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# THE EFFECTS OF SURFACE GEOLOGY ON SEISMIC MOTION

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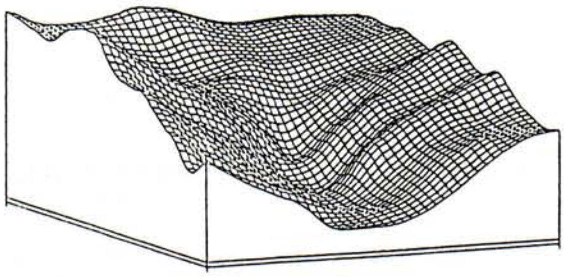

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# REASSESSMENT OF THE INTENSITY OF STRONG MOTIONS EXPERIENCED BY THE SUBURB OF ATHENS HALANDRI DURING THE CORINTH 1981 EARTHQUAKE AND COMPARISON WITH MACROSEISMIC OBSERVATIONS - (I) ONE DIMENSIONAL MODELLING

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## ABSTRACT

For the purpose of studying the effects of local site conditions on earthquake damage to buildings, a prediction of ground motions in the Halandri suburb of Athens during the 1981 Corinth earthquake is made by means of numerical analysis employing one dimensional modelling.

The expected strong ground motion at the bedrock was synthesized by convolving a windowed random time series with an assumed Brune source pulse modified by a high frequency cutoff, taking into consideration all the known source parameters of the rupture process.

The area studied was separated into 720 squares each with dimension of about 114mx114m and the geological, physicomechanical and dynamic properties of the representative ground column groups, were estimated by drilling data , laboratory results or empirical correlations. The seismic response analysis of each ground section group, justify the patterns of damage distribution of buildings in the region occurred during the earthquake. The anomalously distributed macroseismic observations at Halandri seems to be explained by a combined effect of the complex topography of the bedrock and the presence of low-velocity subsurface sediments.

## 1. INTRODUCTION

Local geology plays an important role in changing the characteristics of ground motion during earthquakes, giving rise to large amplifications and spatial variations of shaking.

Effects of soil conditions on ground motion have been observed in well documented earthquakes (e.g. Jennings 1971, Sing et al 1988), and in regression analysis of strong motion data (e.g. Cambell 1985). In addition, there is a strong evidence that localized damage distribution is related to lateral irregularities in subsurface topography (e.g. Bard and Bouchon $1980_{a,b}$, Sanchez-Sesma 1983, Bard and Tucker 1985).

On February 24, 1981 an earthquake of magnitude $M_s$=6.7 occurred in the eastern part of the Gulf of Corinth Central Greece (Fig.1), at a distance of about 60Km from Athens. The present paper was stimulated by the fact that buildings in the Halandri suburb of Athens showed much more structural damages than similar buildings in other parts of the city. The spatial variation of damages in Halandri was also significant. This fact calls for detailed investigations and decisive antiseismic measures at the region. For purposes of seismic microzoning and land-use planning dynamic characteristics of the expected ground motions at Halandri are synthesized and compared with the patterns of damage distribution observed in the region during the above earthquake.

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The main stages of the research are: a) analytical synthesis of the expected earthquake motion at the seismic bedrock of Halandri and b) Modelling the entire region by representative 1- dimensional laminated ground types. A next stage considering the effect of bedrock morphology employing 2-dimensinal models is the subject of another publication (Tselentis and Vasiliou 1992).

## 2. STRONG MOTION SYNTHESIS AT HALANDRI

Ground acceleration was not recorded in the investigated region or in the Athens basin. In order to estimate the seismic characteristics of the motions at Halandri and correlate these with the observed building damages, the seismic field was synthesized numerically by convolving a windowed random time series with an assumed Brune's source pulse modified by a high-frequency spectral cutoff. Only SH waves are taken into account since their contributions to earthquake damages are considered as the most important at small epicentral distances. The ground velocity can be approximately expressed by:

$$u(t) = i(t) * \dot{s}(t) \qquad [1]$$

where i(t)is the impulse response of the medium (dependent on a given site, source location and focal mechanism), and $\dot{s}(t)$ is the displacement source time function. The symbol (*) stands for the convolution operator. The velocity source time function $\dot{s}(t)$ is adopted in the following form (e.g. Boor 1983, Zahradnik and Urban 1989):

$$s(t) = \frac{\partial}{\partial t}(F^{-1}[\frac{M_o}{1+(f/f_c)^2}]) * \frac{\partial}{\partial t}(F^{-1}[\frac{1}{\sqrt{1+(f/f_{max})^8}} \qquad [2]$$

where $M_o$ is the seismic moment and $f_c$ is the corner frequency operator.

The second term of eq.2 is a low-pass filter, rapidly attenuating all frequencies greater than $f_{max}$, which isassumed equal to 20Hz, although the $f_{max}$ cutoff has not yet been confirmed by earthquake data at our territory.

