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# Assessment of Seismic Site Response at Hongseong in Korea Based on Two-dimensional Basin Modeling using Spatial Geotechnical Information

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# 공간 지반 정보를 활용한 이차원 분지 모델링 기반의 국내 홍성 지역에서의 부지 지진 응답 평가

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The site effects relating to the amplification of ground motion under earthquake loading are strongly influenced by both the subsurface soil condition and geologic structure. In this study, the site effects at the Hongseong area in Korea were examined by both the site investigation including borehole drilling and in-situ seismic tests and the site visit for acquiring geologic information of ground surface. Subsurface of Hongseong area with a major instrumental earthquake event in 1978 is composed of weathered layers of a maximum of 45 m thickness overlying bedrock. A geotechnical information system based on GIS framework was implemented to effectively find out spatial geologic structure of study area and it indicated Hongseong is a shallow and wide shaped basin. Two-dimensional finite element (FE) analyses for a representative cross-section of the Hongseong area were performed to evaluate seismic site responses. From the results of seismic responses, it was observed that the ground motions were amplified during the propagation of shear waves through the soil layer overlying the bedrock and the duration of shaking near the basin edges was prolonged due to the surface waves generated by interactions of shear waves with basin geometry. Furthermore, one-dimensional FE seismic response analyses were additionally conducted for soil sites selected in the basin, and it gives similar results to the two-dimensional seismic responses at most locations in the basin with the exception of the locations near the basin edges, because the basin in this study is very shallow and wide.

**Key words :** seismic response, site effects, basin effect, geographic information system, geotechnical information

지진 시 지반 운동의 증폭과 관련되는 부지 효과는 지하 토사 조건 및 지질 구조에 따라 매우 큰 영향을 받는다. 본 연구에서는 국내 홍성 지역을 대상으로 시추 조사와 현장 탄성파 시험을 포함한 현장 조사 및 지표 부근 지질 정보를 획득하기 위한 부지 답사를 통해 부지 효과를 확인하였다. 홍성 지역은 1978년 계기 지진이 발생한 지역으로서 기반암 상부에 최대 45 m 두께의 풍화 지층이 분포한다. GIS 기법 기반의 지반 정보 시스템을 연구 대상 지역의 공간 지층 구조를 효율적으로 확인하기 위하여 구축하였으며, 이로 부터 홍성 지역이 얕고 넓은 분지 형상임을 확인하였다. 홍성 지역의 부지 지진 응답을 평가하기 위하여 대표 단면에 대한 이차원 유한 요소 해석을 수행하였다. 도출된 지진 응답 결과로부터 지반 운동이 기반암 상부 토사층을 통해 전단파가 전파되면서 증폭되고 분지 형상에 따른 전단파의 상호 작용으로 생성된 표면파로 인해 분지 경계 부근 진동 지속 시간이 증가됨을 확인하였다. 뿐만 아니라, 분지 내의 선정된 토사 부지들에 대해서 추가적인 일차원 유한 요소 지진 응답 해석을 수행하였으며, 본 연구 대상 분지가 매우 얕고 넓음에 따라 분지 경계 부근을 제외하고는 분지 내 대부분의 위치에서 이차원 지진 응답과 유사한 결과를 보였다.

**주요어 :** 지진응답, 부지효과, 분지효과, 지리정보시스템, 지반정보

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## Introduction

The stratification structure and physical properties of near-surface soils and geology, as well as the surface topography and basin geometry, affect the site effects relating to the amplification of ground motion during earthquake (Bakir *et al.*, 2002; Raptakis, 2005; Sun and Chung, 2008). During the last several decades, numerous studies on the site effects on seismic site response characteristics have been conducted, and the effects of local geology are well established. Meanwhile, the effects of surface topography and basin geometry still have not been clarified (Sun *et al.*, 2008a). Particularly, in order to estimate correctly the site effects and the corresponding ground motions from two-dimensional (2D) wave propagation analyses, accurate modeling of the subsurface geological structure is preferentially required. Nevertheless, most of the previous 2D analyses have been conducted based on simplified 2D basin models. These models have been developed empirically by the geological judgments without systematic investigation of spatial geologies based on intensive site investigation data (Marrara and Suhadolc, 2001).

