# Application of GIS for earthquake hazard and risk assessment: Kathmandu, Nepal

# Part 4: Seismic hazard assessment

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A frequently used method for assessing and mapping earthquake hazards is seismic hazard zonation. It is the division of an area in smaller areas that have the same hazard level. Two types of seismic hazard zonation exist: The rough method of macrozonation, mapping hazard on a small scale.

Microzonation is used for the same purpose, but on a larger scale. This allows for local geological and site conditions to be taken into account. Macrozonation is usually only based on earthquake recurrence and expected magnitude, and does not take local conditions into account.

This exercise deals with the use of GIS for seismic hazard assessment, using two different methods:

- A simple method, followed by the RADIUS methodology, in which Peak Ground Acceleration is calculated for a scenario earthquake, and the amplification of soil is treated by simple multiplication values. This method gives only a very general approximation of the hazard
- A second method in which we will look more to earthquake spectra, and calculate the natural frequency of the soil, which is used to delineate areas which will experience large ground amplifications at specific frequencies which correspond to natural frequencies of certain building types.

In a real seismic hazard microzonation project the second method should be extended by calculating the response spectra for different soil columns, using strong motion records, and detailed soil column descriptions and properties. This would require a considerable amount of time and input data, and is not feasible within this case study. Here we will not be dealing in detail with the geological conditions of the Kathmandu valley. For this exercise it is important to know that the Kathmandu valley has been filled in by lake-, river-, terrace and talus deposits. The valley is surrounded by steep mountains of the Himalaya In general, large cities like Kathmandu tend to be build on level grounds. Without many exceptions level ground typically is associated with sedimentary (soft) soil deposits. The large damage to high rise buildings in Mexico city in 1985, for example, was mainly due to the fact that this city has been build on very thick and soft lake deposits.

## 4.1 Estimation of PGA in rock in Kathmandu for the various earthquakes in the catalog.

**Objective**:

- Estimation of PGA in rock in Kathmandu for the various earthquakes in the catalog.

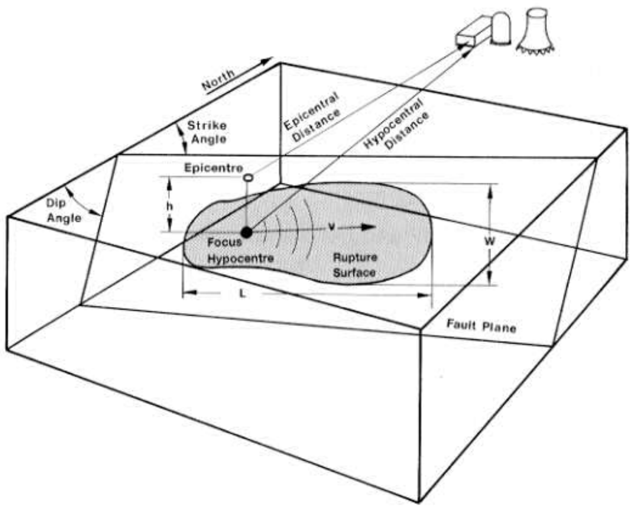
**Time required**: 1 hour

This exercise is a continuation of exercise 1, in which you worked with the information of seismic catalog for Nepal. You will need the distance map that was calculated in exercise 1.

**Data needed**:

- Earthquake catalog of Nepal: `Earthquake catalog` (point map and table)
- Fault map of Nepal : `faults` (segment map)
- City center of Kathmandu: `City Center` (point map)

Now that we know for the earthquake events in the catalog the distance to Kathmandu, as well as the magnitude and the depth (only for those earthquakes for which this information is available), we can make an estimation of the Peak Ground Acceleration in rock in Kathmandu as a result of these events. Input parameters for the scenario earthquake are location, depth, magnitude and occurrence time (hour during the day or night when the event strikes) (see figure below)




The relation between PGA, epicentral or hypocentral distance and Magnitude can be estimated using an attenuation function. In the RADIUS method, PGA can be calculated using one of three attenuation formulas: Joyner & Boore (1981), Campbell (1981) or Fukushima & Tanaka (1990). See table below for functions.