The first term of eq.2 is the derivative of the well known Brune's displacement function. The impulse response of the medium i(t) was adopted in the following form:

$$i(t) = \frac{2}{4\pi \rho V_s} \frac{0.6}{R} h(t) * F^{-1}[e^{\frac{-\pi f R}{V_s Q}}] \qquad [3]$$

where the last term in [3] represents the energy dissipation due to anelastic properties along the propagation path R with a quality factor Q, a shear wave velocity $V_s$ and h(t) is a stochastically modeled time series according to the following equation:

$$h(t) = const.r(t).w(t) \qquad [4]$$

where r(t) is a random time series generated as random numbers occuring at equal intervals $\Delta t$ with a zero mean and standard deviation $\sigma$, and w(t) is a shaping window of the form:

$$w(t) = te^{(1-t/to)}/t_o \qquad [5]$$

where $t_o = T_d/6$ and $T_d$ is the duration of the seismic signal which is related to the corner frequency by:

$$T_d = 1/f_c \qquad [6]$$

By choosing the constant in eq.[4] as $(I\Delta t\sigma^2)^{-1/2}$ where $I = \int w^2(t)dt$, this results according to Parseval's theorem that h(t) has its amplification spectrum oscillating around unity.

All the above formulae serve a target to be fitted by data from the region and earthquake under study (Kim et al 1984). Using a seismic moment of $7.28 \times 10^{25}$ dyne.cm, a stress drop of 34 bar, a shear wave velocity of 3.7 Km/s, a corner frequency of 0.14Hz is determined. The random time series r(t) is generated at time intervals $\Delta t = 0.0076355$ with a standard deviation of 1/3. The mean density of the crust is taken as $3Kg/m^3$ and a value of Q=100 is assumed. The calculated synthetic accelerogram at the seismic bedrock of Halandri is shown in Fig.2. This shows a peak acceleration of about 0.05g. Using the same earthquake characteristics (magnitude 6.7 and epicentral distance of 60Km) and taking into account the relationships published by Cambel (1981) it is estimated that the peak acceleration of bedrock in Halandri is likely to be from 0.05 to 0.07g. The dominant natural period of the motion for bedrock is estimated using the relations of Seed et al (1969) as 0.3s. All these results are in very good agreement with the results from the numerical synthesis.

## 3.GEOLOGICAL AND GEOTECHNICAL CHARACTERIZATION

The geological setting of Halandri area and the physical and mechanical properties of the various soil and rock formations play an important role in estimating the seismic motion and damage of the region. All these data are relatively well established from an extensive investigation carried out by the Soils Division of Central Public Works Laboratory (C.P.W.L.), after the 1981 earthquakes (Christoulas et al. 1985). Some other geotechnical surveys have also been carried out in Halandri area for design and construction purposes: (Athens Subway project, subsurface passings, private and public buildings, reports by C.P.W.L.,1969, 1979, 1980, 1981, 1983, 1986).

During these investigations, 66 boreholes were drilled all over the region, which was approximately $10Km^2$. Based on collected borehole and laboratory data, the encountered lithological units were simplified and the stratigraphic model of Halandri area (from the bottom to the top of the coloumn) was found to be composed of the following three distinct ground units (Fig.3):

-Bedrock, represented by "Athenian Schist" (SL), consisting of brownish yellow shale, strongly weathered at the upper part of the layer (ground unit 3).

-Upper Tertiary formations, consisting of red brownish sandy clay (ground unit 2)

-Recent deposits, consisting of brownish-brownish yellow sandy clay and some brownish sandy silt-clay (ground unit 1).

For a more accurate estimation of seismic motion, a reliable and detailed assessment of surface and subsurface ground classification of geotechnical properties was found necessary. For this purpose, the region under study was divided into 720 squares, each with dimensions of about 114mx114m (Fig.4). In this figure, according to drilling results and the simplified ground model of Fig.3, the depth of bedrock and thickness of recent deposits, in different symboles, is represented for each square.

The total number of squares, define 18 different ground column groups (Fig. 5). Next, ground properties such as the soil classification according to the USCS and the unit weight ($\rho$), as well as the unconfined compressive strength ($q_u$) of each Halandri formation are considered important for the seismic response analysis of the region.

On the basis of collected laboratory data, the ground unit 1, is characterized as CL, SC, SM-SC and the average unit weight for this type is 2.1 $t/m^3$, the ground unit 2 is characterized as very stiff to hard clay (according to SPT results) of low to high plasticity (CL, CH), with an average unit weight of about 2.2 $t/m^3$. The unit weight for ground unit 3 has been found to be 2.3 $t/m^3$, from conventional rock-mechanic laboratory tests carried out on "Athenian Schist".