In this study, the geographic information system (GIS)-based spatial geotechnical information system (GTIS) is implemented for constructing a reliable model of the subsurface geological structure in the Hongseong area located on the Korean peninsula. On the basis of spatial geological information predicted across the study area within the three-dimensional (3D) GTIS, a representative cross section is selected and the seismic response analyses using a finite element (FE) method are performed for more realistically evaluating the site effects. Moreover, one-dimensional (1D) FE seismic response analyses were conducted, and by comparing their results with those of 2D analyses, the 2D basin effects are evaluated.

## Framework of Spatial Geotechnical Information System

A geotechnical information system (GTIS) was recently developed, based on the GIS tool, to enable the reliable prediction and application of spatial geotechnical information in the evaluation of earthquake ground motion in conjunction with subsurface geologic structure (Sun and Chung, 2006; Sun *et al.*, 2008a). A conceptual framework for this GTIS was designed so as to predict geotechnical results more reliably by incorporating a geostatistical kriging estimation method. This method is known as the best linear unbiased estimate method that can be used in geological and geotechnical predictions in space(Oliver and Webster, 1990; Caruso and Quarta, 1998). The basic premise of kriging interpolation is that every unknown point can be estimated by the weighted sum of the known points. The estimated value, $Z^*(x_i, y_j)$ at the coordinates of $(x_i, y_j)$, can be calculated by

$$Z^*(x_i,y_i)=\sum_{\alpha=1}^{n}\omega_{ij\alpha}\times Z_\alpha \qquad (1)$$

where $n$ is the number of the known values, $Z_\alpha$. A set of weights, $w_{ij\alpha}$, is calculated for every point, and the weights are computed to place greater emphasis on the known points close to the unknown points, and less emphasis on the known points farther away. This process is done by calculating a variogram, which characterizes the spatial continuity or roughness of a point data set with the distance between each pair of points.

In this study, asa synthetic and distinct GIS-based information system for geotechnical practices (Sun and Chung, 2006; Sun *et al.*, 2008a), a GTIS was constructed for the Hongseong area in Korea. As presented in Fig. 1, the resulting GTIS is composed of a total of three primary functional components: spatial analysis, database, and visualization. Also in Fig. 1, the data flow is expressed by arrows. The database component herein contains information about the geotechnical sub-layers with their shear wave velocity ($V_S$) data and the spatial coverage data of waterways, buildings, and roads. Data in the database component are provided to the spatial analysis component, where the point data are interpolated or extrapolated over the entire study area by the geostatistical kriging method. And in the spatial analysis component the interpolated

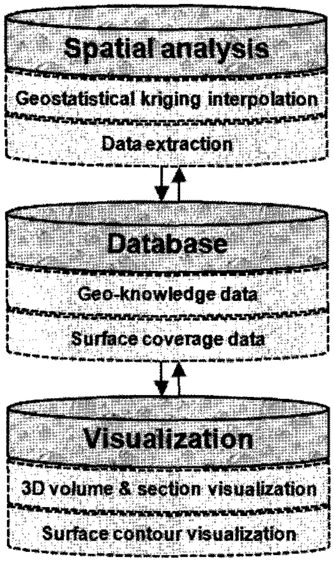


**Fig. 1.** Functional components of spatial geotechnical information system.

data can be extracted to use in other analysis or management tools. Finally, the interpolated data are displayed in 3D or 2D, together with the spatial coverage data, within the visualization component.

