SITE EFFECTS OF SHALLOW AND WIDE BASIN
BASED ON 2-DIMENSIONAL MODELING
WITHIN SPATIAL GEOTECHNICAL INFORMATION SYSTEM

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ABSTRACT

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 Gyeongju area in Korea were examined by site investigation including borehole drilling and in-situ
seismic tests. Geologic information of ground surface obtained by site visit and collected pre-existing site
investigation data were also accumulated into geo-knowledge database. Subsurface of Gyeongju area
with abundant historical earthquake events is composed of alluvial soil deposit of a maximum of 40 m
thickness overlying weathered residual soils and rock bed. A Geotechnical Information System (GTIS)
based on GIS framework were implemented to effectively find out spatial geologic structure of study area
and it indicated Gyeongju basin has a shallow and wide shape. 2-dimensional finite element (FE)
alyses for two typical cross sections of the study area were performed and the resulting seismic
responses show that the earthquake 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, 1-dimensional FE seismic response analyses for representative soil sites in the basins were
additionally conducted, and it gives identical results with the 2-dimensional seismic responses at most
locations in the basins with the exception of the locations near the basin edges, because the basins in this
study are very shallow and wide.

Keywords: Site effects, GIS, Geotechnical information system, Seismic response analysis, Basin
effects

INTRODUCTION

The stratification structure and physical properties of near surface soils and geology as well as the
surface topography and basin geometry cause the site effects on ground motions under seismic loading
(Bakir et al., 2002). During the last several decade years, the numerous studies on the site effects have
been conducted, and the local geology effects can be well established. Meanwhile, the effects of
surface topography and basin geometry have still not been clarified (Yegian et al., 1994). However,
the seismic response observed from recent earthquake events, particularly in the regions of
gemorphological and geological irregularities, invokes the importance of the effects of topography and
basin geometry. Although 1-dimensional site response analyses are known to capture most essential
aspects of seismic response in level or gently sloping sites with parallel material boundaries, they may
have limitations to describe the complex wave fields and long durations produced by multiple
reflections in basins and hills with steep material boundaries, where 2- and 3-dimensional wave

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propagation analyses with the finite element, the finite difference, the boundary element, the pseudo-spectral and their hybrid methods can be more appropriate. Since many large cities are located on alluvial basins, the effects of basin geometry on ground motion are of great interest in the earthquake engineering field. In practice, at a number of regions damaged by recent earthquakes, such as Caracas in 1967, San Fernando in 1971, Leninakan in 1988, Kobe in 1995 and Dinar in 1995, significant differences between the amplifications at the center and edges of the basin were observed (Kramer, 1996; Bakir et al., 2002).

In order to estimate correctly the site effects and the corresponding ground motions from 2-dimensional wave propagation analyses, accurate modeling of the subsurface geological structure is preferentially required. Nevertheless, most of the previous 2-dimensional analyses have been conducted based on simplified 2-dimensional basin models. These models have been developed empirically by the geological judgements without systematic investigation of spatial geologies based on intensive site investigation data (Marrara and Suhadolc, 2001). In this study, the GIS-based spatial Geotechnical Information System (GTIS) is implemented for constructing a reliable model of the subsurface geological structure in the Gyeongju area located on the Korean peninsula. On the basis of spatial geological information predicted across the study area within the 3-dimensional GTIS, two representative cross sections are selected and the seismic response analyses using a finite element method (FEM) are performed for more realistically evaluating the site effects. Moreover, 1-dimensional finite element (FE) seismic response analyses were conducted, and by comparing their results with those of 2-dimensional analyses, the 2-dimensional basin effects are evaluated.