The unconfined compressive strength $q_u$, and the indirect resulting undrained shear strength, $C_u$, ($C_u = q_u/2$) were calculated for each profile of Fig.5 as average values of $q_u$ estimated in each zone of different depth for ground units 1 and 2. In ground unit 1, the mean $C_u$ varies between 69 and 136 $KN/m^2$ whereas in ground unit 2, a considerable variation of average $C_u$ values was observed, showing a mean increase with depth (126 $KN/m^2 \leqslant C_u \leqslant$ 411$KN/m^2$).

## 4. ESTIMATION OF DYNAMIC CHARACTERISTICS

For the estimation of seismic motion, the dynamic properties such as the shear wave velocity, $V_s$, dynamic shear modulus, $G_o$, ($G_o = \rho V_s^2$) and the critical damping ratio ($\xi$) are required. Due to the small number of Cross-Hole tests carried out over Halandri area, values of the dynamic shear modulus of ground units 1 and 2 were taken, using the empirical correlation (Sabatakakis and Vasiliou 1989):

$$G_o = 1000\, q_u \qquad [7]$$

This equation was established for clayey and marly Greek formations and gives the distribution of $G_o$ with depth. In order to check the applicability of equation 7 in this investigation, the values of $G_o$ obtained from in situ Cross-Hole testing and those estimated from equation 7 were compared. In Fig.6, pairs of values of $G_o$ obtained from the same depth of a single borehole (used for both Cross-Hole testing and sampling) were plotted. It can be seen from this figure, that there is a negligible scattering and thus the use of eq.7 is justified.

The resulting average $G_o$ values for ground unit 1, varies from 138 to 272 MPa, but for ground unit 2, a considerable variation of $G_o$ (252 MPa $\leqslant$ Go $\leqslant$ 822 MPa) is observed. For ground unit 3, a value of shear wave velocity of about 800 m/sec is assumed, which is considered as representative of the upper part of strongly weathered "Athenian Schist".

The usual shearing strains encountered during earthquakes are between $10^{-6}$ and $10^{-3}$ and critical damping ratio values decrease with increasing stiffness of cohesive soils. For this reason, the following damping ratio values ($\xi$), based on the empirical curves proposed by Seed and Idriss (1970) and the depth zoning of ground section groups of Fig.5 were assumed as: a) $\xi$=0.1 for depths up to 10m, b) $\xi$=0.08 for depths between 10m and 15m and c) $\xi$=0.05 for depths greater than 15m.

Results of geological and geotechnical investigations as modified for the ground column groups of this investigation and also the dynamic properties characterizing the three ground units of each section, are illustrated in Table1.

## 5. ESTIMATION OF SURFACE ACCELERATION

The data of representative ground column groups of Table1, were numerically modelled and the seismic response of each column was computed, assuming vertically incident SH-waves, described by the previously synthesized accelerogram. The seismic motion distribution at the ground surface was derived for each square of the grid.

Due to the order of magnitude difference between the epicentral distance and the intersite distances, it was assumed that the incident motion from bedrock was the same beneath each soil column group.

Nonlinear, viscoelastic properties of the soil layers and one-dimensional wave propagation were taken into account using equivalent linear soil properties (Idriss and Seed 1968, Seed and Idriss 1970). Initial estimated values of dynamic properties shown in Table1, were also modified to be compatible with the strains in the layers, calculated from the response analysis of the models subjected to incident seismic waves.

The multiple reflection method has been applied to calculate the corresponding transfer functions. The amplification curves for all the representative ground column groups in Halandri area, are shown in Fig.7. Surface accelerations were calculated in all 720 squares.

## 6. DISCUSSION OF THE RESULTS

Halandri is one of the regions of the Athenian basin which suffered severe structural damage despite the high construction quality and foundation type of the buildings as compared with other nearby regions.

Ninety buildings with severe structural damage were recorded by the Restoration of Earthquake Damages Section of the Ministry of Public Work immediately after the earthquake. About 20% of the cases were related to one-to-three storey buildings and the remaining to four-to-six storey buildings. Despite the uniform building density the percentage of damages for low and multi-storey buildings was found to vary considerebaly all over the region. Christoulas et al (1985), found a correlation between the thickness of recent deposits, depth to bedrock and type of building damages. In the present research we will try to explain the spatial distribution of damages from the features of the synthesized strong motion at the ground surface.

The calculated surface accelerations for the entire region are presented in Fig.7. Judging from this diagram we see that there is a considerable variation of the experienced acceleration all over the area which can be explained as the effect of the varying thickness and geotechnical properties of the uper layers.

More precisely, the values of the calculated acceleration vary between 0.05g and 0.1g. Comparing Fig.7 and Fig.4 we can see that there is a correlation between the calculated accelerations and the thickness of the recent deposits. Furthermore, a similar pattern is obtained when we calculate the predominant periods of the synthesized ground motion at the surface (Fig.8).

Based on the derived distribution of the predominant periods we can recognize 3 distinct zones. Zone A is characterized by small thickness of recent deposits and depth to bedrock. The predominant periods of the ground motion which were calculated within this zone are relatively low (0.07-0.37sec). These characteristics of the motion are likely to cause severe damage to low rise buildings. This explains the high degree of damage experienced by many low rise buildings (T=0.1-0.35sec), in this zone.