## Geotechnical Characteristics at Hongseong by Building GTIS

The Korean peninsula belongs to a region of moderate seismicity, and thus only a small amount of instrument-collected strong earthquake data has been recorded in and near the peninsula (Sun *et al.*, 2005). Nevertheless, abundant historical seismic activities, including a few strong events, were recorded in the Korean peninsula, and several earthquakes with moderate magnitude occurred in the southern part of the peninsula (Sun *et al.*, 2008b). Particularly, Hongseong has records of damage by an earthquake of magnitude 5.0 on October 7, 1978, as well as some historical seismic events (Sun *et al.*, 2005). For these reasons, Hongseong was chosen for an estimation of the site effects affecting ground motions. For evaluating the earthquake ground motions at Hongseong by means of numerical methods, informative topographic and geologic data were compiled, and extensive geotechnical site investigations were performed as part of this study.

Hongseong is a typical topography of old age with gentle relief. To determine the local geologic characteristics and estimate the corresponding site effects, various geotechnical investigations, which include boring investigations and seismic tests in field and resonant column tests in laboratory, were conducted at the Hongseong area (a square area of 4 km × 4 km). In addition, for reliably predicting spatial geotechnical information within the GTIS (Sun *et al.*, 2008a), a walk-over site visit was made to obtain the geo-knowledge data composed of the surface geotechnical material data mostly in areas where borehole data were lacking. Based on both the site investigation data and the geo-knowledge data obtained from site visit, a database was built as the resources for predicting spatial geotechnical information across the area of interesting for Hongseong. Geotechnical layers examined from the geotechnical investigations and site visits were classified into five categories: fill, alluvial soil, residual soil, weathered rock, and bedrock (Sun *et al.*, 2005; 2008a). Fig. 2 shows the spatial locations of the investigated geotechnical data in the area of 4 km × 4 km for Hongseong. Especially, Fig. 2 was established by overlaying the coverage information of iso-elevation contour lines for surface terrain, waterways and roads on the transparent topographic surface within the GTIS. In this paper, the vertical scales in 3D spatial figures with the TM coordinate system were exaggerated three

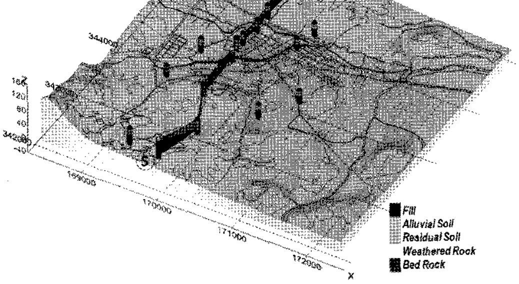
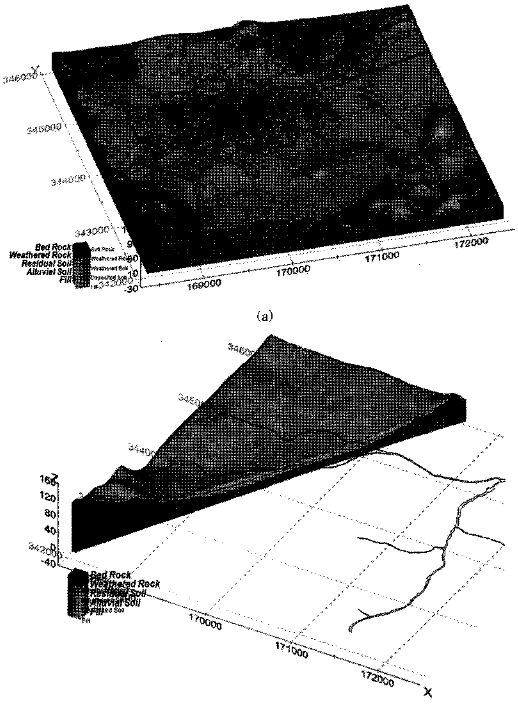


**Fig. 2.** Spatial distribution of site investigation data in the area of interest for Hongseong.

times so that the details of surface and subsurface features could be clearly identified.

