlaid with borehole logs.

Figure 7 shows a crossplot of RMR values from the core recovered, and shear-wave velocity from REMI at the same location. We can infer a linear relationship between them, as we do in the case of SPS logging (Figure 4(b)).

Using a simple regression analysis, we can derive a linear relationship:

$$RMR = 0.036 \times Vs - 10 \qquad (1)$$

Table 1 shows the shear-wave velocities that are the criteria for determining RMR using equation (1). Figure 8 shows the RMR cross-section for the new tunnel determined in this way. From this rock classification, the construction details could be decided and the cost for constructing the tunnel could be estimated.

CONCLUSIONS

In order to circumvent the unfavourable conditions for conventional geophysical surveys in the proposed tunnel area, a refraction microtremor technique using a linear array (REMI) has been applied. To generate quantitative information such as Rock Mass Rating (RMR), statistical relationships were derived by inspection of the RMR values of the cores recovered and the shear-wave velocities from both laboratory tests and SPS logging. The correlations between shear velocity from SPS logging and

RMR or compressive strength were found to be good. Therefore, a relationship between shear velocity from REMI and RMR was inferred and it then became possible to estimate the RMR of the total zone of interest for the design of the proposed tunnel.

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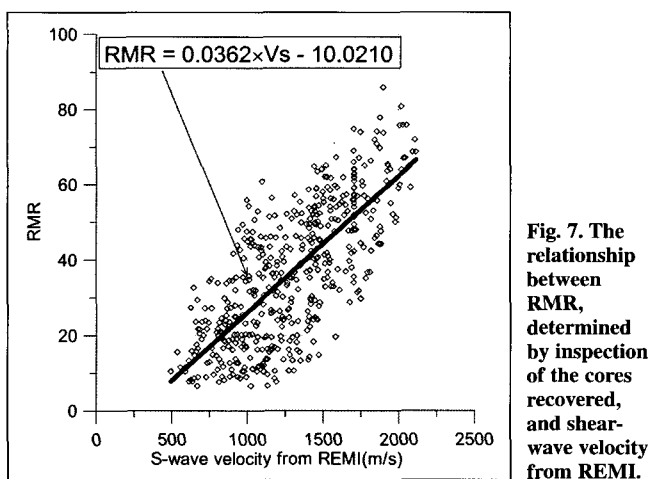

Fig. 7. The relationship between RMR, determined by inspection of the cores recovered, and shear-wave velocity from REMI.

RMR	Shear-wave velocity (m/s)
20	830
40	1380
60	1930
80	2490

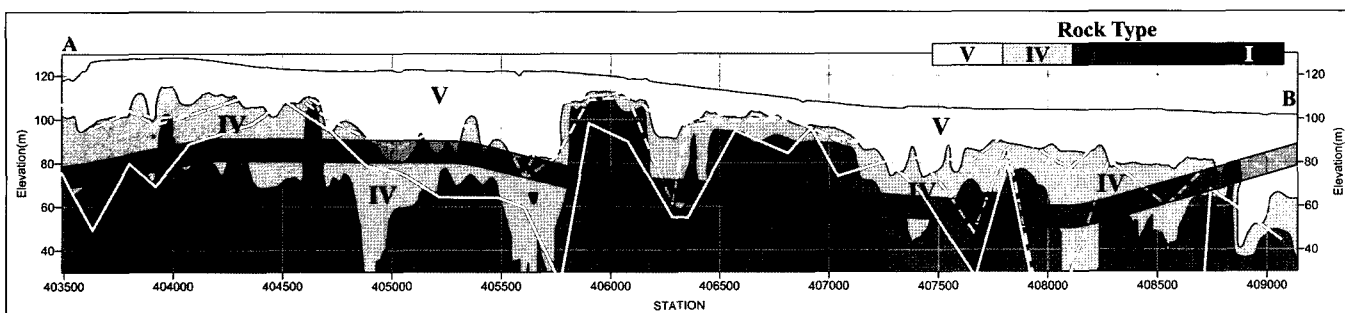Table 1. The criteria for determining RMR from shear-wave velocity derived from REMI.

Fig. 8. The RMR section estimated from the relationship between RMR and the shear velocity from REMI.