**Table 3 --- Attenuation Equations**

| AttnID | Source | Attenuation Equation |
|---|---|---|
| 1 | Joyner & Boore - 1981 | PGA=10^(0.249*M-Log(D)-0.00255*D-1.02, D=(E^2+7.3^2)^0.5 |
| 2 | Campbell - 1981 | PGA=0.0185*EXP(1.28*M)*D^(-1.75), D=E+0.147*EXP(0.732*M) |
| 3 | Fukushima & Tanaka - 1990 | PGA=(10^(0.41*M - LOG10 (R + 0.032 * 10^(0.41*M)) - 0.0034*R + 1.30))/980 |
| | Note: | E-----Epicentral distance R----Hypocentral distance |

The MMI will be calculated by the formula:

**log(PGA*980)=0.30*MMI+0.014**

**or MMI=1/0.3*(log10(PGA*980)-0.014)**

by Trifunac & Brady (1975). PGA unit is G.

In this exercise we will use the function of Joyner & Boore – 1981. This formula is:

**PGA=10^(0.249*M-Log(D)-0.00255*D-1.02)**

**D=(E^2+7.3^2)^0.5**

E = Epicentral distance

M = Earthquake Magnitude

The distance map was already calculated in exercise 1.

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- Open the table `Earthquake catalog`. Calculate a new column `D` with the formula in the command line:

  ~ **D=(distance^2+7.3^2)^0.5**

- Then calculate PGA using the formula:

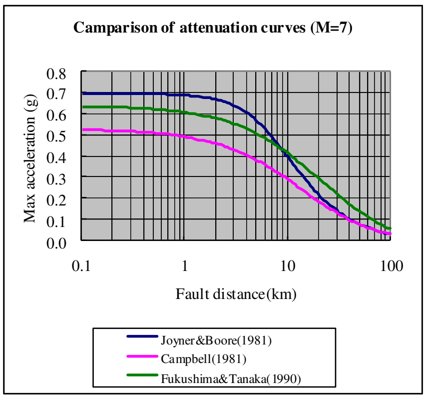
  ~ **PGA=10^(0.249*M-Log(D)-0.00255*D-1.02)**

- Make a graph and display the distance against PGA.
- Also display the PGA values for the earthquake events in the map, and add the map `Distance` to it.

What can you conclude about the PGA values that can be expected based on the earthquake catalog?

Are these values realistic?

What can be concluded about the completeness of the catalog…..



## 4.2 Generating PGA maps for Kathmandu city

**Time required**: 2 hours

**Objectives:**

- Select a scenario earthquake, for which PGA values in rock are calculated
- Use the surficial geological information in order to define ranges of soil amplification
- Generate PGA map for the city
- Evaluate possibility for earthquake induced landslides
- Evaluate liquefaction potential

**Data needed:**

- Geological map: `Geological units` (polygon map)
- Landslide map: `Landslides` (polygon map)
- Watertable depth: `Watertable` (segment map)
- Digital elevation model: `Elevation` (raster map)

Apart from the incomplete earthquake catalog we can also use another source of information, namely the results of the Global Seismic Hazard Assessment Program. The Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR). In order to mitigate the risk associated to the recurrence of earthquakes, the GSHAP promotes a regionally coordinated, homogeneous approach to seismic hazard evaluation; the ultimate benefits are improved national and regional assessments of seismic hazards, to be used by national decision makers and engineers for land use planning and improved building design and construction.