GEOTECHNICAL INFORMATION SYSTEM BASED ON GIS

The Geographic Information System (GIS) in recent years has emerged as a powerful tool. It has integrated capabilities of spatial analysis database management and graphic visualization and has been widely adopted for building geotechnical expert systems. GIS-based geotechnical expert systems have been developed to forecast and reduce natural hazards. For instance, a landslide can be predicted resulting from rainfall or earthquakes. Particularly, in geotechnical earthquake engineering, a number of research studies based on GIS have been presented. The potential of using a GIS in earthquake engineering practices has more recently been recognized (Kiremidjian, 1997). The GIS applications in geotechnical earthquake engineering are usually represented as seismic zonation and the seismic modeling. The former is for prediction and mitigation of earthquake-induced hazards and the latter is for the analysis of earthquake-induced geotechnical phenomena containing the site effects. However, accurate prediction of spatial geotechnical information, such as soil or rock layers and geotechnical properties, across interesting areas is fundamental. So applications of GIS are developed and then used for geotechnical and earthquake engineering problems.

In order for the reliable prediction and application of spatial geotechnical information in the evaluation of earthquake ground motion with the subsurface geologic structure, in this study, a Geotechnical Information System (GTIS) was developed based on GIS technology. A conceptual framework for this GTIS was designed to predict more reliably geotechnical information by incorporating a geostatistical kriging prediction 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). In the field of geotechnical and earthquake engineering, a GIS is used either alone or in conjunction with specified model analysis techniques (Gangopadhyay et al., 1999). For the practical research described in this paper, the GTIS was developed based on GIS tools, EVS-Pro from CTech and AutoCAD LDDT from Autodesk, in combination with various specified expert techniques (Sun, 2004). The EVS-Pro was utilized mainly for advanced spatial visualization, and the AutoCAD LDDT was used to manipulate digital topographic maps. Moreover, for the more reliable spatial estimation of geotechnical information, a sophisticated kriging interpolation program that used FORTRAN code was developed and adopted herein, although ordinary kriging estimation can be provided within the EVS-Pro tool.

For judiciously constructing the GTIS over the entire study area, a procedure for building a GTIS was developed by devising a couple of new concepts, which contain the extended area surrounding the study area and the geo-knowledge for acquiring additional surface geotechnical data. As data is fundamental in an information system (Rockaway, 1997), in this study, a geo-knowledge concept was
adopted to obtain enough data for the prediction of reliable spatial geotechnical information across the entire study area. To acquire geo-knowledge data in the extended area, landscapes were analyzed based on topographical maps and remote sensing images. And geologies were preliminarily analyzed using the surface geological maps. Then, a site visit for the extended areas was conducted to acquire geotechnical materials data on the ground surface referenced by the spatial coordinates using the GPS (Global Positioning System). The expectation of more reliable results on the interpolation rather than extrapolation led to an application for the extended area containing the study area for the kriging technique. Finally, the geotechnical information for the study area was extracted from that of the extended areas within the GIS tool. Then this information could be utilized in 2-dimensional modeling for evaluating the site effects in the study area.

EARTHQUAKE GEOTECHNICAL CHARACTERISTICS OF THE STUDY AREA

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. Nevertheless, abundant historical seismic activities including a few strong events were recorded in Gyeongju, which is located in the southeastern part of the Korean peninsula. Gyeongju is close by capable faults such as the Yangsan fault (Sun et al., 2005). For these reasons, Gyeongju, which was the old capital of the Silla dynasty for a thousand years, was chosen for an estimation of the site effects affecting ground motions. For evaluating the earthquake ground motions at Gyeongju by means of numerical methods, topographic and geologic informative data were compiled and extensive geotechnical site investigations were performed as part of this study.

Topographic and Geologic Features

Gyeongju (35.84°N and 129.21°E) is a typical inland city area located at the lower end of the Taebaek Mountains, the great backbone of the Korean peninsula. The topography of Gyeongju is represented as a basin of plains, in which the downtown and farms are located, with surrounding mountains. The Hyeongsan River flows northward across the area. Several creeks from valleys join the river. Waterways in the basin are now restricted within a narrow area for flood control. In ancient times, however, the river and creeks across the basin were frequently in flood. Most parts of the basin were in the flooding area. Accordingly, the subsurface soils of Gyeongju are mainly composed of somewhat thick alluvium over bedrock influenced by rivers and creeks.