In Hongseong, 9 boring investigations, 3 crosshole tests, 6 downhole tests and 15 SASW (spectral analysis of surface waves)tests were performed in total 16 sites, including 2 riverbeds, 8 hill sides, and 6 plain sites. A fence for geotechnical layers distribution along 9 sites from south to north is also shown in Fig. 2. Most areas in Hongseong are composed of 10 to 50 m thick residual soils and weathered rocks beneath thin alluvial sands and silts. Furthermore, compiling synthetically overall in-situ seismic testing results, the shear wave velocity ($V_S$) was determined representatively to be 330 m/s for alluvial soil with fill, 450 m/s for residual soil, 560 m/s for weathered rock, and 1,000 m/s for bedrock. These data are then utilized as the input properties for the seismic response analyses. In the laboratory, resonant column tests were performed to obtain the variation curves of normalized shear moduli ($G/G_{max}$) and the damping ratio ($D$) with shear strain using the undisturbed samples for the residual soils (Kim *et al.*, 2002; Sun *et al.*, 2005). The resultant $G/G_{max}$ and $D$ curves are utilized as input data for considering the material nonlinearity in the seismic response analyses.

A GTIS based on GIS framework was constructed for Hongseong, adopting a procedure to predict more reliably the spatial geotechnical information such as the surface and subsurface geotechnical layers developed by Sun *et al.* (2006; 2008a). Based on a database containing the performed geotechnical investigation data and the surface geo-knowledge data, the GTIS, providing the spatial variation of the geotechnical layers at Hongseong, was constructed first for the extended area including the area of interesting by adopting the geostatistical kriging interpolation method (Sun *et al.*, 2008a). Then the spatial geotechnical layers for the study area were extracted from those of the extended area, using the shape-cut methodology within the GTIS for applying interpolation only, which is usually more reliable than extrapolation (Sun *et al.*, 2006; 2008a Sun and Chung, 2008). Fig. 3, generated from the GTIS, shows the variation of geotechnical layers across the study area and a representative section sliced from south to north in Hongseong. In Fig. 3(a), the spatial building coverage data are overlain on the topographic surface to examine the distribution pattern of the structural buildings with the near surface geotechnical layers. The spatial geotechnical information within the GTIS was reliable in terms of geological expert judgment (Kumar *et al.*, 2000; Sun *et al.*, 2008a), as illustrated in Fig. 3(b) with the representative geotechnical section. The section that applies the procedure for building the GTIS shows exactly the shape of the geologic basin, corresponding to the topographic features. This GTIS, based on the GIS framework, enables users to examine the geotechnical data referenced by spatial coordinates using the function of a vertical and/or a horizontal slice and cut of a 3D ground volume and to export these data in the form of an ASCII or a DXF file, which can be easily imported in other numerical tools.



(a)

(b)

**Fig. 3.** Spatial variation of geotechnical layers information at Hongseong built within the GTIS: (a) across the study area; (b) for a representative section.

## Seismic Responses at Two-dimensional Basin of Hongseong

For the evaluation of the site effects in the Hongseong which shows geologic basin shape especially in the direction of north to south (N-S), 2D seismic response analyses were performed using the general-purpose FE method program, ABAQUS (HKS, 1998). We used an explicit solver in this study for computational efficiency. A representative 2D section that shows the typical geologic basin shape in the Hongseong area were chosen to use for investigating the 2D basin effects through FE nonlinear analyses, treated as a 2D plane strain problem in the time domain.

In this study the spatial coordinates of the interfaces between geotechnical layers predicted within the GTIS were imported to use for the generation of an accurate 2D model reflecting the actual geologic basin geometry in Hongseong. This generation was distinct from previous general 2D models. Previous 2D geotechnical modeling efforts for the evaluation of basin effects have generally been performed on the basis of restricted site investigation data without a cogent prediction of subsurface structures (Bakir *et al.*, 2002). The representative 2D section (N-S), selected for the seismic response analyses in Hongseong, is illustrated in Fig. 4. The dimensions of the selected cross-section for FE modeling consist of 3,900 m in length and 128 m in height. It is true that the subsurface soil structures show very shallow and wide (flat) shapes with about 3,620 m in width and 60 m in maximum depth.