In zones B and C, where the depth to bedrock and the thickness of the recent deposits increases considerably, the calculated predominant periods are greater (0.4-0.65sec). This is in agreement with the characteristic damages experienced by the multi-storey buildings located in these zones.

## 7. CONCLUSIONS

It is considered that the above tendencies of the ground motions of the alluvium models interpret the actual damage distribution of the buildings in Halandri due to the Corinth 1981 earthquake.

The peculiar spatial variation of structural damages for low rise and multi-storey buildings is explained by the relationship found between the geological conditions at each site and the foundamental periods of the structures.

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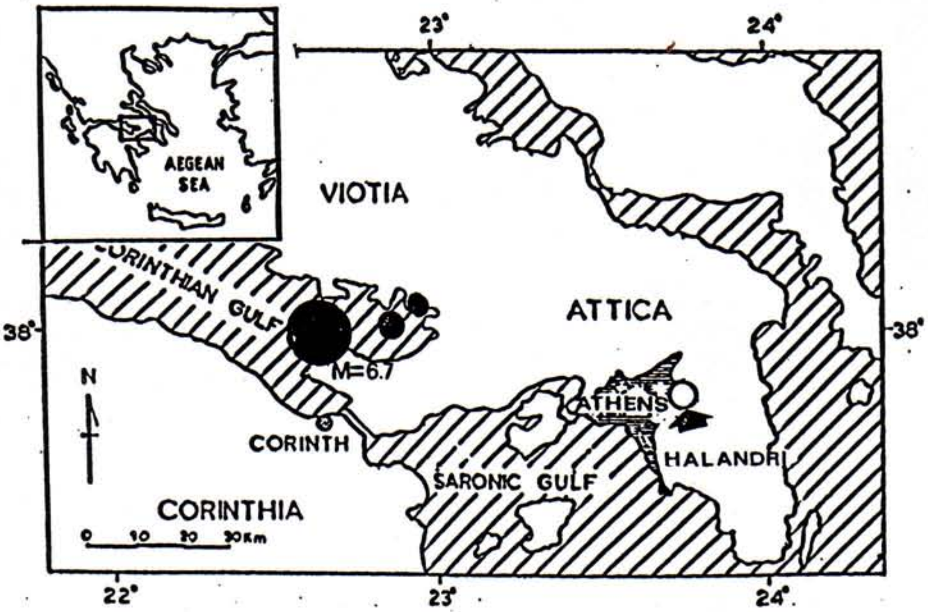


Fig. 1: The Corinth 1986 earthquake and its two major epicenters.

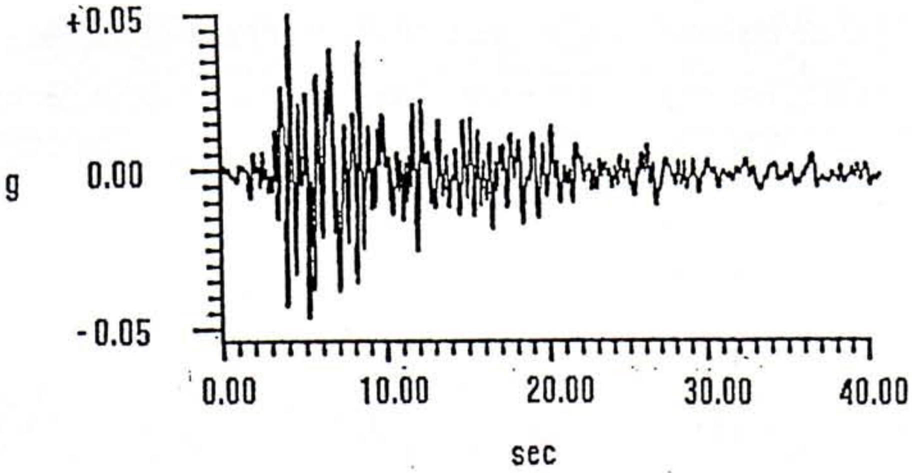


Fig. 2: The synthesized acceleration at Halandri bedrock.