Gyeongju lies within the Gyeongsang basin at the southeastern part of the Korean peninsula. This area mostly consists of sedimentary rocks formed in the Cretaceous period (Sun et al., 2005). Nevertheless, as shown in Fig. 1, the geology of Gyeongju is mainly covered by intrusive granite and partially covered by sedimentary rocks such as sandstone and shale. The geology with topography in Gyeongju (square areas of 6 km by 6 km), illustrated in Fig. 1, was established by overlaying the surface geologic map and the building, waterway, and road layers on the topographic surface within the GTIS. In the central plain, the Quaternary alluvial formation, underlain by Bulgugsa granite, which is mainly comprised of gravel, boulder, and sand, is widely distributed. Granitic rocks are classified as granodiorite, biotite granite, and hornblende granite.

Site Investigations for Earthquake Geotechnical Characterization

To determine the earthquake geotechnical characteristics, including the geologic profiles and the shear wave velocity ($V_S$) as representative dynamic property in Gyeongju, various site investigations, such as
borehole drilling, and in-situ seismic tests including crosshole, downhole and SASW tests, were conducted over the extended area containing the study area. Pre-existing boring data was also collected. Fig. 2 shows the spatial locations of the investigated and collected geotechnical data in the extended area together with the coverage information of the iso-elevation contour lines for surface terrain, waterways and roads for the study area. The surface and subsurface geologic layers, examined from the site investigations, were classified into five geotechnical layer categories: fill, alluvial soil, weathered residual soil, weathered rock, and bedrock. In accordance with the geotechnical investigation data, the subsurface soils in Gyeongju are composed of 10 to 40 m thick alluvial sands and gravels over the weathered residual soils in most sites with the exception of the mountain zones.

Especially, the thick alluvial soils of 30 to 40 m thickness are distributed in plain zones adjacent to a river or creeks. These characteristics in soil formation represent the general topographic basin area where soils could have been developed mostly by fluvial actions during frequent floodings along the rivers and creeks surrounding the mountains, and, of all things, indicate the geologic basin shape in the Gyeongju area. Furthermore, compiling synthetically overall in-situ seismic testing results, the $V_S$ was determined representatively to be 330 m/s for alluvial soil with fill, 550 m/s for weathered layer (weathered residual soil and weathered rock), and 1,000 m/s for bedrock. These data were then utilized as the input properties for the seismic response analyses.

**Building the Geotechnical Information System (GTIS)**

A GTIS, based on GIS framework, was constructed for Gyeongju adopting a procedure developed to predict more reliably the spatial geotechnical information such as the surface and subsurface geologic layers. To build the GTIS, many available geologic, geomorphic, and geotechnical resources were gathered and analyzed across the extended area. After that, various site investigations were performed to obtain the subsurface characteristic data considering the geologic and geomorphic features and the geotechnical data locations. As data is fundamental for information systems (Rockaway, 1997), a site visit for the extended area was conducted to acquire the geotechnical material data on the ground surface for geo-knowledge. This data was classified into one of the five geotechnical layer categories. The site visits to acquire the surface geotechnical data for geo-knowledge were especially concentrated on some parts where collected and investigated geotechnical data are deficient. Based on a database containing the collected pre-existing boring data, the performed geotechnical investigation data, and the geo-knowledge data obtained from the site visit, the GTIS providing the spatial variation of geotechnical layers was constructed first for the extended area. 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 only interpolation which is more reliable than extrapolation for the prediction of geotechnical layers for the study area.