도심지 터널 암반분류를 위한 선형배열 상시진동 탄성파 탐사 적용

차영호 [1], 강종석 [1], 조철현 [1]

요　약 :　일반적인 물리탐사기법은 도심지 내에서 구조물, 전도성 지하매설물, 차량 등 인공 잡음으로 인하여 그 적용성에 많은 제약을 받는다. 특히 이 과업은 철도가 운행 중인 철로 하부의 지반 정보의 획득을 목적으로 하는데, 이를 위한 일반적인 물리탐사 적용이 어려웠으며 그 대안으로 선형배열 상시진동 탄성파탐사를 적용하였다. 상시진동 탐사(mircotremor survey)기법에는 철로를 운행하는 기차와 주변 도로의 차량에 의한 진동이 오히려 양호한 송신원으로 활용 될 수 있다. 선형배열 상시진동 탐사기법에서는 일반적인 굴절법 장비를 이용하여 일상적인 진동을 기록하고, 파동장의 변환을 수행하여 표면파의 분산곡선을 얻는다. 이후 발췌한 분산곡선에 대한 반복적인 수치모델링을 통하여 전단파 속도를 구한다.

이 과업에서는 기존 철로를 따라 하부의 터널심도까지의 전단파 속도를 전체 터널구간에 대하여 얻기 위하여 40 m 간격으로 선형배열을 이동하면서 자료를 획득하였다. 측선상의 시추를 통하여 회수한 코어를 이용한 실내시험을 통한 RMR 의 구성요소 중 하나인 일축압축강도와 전단파 속도와의 높은 상관관계를 확인하여 RMR 이 전단파 속도와 연관성이 있음을 유추할 수 있었다. 시추공에서 수행한 SPS 검층에서 획득한 전단파 속도와 RMR 의 비교한 결과 전단파 속도와 RMR 이 높은 상관관계에 있음을 확인할 수 있었다. 상시진동 탐사기법을 통하여 획득한 전단파 속도 역시 RMR 과의 양호한 상관관계를 나타냄을 알 수 있었다. 이러한 상관관계를 이용하여 도심지 철도터널 전체 구간에서 터널 설계시 필수적인 암반분류를 위한 RMR 추정이 가능하였다.

주요어 : 선형배열 상시진동 탄성파 탐사, 전단파 속도, RMR, 레일리파, 철도터널

市街地のトンネル設計における岩相分類のための線形アレイ微動探査の適用

車　榮皓（チャ　ヨンホ）[1]・姜　宗錫（カン　ジョンスェク）[1]・曺　哲鉉（ジョ　チョルヒョン）[1]

要　旨 :　地下施設や環境騒音のある市街地では、通常の物理探査法の適用が困難である。市街地中の現存の鉄道に沿って トンネル掘削が実施されている現場において、地質工学的情報収集のために、線型アレイ微動探査(ReMi)法 (Louie, 2001)が 通常の物理探査手法の代わりに実施された。ReMi 法では環境ノイズを屈折法用の線型アレイで記録し、S 波速度を推定する。 インバージョン過程では波動場を周波数と位相速度の関係に変換したうえで、レイリー波の分散曲線を抽出し、モデルを変更 しながら S 波速度構造を得る。

　ReMi 探査は計画された鉄道トンネル路線に沿って行なわれた。　このサイトでは、列車と車からの振動が強く、それらは ReMi の震源として非常に効果的であった。　調査の目的は REMI からの S 波速度情報を使用して、岩盤評価(RMR)をするこ とであった。　まず最初に RMR 構成要素の一部である一軸圧縮強度と、S 波速度との関係を室内実験によって研究した。　次 に、調査測線に沿った坑井でサスペンション PS(SPS)検層を実行し、SPS 検層から求められた S 波速度と同一坑井のコア試験 から求められた RMR との関係を定量化した。　これらのテストで、S 波速度は RMR と良い相関関係を示した。ReMi から求 められた S 波速度と RMR との間に良い相関関係が成り立つことがわかったので、地下トンネルの設計時に使用される RMR を全体区間で見積もることが可能となった。

キーワード : 線形アレイ微動探査、S 波速度、RMR、レイリー波、鉄道トンネル

1 지하정보기술㈜
　서울시 금천구 가산동 481-10 번지 벽산 디지털 밸리 2 321 호

1 地下情報技術（株）