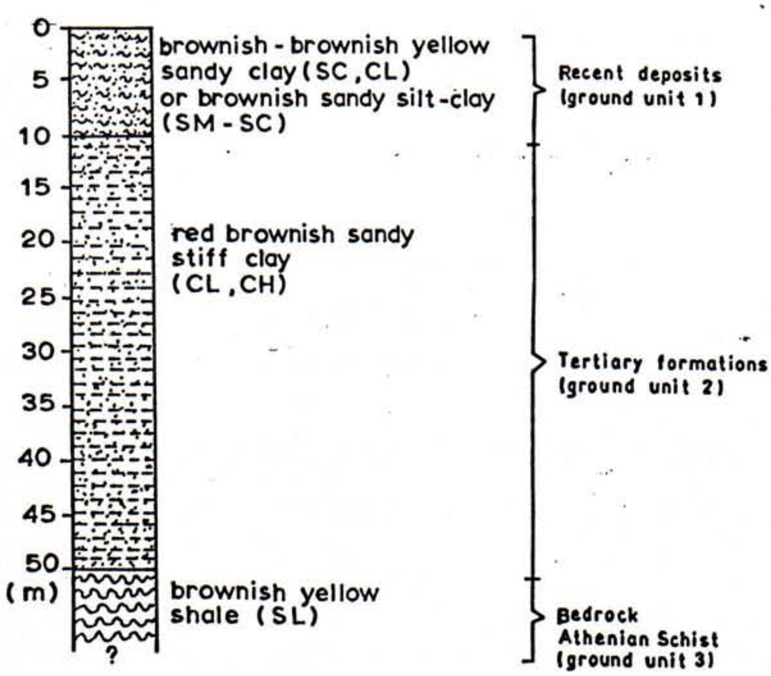


Fig. 3: Representative geological section of the region.

HALANDRI REGION

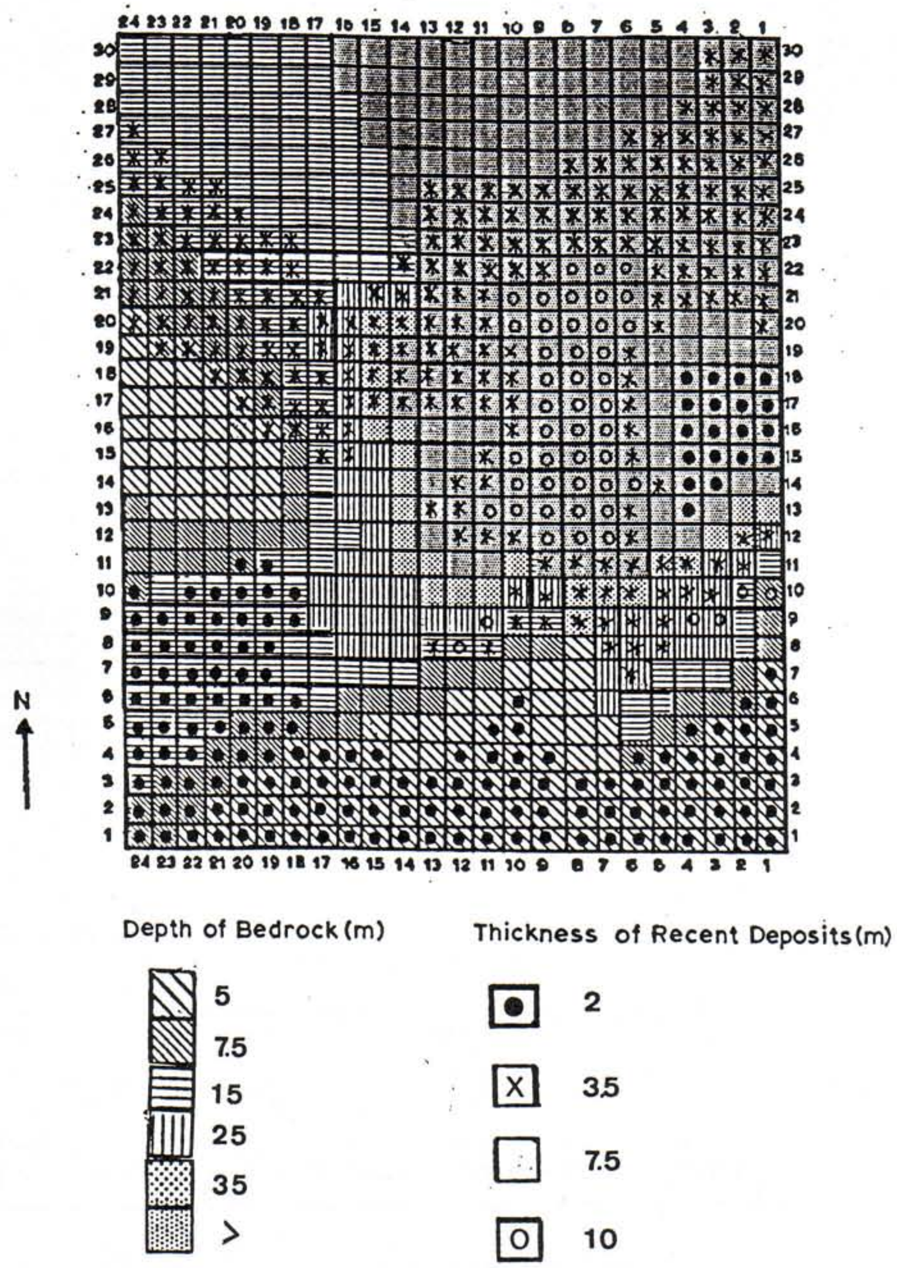


Fig. 4: Subsurface soil map of the investigated region.