Fig. 3, generated from the GTIS, shows the spatial distribution of one (bedrock outcrop) of the surface geo-knowledge data in the extended area and the variation of geotechnical layers particularly expressing the simulated process of the extraction of geotechnical layers for the study area from the extended area. The soil basin shape in Gyeongju was also identified from the constructed GTIS for the geotechnical layers. This GTIS based on the GIS framework enables users to examine the geotechnical data referenced by spatial coordinates using the function of vertical and/or horizontal slice and cut of a 3-dimensional ground volume and to export this data in the form of ASCII or DXF, which can be easily imported in other numerical tools.
2-DIMENSIONAL SEISMIC RESPONSE ANALYSES

For the evaluation of the site effects in the Gyeongju which shows geologic basin shape, 2-dimensional seismic response analyses were performed using the general-purpose finite element method (FEM) program, ABAQUS (Hibbitt et al., 1998). We used an explicit solver in this study for computational efficiency. Two 2-dimensional sections showing the typical geologic basin shape in the Gyeongju area were chosen to use for investigating the 2-dimensional basin effects through finite element (FE) analyses treated as a 2-dimensional plane strain problem in the time domain.

Efficient and Reliable Modeling of the 2-dimensional Basins Based on the GTIS

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 2-dimensional model reflecting the actual basin geometry in Gyeongju. This generation was distinct from previous general 2-dimensional models. Previous 2-dimensional geotechnical modeling efforts for the evaluation of basin effects have generally been performed based on restricted site investigation data without a cogent prediction of subsurface structures (Bakir et al., 2002), although several systematic research projects have been conducted for assessing 2-dimensional site effects, for instance, at Euroseistest, by performing extensive site investigations and by expert estimation of geologic structure (Raptakis et al., 2000; Marrara and Suhadolc, 2001). A couple of 2-dimensional sections (N-S and W-E sections) selected for the seismic response analyses in Gyeongju are illustrated in Fig. 4. The dimensions of the selected cross sections for FE modelings consist of 4,152 m in length and 124 m in height for the N-S section and 3,763 m in length and 116 m in height for the W-E section. It is true that the subsurface soil structures show very shallow and wide (flat) shapes with about 3,650 m in width and 48 m in maximum depth for the N-S basin and 3,020 m in width and 51 m in maximum depth for the W-E basin.

The FE meshes for the 2-dimensional analyses were generated based on the spatial coordinates of the subsurface structures exported from the GTIS. Fig. 5 shows the FE meshes for the N-S section between two sections and the element type and boundary together with the applying condition of the input motions. In addition, the properties of shear wave velocity ($V_S$) and Poisson’s ratio ($\nu$) are
presented in Fig. 5. Here, the geotechnical layers were simplified by merging five layers into three layers for the efficiency of modeling. The mesh for the geotechnical layers, such as alluvial soil, weathered layer, 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. 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 (Psarropoulos et al., 2001). In this FE analyses, the material nonlinearity was considered by adopting the elasto-plastic model reflecting the material plasticity that uses the von Mises yield surface (Desai and Sirwardance, 1984). The nonlinearity was determined based on the results of laboratory resonant column tests. As presented in the lower subset of Fig. 5, two artificial input motions composed of a total duration time of 16 seconds and 25 seconds were synthesized with a peak acceleration of 0.10g in bedrock underlying soil layers for the seismic response analyses. In view of geotechnical engineering, since it was assumed that the earthquake source is very far away from the basin sections, the input motions impinge horizontally from the bottom of the bedrock, which indicates the top of infinite boundary.