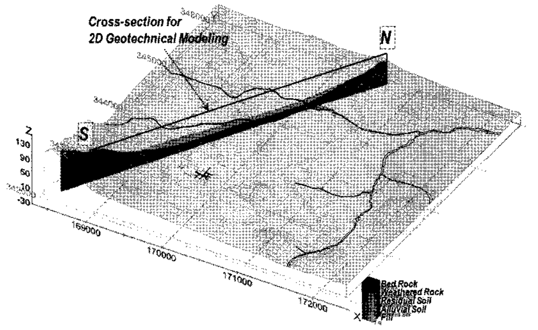


**Fig. 4.** Cross-section selected for 2D modeling of seismic response analysis in Hongseong.

The FE meshes for the 2D seismic response analyses were generated on the basis of the spatial coordinates of the subsurface geologic structures exported from the GTIS. Fig. 5 shows the FE meshes for the selected basin cross-section and the element types and boundary. In this study, the input properties, including $V_S$, were assigned a representative value in each geotechnical layer for assessing the 2D site effect that represents the effects of buried topography (Marrara and Suhadolc, 2001 Makra *et al.*, 2005). The properties of shear wave velocity ($V_S$), Poisson' s ratio (v), and density (ρ) are also illustrated in Fig. 5.

The mesh for the geotechnical layers, such as alluvial soil, residual soil, weathered rock, and bedrock, consists of 4-noded quadrilateral elements and 3-noded triangular elements. The size of all the elements has been tailored to the wavelength of the propagating waves and mostly ranged from about 2 to 3 m in

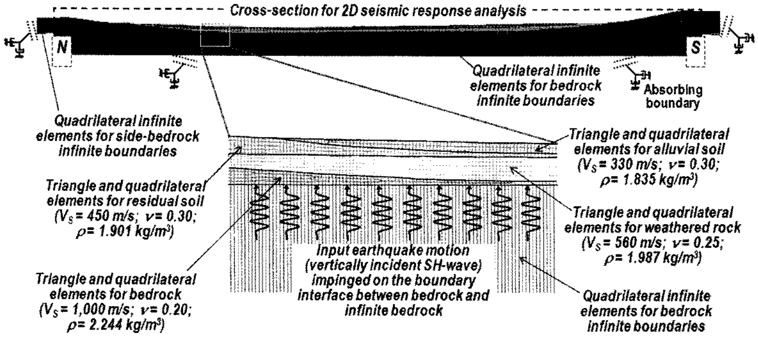
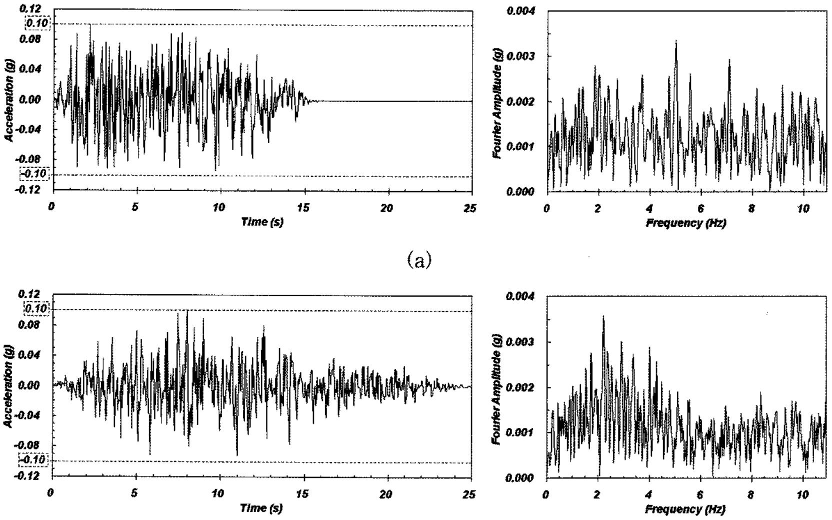


**Fig. 5.** Finite element discretization of the cross-section for 2D basin in Hongseong.



(a)

(b)

**Fig. 6.** Acceleration time histories and Fourier spectra of synthesized motions for 2D seismic response analyses in Hongseong: (a) for duration of 16 s (AS 16) motion; (b) for duration of 25 s (AS 25) motion.

length (Sun, 2004). In the infinite boundary surrounding the bedrock, viscous dashpots are placed independently to absorb the scattered energy. A material damping of the geotechnical layers was adopted as the order of 5% for the Rayleigh type. This means that the damping ratio is frequency dependent (Sun, 2004). In this FE nonlinear analysis, the material nonlinearity was considered by adopting the elasto-plastic model reflecting the material plasticity (Desai and Siriwardance, 1984). The nonlinearity was determined on the basis of the results of laboratory resonant column tests.