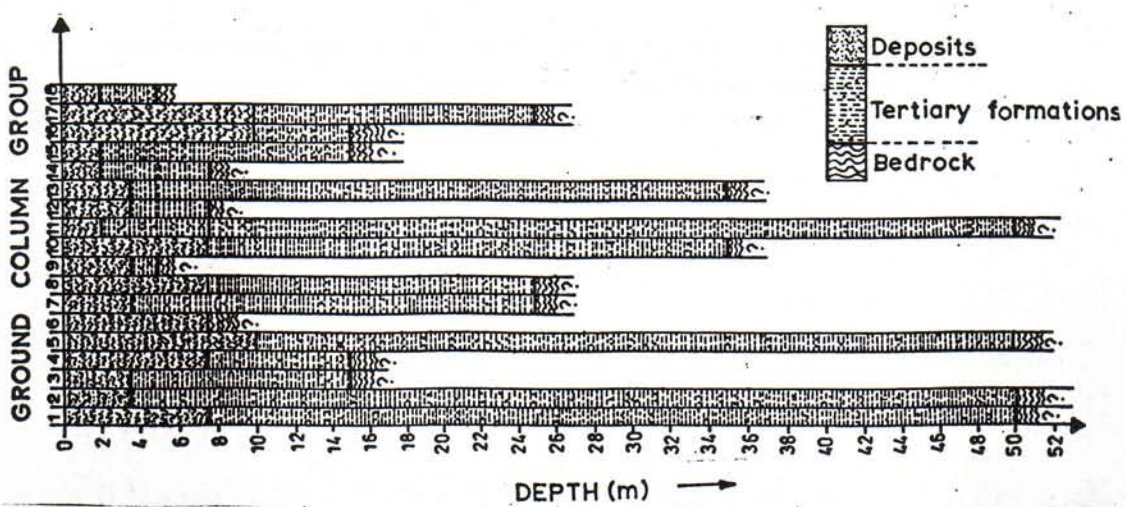


Fig. 5: Typical ground motion column groups.

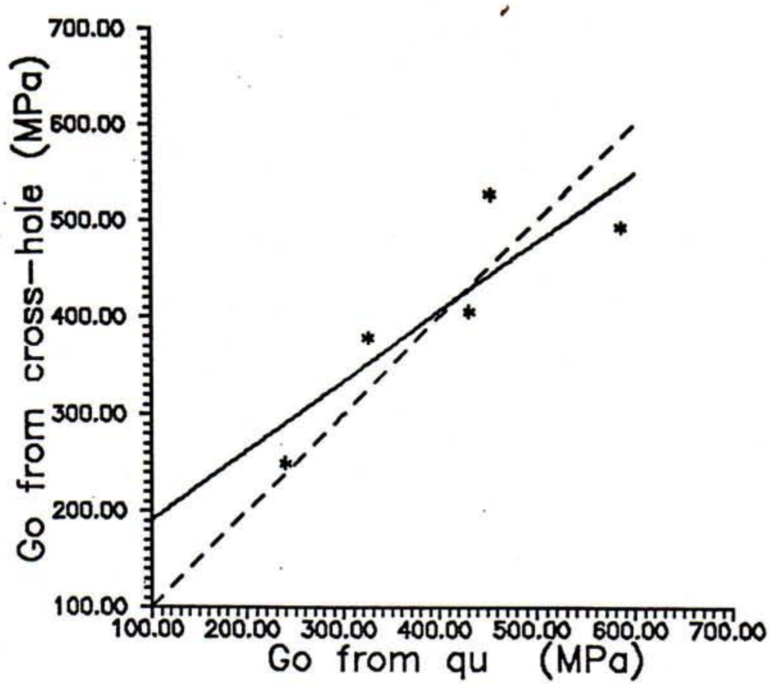


Fig. 6: Comparisson between $G_o$ determined from cross-hole measurements and from $q_u$.