Surface Acceleration Responses in Basins from 2-dimensional Analyses

It is usual in engineering applications to adopt a single parameter for estimating the severity of an earthquake at a particular location or along an interesting area. The peak acceleration on the ground surface is perhaps the most common parameter (Xu et al., 2003). In this study, based on the results of the 2-dimensional seismic response analyses with an input bedrock acceleration level of 0.10g at the peak for Gyeongju, first, we examined the horizontal peak ground accelerations (PGA) with lateral distance from the left side boundary of each model for assessing the seismic responses according to the basin geometry. Fig. 6 shows the distributions of peak ground accelerations in the N-S and W-E basin of Gyeongju. The basin section shapes are also drawn in the lower subset of each figure.
On the whole, the interior parts in the basins adjacent to the edges showed larger accelerations than the central parts primarily because of the reflection of shear waves and the corresponding generation of surface waves in the basin edges. Particularly, in the N-S basin (Fig. 6(a)), the accelerations in case of a motion of 16 seconds in duration (AS 16 motion) were higher than those of a motion of 25 seconds in duration (AS 25 motion). On the other hand in the W-E basin (Fig. 6(b)), the accelerations of the AS 16 motion were mostly similar to those of the AS 25 motion despite their significant differences at some locations. These differences with the input motions for the analyses indicate that the seismic responses in terms of the peak ground acceleration in basins can be significantly influenced by the characteristics of incident motions. At the inside parts of basins, the peak ground accelerations ranged mostly from 0.35g to 0.50g for the N-S basin and from 0.25g to 0.40g for the W-E basin. The accelerations in the N-S basin were generally larger than those in the W-E basin because of the differences in the geometry of subsurface geotechnical layers and the thickness of modeled bedrock.

With regard to the time responses of the basins, the acceleration time-histories across both basin sections were examined based on those on the output nodal points from the 2-dimensional analyses. Fig. 7 shows the typical results of acceleration time responses for the N-S and W-E basin in Gyeongju. These results were built by interpolating the time-histories at surface output nodes. Fig. 7(a) is the bird view illustrated with both positive and negative fluctuations in acceleration levels. Fig. 7(b) is the plane view illustrated with shade in duration.

As indicated with the solid elliptical lines in Fig. 7, the duration of motions was considerably prolonged at the interior locations adjacent to the basin edges. This phenomenon is mainly interpreted 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 elliptical lines in Fig. 7(a) and the dashed rectangle lines in Fig. 7(b) because the waves were reflected at the inclined bedrock. At the central part of the basins, the motion of low frequency was dominant as indicated by the dotted rectangle line 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 the typical 1-dimensional seismic response. Generally, the seismic responses were greatly influenced by the subsurface geotechnical structures modeled into alluvial soil and weathered layer overlying bedrock in this study. Also, the acceleration responses on ground surfaces over the boundary of the weathered layer differed from those on their outskirts as illustrated with solid rectangle lines in Fig. 7(b). Therefore, the exact modeling of the subsurface structure composed of multiple geotechnical layers has been very important in predicting reliably the surface seismic response.

**COMPARISONS BETWEEN 1- AND 2-DIMENSIONAL SEISMIC RESPONSES**

For the purpose of comparing with the 2-dimensional results and assessing the 2-dimensional site effects, additional 1-dimensional FE seismic response analyses were conducted at a total of 17 selected soil sites composed of 10 and 7 locations, respectively, for the N-S and W-E basin. From the
results of the 1- and 2-dimensional seismic response analyses, the peak ground accelerations were first investigated as depicted in Fig. 8, of which the additional locations (named as the distance) selected for the 1-dimensional analyses were also shown in the lower subset.

![Fig. 8. Comparisons of peak ground accelerations from the 1- and 2-dimensional analyses in Gyeongju](image)

Throughout the inside of both basins, the trend of the quantitative differences in the accelerations between the 1- and 2-dimensional analyses was not observed with the exception of the basin edges. The surface accelerations at the basin edges from the 2-dimensional analyses were considerably lower than those from the 1-dimensional analyses. Considering the input motion level of 0.10g, however, the ratios of surface to bedrock acceleration based on the results of 2-dimensional analyses were generally decreased from the center to the edge. This trend agreed with that from the previous 2-dimensional analyses studies for other basins or valleys (Stewart et al., 2001). These previous numerical research results have mostly been conducted for basins deeper than Gyeongju. The depth to width ratios at the basins from the previous researches were practically more than 0.1. 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 two basin sections chosen in Gyeongju for the seismic response analyses, the ratios were about 0.013 for the N-S basin and 0.017 for the W-E basin. These ratios indicated an extremely shallow and wide basin shape having an average ratio of 0.015. The subsurface geometry in the basin edges showed a gently sloped bedrock shape.