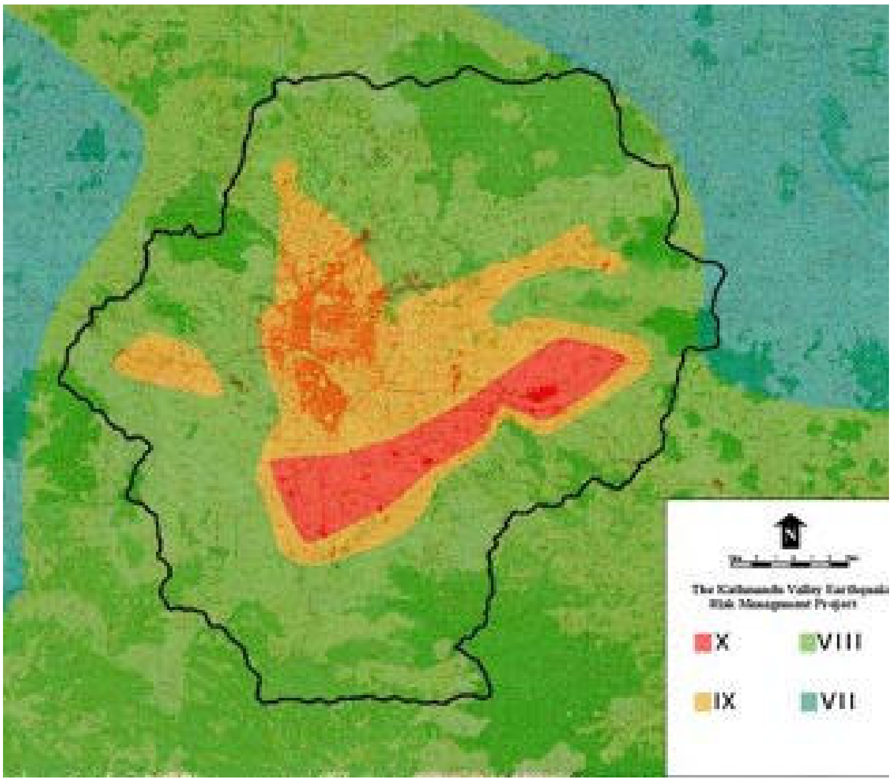
Regional reports, GSHAP yearly reports, summaries and maps of seismicity, source zones and seismic hazard are on the GSHAP homepage on http://seismo.ethz.ch/GSHAP/. This report summarizes the development, the regional activities and the achievements of the GSHAP.

One of the regions of the GSHAP was India-Nepal-Tibet. In this region eighty six potential seismic source zones were delineated based on the major tectonic features and seismicity trends. Using the probabilistic hazard assessment approach of McGuire, adopted by GSHAP, the Peak Ground Accelerations (PGA) were computed for 10 % probability of exceedence in 50 years, at locations defined by a grid of $0.5^{o}$ X $0.5^{o}$. Since no reliable estimates of attenuation values are available for the Indian region, the attenuation relation of Joyner and Boore (1981) was used. The PGA values over the grid points were contoured to obtain a seismic hazard map. The hazard map depicts that a majority of the northern Indian plate boundary region and the Tibetan Plateau region have hazard level of the order of 0.25g with prominent highs of the order of 0.35-0.4g in the seismically more active zones. Based on the GSHAP information Kathmandu source zone 86 is characterized by a PGA of 0.25 g with a 10% exceedence probability in 50 years, corresponding with a return period of 475 years. The maximum magnitude in this zone is: 8.5 .

The earthquake that happened in 1934 was almost the maximum possible one, with a Magnitude of 8.4.

The work of NSET for the KVERMP shows that the 1934 earthquake resulted in Intensities up to 10 in Kathmandu, corresponding to PGA values in the order of 0.9 to 1.0. These can only be explained as a result of intense soil amplification and liquefaction.

Figure: Seismic intensity map of the 1934 earthquake event in Kathmandu, reconstructed by NSET.




In this exercise we will calculate with a scenario earthquake with a magnitude of 8.5 occurring at a distance of 50 kilometers from the city.

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- Calculate the corresponding PGA value for this scenario, using the following formulae:
  - **D=(distance^2+7.3^2)^0.5**
  - **PGA=10^(0.249*M-Log(D)-0.00255*D-1.02)**
- Is this PGA value in accordance with an Intensity of VII to X (see 4.3). Discuss what may cause the difference……..
- Close the map and table windows.

### 4.2.1 Soil Amplification

Soil amplification is estimated by the results from the previous steps, combined with a simple map with soil types. For each soil type a general amplification value from the table below will be used (values are according the the RADIUS method). You may also decide to adapt these values, after discussion.