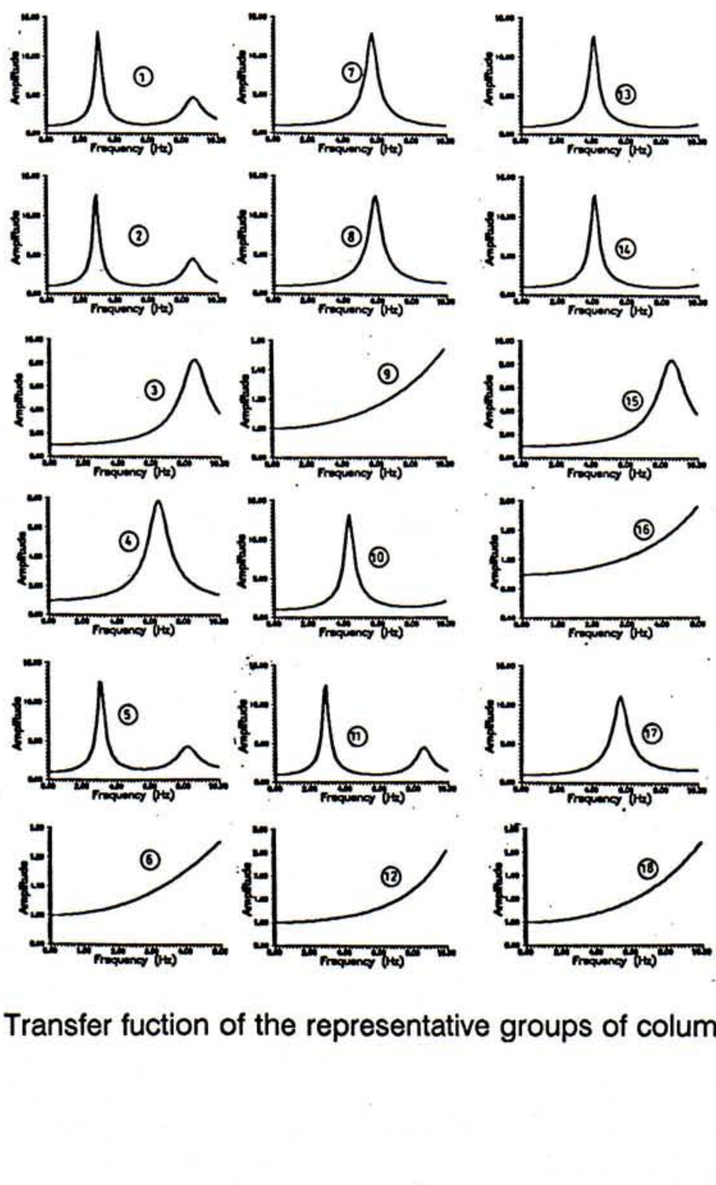

Fig. 7: Transfer fuction of the representative groups of columns.

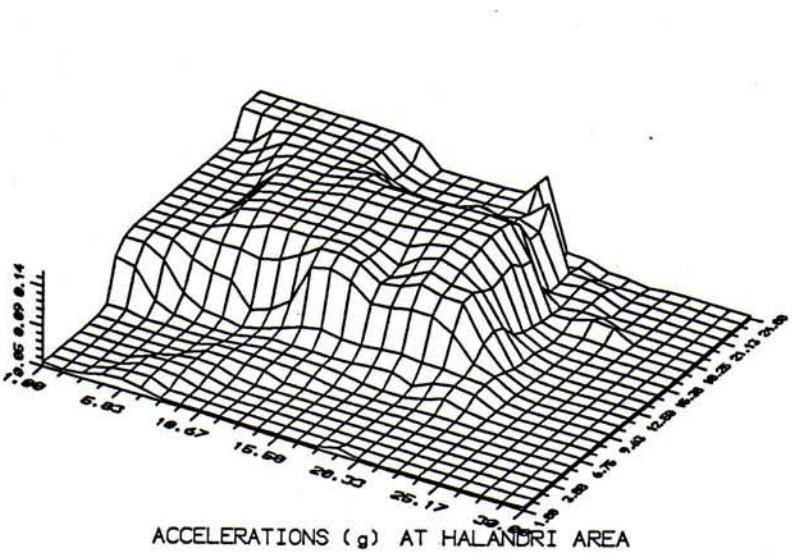


Fig. 8: Calculated accelerations of the region.

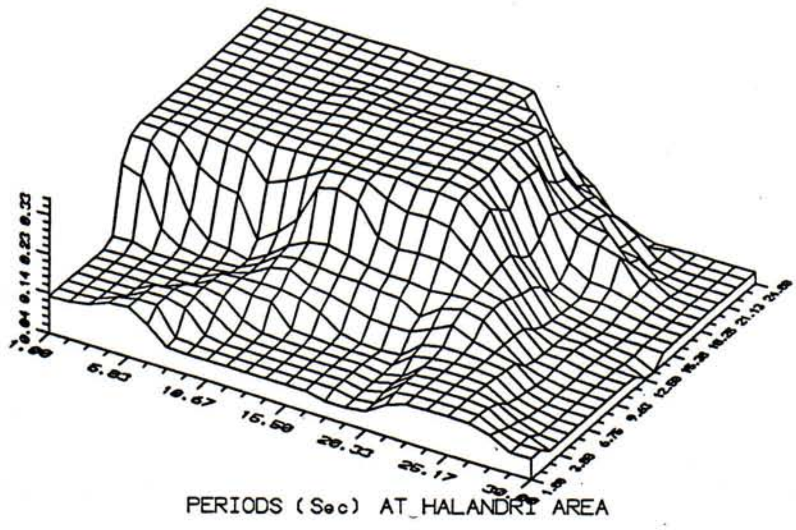


Fig. 9: Calculated periods of the region.