In order to estimate 2-dimensional basin effects based on the results from 1- and 2-dimensional analyses, the acceleration response spectra at the selected soil sites were also determined from both analyses techniques. The spectral ratio of the 2-dimensional (2D) to 1-dimensional results (1D) was additionally calculated and compared at the soil sites in the basins. From the comparisons at the sites located at or near the basin edges as presented representatively in Fig. 9, it was roughly observed that the spectral accelerations from the 2D were somewhat higher than those from the 1D in a long period range despite those of the 1D being higher than those of the 2D results in a short period range for a few cases. This can be explained by the generation of surface waves as noted previously in Fig. 7. Nevertheless, the 2-dimensional effects showing a large spectral acceleration in 2D were not distinguished because the basins for Gyeongju showed the shallow and wide basin shape.

At the soil sites located inside the basins of Gyeongju, the acceleration response spectra and the 2D to 1D spectral ratios based on the results from the 2- and 1-dimensionsional analyses were also compared to each other as shown representatively in Fig. 10. For the inner plain sites of basins according to the comparison results, the spectral accelerations of the 2D were generally similar to those of the 1D for both input motions and both basin sections, although those were dissimilar in some period ranges of a few sites. In some cases, particularly, the spectral accelerations from the 2D analysis were dramatically identical with those from the 1D analysis in the entire period range. Accordingly, the spectral ratios of 2D to 1D were almost the value of 1.0 over the whole period range. For the basins of Gyeongju which were represented as flat basins, the differences in spectral accelerations of 2D from 1D could not be observed at the plain sites inside the basins. This could be predicted from the results at the central parts indicated in Fig. 7(b). Therefore, the 2-dimensional effects in a shallow and wide basin like Gyeongju were insignificant at the inner locations, in which a 1-dimensional analysis method would be easily utilized for evaluating the site effects. Nevertheless, the analyses for a restricted number of sites in the Gyeongju area adopting only two input motions were
performed. Thus additional numerical studies using various input motions at a number of sites are required for a quantitative assessment of 2-dimensional effects in shallow and wide basins.

![Graphs showing comparisons between response spectra at the basin edges from 2- and 1-dimensional analyses](image1)

**Fig. 9.** Comparisons between response spectra at the basin edges from 2- and 1-dimensional analyses

![Graphs showing comparisons between response spectra at the basins inside from 2- and 1-dimensional analyses](image2)

**Fig. 10.** Comparisons between response spectra at the basins inside from 2- and 1-dimensional analyses

**CONCLUSIONS**

In order to sensibly estimate the site effects at Gyeongju which is located near several capable faults, a GTIS within a GIS framework for predicting reliably of spatial geotechnical information was built. It was based on both extensive site investigation data and the geo-knowledge data obtained from a site visit. Two-dimensional seismic response analyses for a couple of typical cross sections (N-S and W-E basin sections) 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 2-dimensional basins in Gyeongju showed very shallow and wide shapes having the value of 0.015 for the ratio of depth to width.

From acceleration time-responses on the ground surfaces from the 2-dimensional 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 contrary to the locations at and near the basin edges because the incident waves were propagated vertically along the horizontal soil layers in which the high frequency contents were filtered.

For evaluating the 2-dimensional site effects, 1-dimensional FE seismic response analyses were additionally performed at the selected 17 soil sites. These results were compared with those of the 2-dimensional analyses. From the comparison results of the response spectra, the differences between the 2- and 1-dimensional analyses were scarcely observed at most plain sites located inside the basins. However, the larger spectral accelerations of the 2-dimensional analyses in the long period range were partly observed at and near the basin edges. Predominantly, at several locations, the response spectra were dramatically identical with each other. This indicated that a simple 1-dimensional analysis method would be appropriate in the plain locations and that the 2-dimensional basin effects could be negligible at the interior parts in the shallow and wide basins.

REFERENCES