As presented in Fig. 6, two artificial input motions composed of a total duration time of 16 s (AS 16) and 25 s (AS 25) were synthesized with a peak acceleration of 0.10 g in bedrock underlying soil layers for the seismic response analyses. AS 16 motion contains various frequency contents from low frequency to more than 10 Hz, despite having the peak Fourier amplitude of about 5 Hz, whereas AS 25 motion shows the dominant frequency contents ranging between about 1.5 Hz and 4.5 Hz. In particular, the acceleration time history of AS 25 motion was generated according to the design response spectrum for the site class B (Sun *et al.*, 2005).In view of geotechnical engineering, assuming that the earthquake source is very far from the basin sections, the input motions impinge horizontally from the bottom of the bedrock, which indicates the top of infinite boundary. The analysis times are 25 s for AS 16 motion and 35 s for AS 25 motion, with time step set to 0.05 s.

With regard to the time responses of the basin, the acceleration time histories across the basin section were examined on the basis of those of the output nodal points on the ground surface from the 2D seismic response analyses. Fig. 7 shows typical results of acceleration time responses in Hongseong. These results were built by interpolating the time histories at surface output nodes. Fig. 7(a) is a bird's eye view illustrated with both positive and negative fluctuations in acceleration levels. Fig. 7(b) is a plane view, shaded to show duration. As indicated for the solid-line ellipses in Fig. 7, the duration of motions was considerably prolonged at interior localities adjacent to the basin edges. This phenomenon is interpreted mainly as the trapping of shear waves and the generation of surface Rayleigh waves. Moreover, the complexity of seismic responses was clearly observed at the basin edges, as marked with the dashed-line ellipses in Fig. 7(a) and by

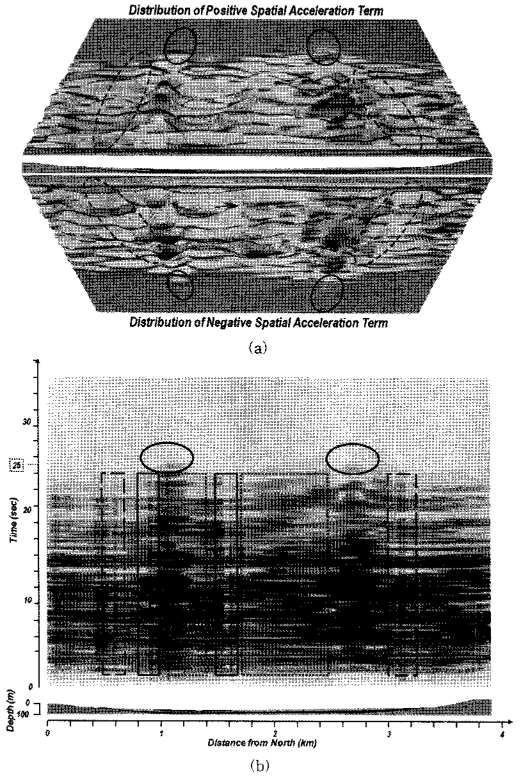


**Fig. 7.** Acceleration time responses on ground surface from 2D seismic response analyses in Hongseong: (a) Bird's eye view for the AS 16 motion; (b) Plane view for the AS 25 motion.

the dashed-line rectangles in Fig. 7(b) because the waves were reflected at the inclined bedrock. In the central part of the basin the motion of low frequency was dominant, as indicated by the dotted-line rectangles in Fig. 7(b) because the incident waves were mainly propagated vertically without any wave reflection, and the high frequency components of motions were filtered through soil layers like a typical 1D seismic response. Generally, the seismic responses were greatly influenced by the subsurface geotechnical structures modeled into the alluvial soil, residual soil and weathered rock, overlying bedrock, in this study. Also, the acceleration responses from the ground surface over the boundary of the residual soil differed from those on their outskirts, as illustrated by solid-line rectangles in Fig. 7(b). Therefore, the exact modeling of the subsurface structure, composed of multiple geotechnical layers, has been very important in reliably predicting the surface seismic response.