**TABLE1: GEOTECHNICAL PROPERTIES OF THE GEOLEOGICAL FORMATIONS**

| No Co-ordinate | Layer | Soil Type (m) | Thickness ($t/m^3$) | Density ($KN/m^2$) | $C_u$=qu/2 (m/s) | $V_s$ ($KN/m^2$) | $G_o$ | ξ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | CL,SC,SM-SC | 7.5 | 2.1 | 130 | - | 260000 | 0.1 |
| 1 (1,30) | 2 | CL | 42.5 | 2.2 | 396 | - | 792000 | 0.05 |
| 1 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 2 | 1 | CL,SC,SM-SC | 3.5 | 2.1 | 136 | - | 272000 | 0.1 |
| 2 (4,30) | 2 | CL | 46.5 | 2.2 | 358 | - | 716000 | 0.05 |
| 2 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 3 | 1 | CL,SC,SM-SC | 3.5 | 2.1 | 136 | - | 272000 | 0.1 |
| 3 (17,30) | 2 | CL | 11.5 | 2.2 | 286 | - | 572000 | 0.08 |
| 3 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 4 | 1 | CL,SC,SM-SC | 7.5 | 2.1 | 130 | - | 260000 | 0.1 |
| 4 (24,27) | 2 | CL | 7.5 | 2.2 | 356 | - | 332000 | 0.08 |
| 4 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 5 | 1 | CL,SC,SM-SC | 10 | 2.1 | 130 | - | 260000 | 0.1 |
| 5 (6,22) | 2 | CL | 40 | 2.2 | 411 | - | 822000 | 0.05 |
| 5 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 6 | 1 | CL,SC,SM-SC | 7.5 | 2.1 | 130 | - | 260000 | 0.1 |
| 6 (24,24) | 2 | SL | - | 2.3 | - | 800 | - | - |
| 7 | 1 | CL,SC,SM-SC | 3.5 | 2.1 | 136 | - | 272000 | 0.1 |
| 7 (16,21) | 2 | CL | 21.5 | 2.2 | 341 | - | 682000 | 0.05 |
| 7 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 8 | 1 | CL,SC,SM-SC | 7.5 | 2.1 | 130 | - | 260000 | 0.1 |
| 8 (15,21) | 2 | CL | 17.5 | 2.2 | 386 | - | 772000 | 0.05 |
| 8 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 9 | 1 | CL,SC,SM-SC | 3.5 | 2.1 | 136 | - | 272000 | 0.1 |
| 9 (24,19) | 2 | CL | 1.5 | 2.2 | 126 | - | 252000 | 0.1 |
| 9 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 10 | 1 | CL,SC,SM-SC | 7.5 | 2.1 | 130 | - | 260000 | 0.1 |
| 10 (15,20) | 2 | CL | 27 | 2.2 | 391 | - | 782000 | 0.05 |
| 10 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 11 | 1 | CL,SC,SM-SC | 2.0 | 2.1 | 69 | - | 138000 | 0.1 |
| 11 (4,18) | 2 | CL | 48 | 2.2 | 358 | - | 716000 | 0.05 |
| 11 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 12 | 1 | CL,SC,SM-SC | 3.5 | 2.1 | 136 | - | 272000 | 0.1 |
| 12 (18,15) | 2 | CL | 4.0 | 2.2 | 166 | - | 332000 | 0.1 |
| 12 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 13 | 1 | CL,SC,SM-SC | 3.5 | 2.1 | 136 | - | 272000 | 0.1 |
| 13 (14,15) | 2 | CL | 31.5 | 2.2 | 352 | - | 704000 | 0.05 |
| 13 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 14 | 1 | CL,SC,SM-SC | 2.0 | 2.1 | 69 | - | 138000 | 0.1 |
| 14 (20,21) | 2 | CL | 5.5 | 2.2 | 166 | - | 332000 | 0.1 |
| 14 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 15 | 1 | CL,SC,SM-SC | 2.0 | 2.1 | 69 | - | 138000 | 0.1 |
| 15 (19,11) | 2 | CL | 13.0 | 2.2 | 286 | - | 572000 | 0.05 |
| 15 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 16 | 1 | CL,SC,SM-SC | 10 | 2.1 | 130 | - | 260000 | 0.1 |
| 16 (2,10) | 2 | CL | 5.0 | 2.2 | 396 | - | 792000 | 0.05 |
| 16 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 17 | 1 | CL,SC,SM-SC | 10 | 2.1 | 130 | - | 260000 | 0.1 |
| 17 (11,9) | 2 | CL | 15 | 2.2 | 404 | - | 808000 | 0.05 |
| 17 | 3 | SL | - | 2.3 | - | 800 | - | - |
| 18 | 1 | CL,SC,SM-SC | 2.0 | 2.1 | 69 | - | 138000 | 0.1 |
| 18 (1,7) | 2 | CL | 3.0 | 2.2 | 126 | - | 252000 | 0.1 |
| 18 | 3 | SL | - | 2.3 | - | 800 | - | - |