For the purpose of comparing with the 2D results and assessing the 2D site effects, additional 1D FE seismic response analyses were conducted at a total of 9 selected soil sites. From the results of the 1D and 2D seismic response analyses, the peak ground accelerations (PGAs) were investigated as depicted in Fig. 8, of which the additional locations (named as the distance)

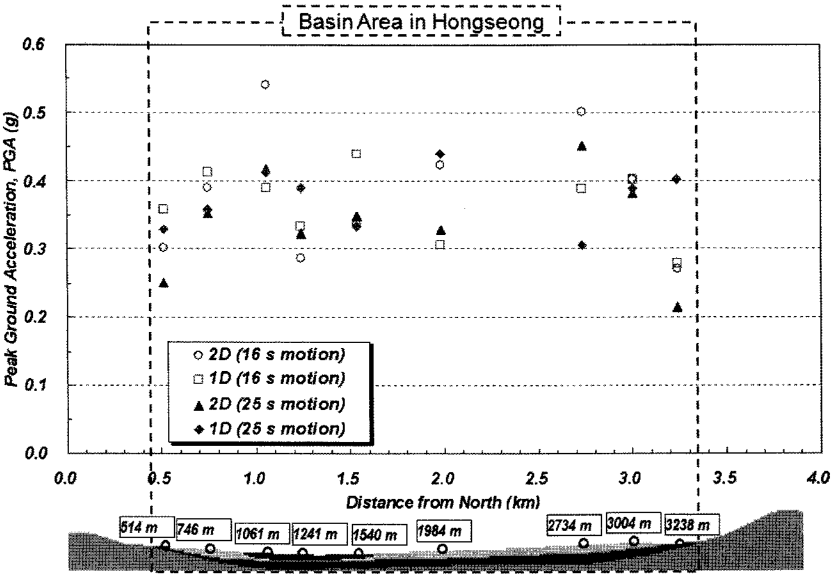


**Fig. 8.** Comparison of peak ground accelerations from 1D and 2D seismic response analyses in Hongseong.

selected for the 1D analyses were also shown in the lower subset. Throughout the inside of basin, the trend of the quantitative differences in the accelerations between the 1D and 2D analyses was not observed with the exception of the basin edges. In general, the basins are divided into a shallow and wide basin and a deep and narrow basin, according to the value of 0.25 in the ratio of depth to width (Kramer, 1996). For the basin section chosen in Hongseong, the ratio was about 0.017, which indicates an extremely shallow and wide basin shape. The subsurface geometry in the basin edges showed a gently sloped bedrock shape.

## Conclusions

In order to sensibly estimate the site effects at Hongseong, a GIS-based GTIS for predicting reliably of spatial geotechnical information was built. 2D seismic response analyses for a cross-section (N-S basin) were conducted by generating FE models based on the spatial coordinates of the geotechnical layers interpolated within the GTIS. Particularly, the subsurface soil structures at the 2D basin in Hongseong showed very shallow and wide shapes having the value of 0.017 for the ratio of depth to width. From the 2D analyses, it was observed that the durations at the interior parts near the basin edges were prolonged primarily because of the surface waves generated by the reflection of shear waves. On the other hand, the central parts of the basins exhibited low frequency motion. 1D FE seismic response analyses were additionally performed at the selected 9 soil sites. From the comparison results of the PGAs, the differences between the 2D and 1D analyses were scarcely observed at most plain sites in the interior of the basin with the exception of the basin edges owing to the shape of flat basin.

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