**Table --- Soil Type**

| Code | Description | Amplification Factor |
|---|---|---|
| 0 | Unknown | 1.00 |
| 1 | Hard Rock | 0.55 |
| 2 | Soft Rock | 0.70 |
| 3 | Medium Soil | 1.00 |
| 4 | Soft Soil | 1.30 |

Soil information can be obtained from the Geological map (called `Geological units`).

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- Rasterize the map `Geological units.` Use the same georeference as for the map `Elevation.`
- Create an attribute table for the map, and add a column for the amplification values.
- Determine for each lithological unit what will be the amplification value from the table above
- Reclassify the geological units with the amplification factors, and name the map: `Amplification factor`
- Multiply the amplification map with the PGA value that you obtained from the previous step. Call the map: `PGA`

**Note:**

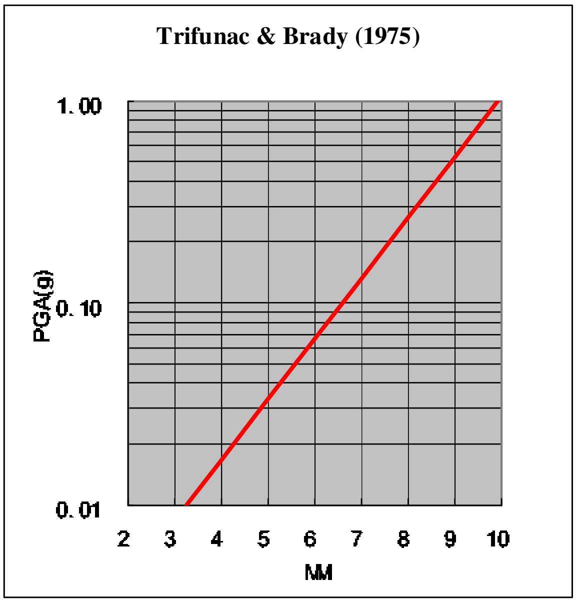
It should be mentioned here that this method is a simplification, and has severe drawbacks:

- Earthquake acceleration should not be presented as a single PGA value, because the natural frequency for buildings with different number of floors, should be related to accelerations in these specific frequencies, in order to be able to cause building resonance. As a rule of thumb, the frequency for building resonance can be evaluated with the formula: $f = 10/N$ (where N = number of floors). Therefore response spectra should be used in stead of single PGA values.
- The amplification factors in the table are just a rough indication. Apart from the type of material, it is the soil depth which plays a very important role in amplification. However, for Kathmandu we didn't have soildepth information available, although one of the input maps was on Boreholes, no depth data was stored in the accompanying table.

## 4.2.2 Converting PGA to MMI

In order to convert the Peak Ground Acceleration values to Modified Mercalli Intensity, the general relation of Trifunac & Brady (1975) is used:

**MMI=1/0.3*(log10(PGA*980)-0.014)**

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- Create a formula in Mapcalc (using the command line) for the PGA to MMI conversion and apply this for the map `PGA` calculated earlier. Name the output map: MMI
- Classify the MMI map in classes of 1 unit (e.g. from 0.5 - 1.5 will be class 1, etc).

**Note:**

According to the figure, an Intensity of 10 corresponds with a very high PGA value of 1 g.

## 4.3 Earthquake microzonation using overburden thickness: Kathmandu, Nepal

**Time required**: 2 hours

**Objectives:**

- Calculate the natural frequency of the soil in Kathmandu valley
- Relate this with the natural frequency of buildings
- Make a zonation for different building altitudes

**Data needed:**

- Soilthickness map: `Soilthickness` (raster map)

A very important factor in the response of the subsurface to an earthquake is the (soft) soil or overburden thickness. Soft soil sediments have a certain natural frequency which depend mainly on their internal (stiffness and strength) properties and thickness. Large ground motion at the surface is often a result of the fact that the soft soil start to resonate at their natural frequency under influence of an earthquake.

This exercise demonstrates how soil or overburden thickness can be used to delineate areas which will experience large ground amplifications at specific frequencies which correspond to natural frequencies of certain building types. In this manner a seismic microzonation map can be made for different building types, mainly based on the overburden thickness map.

### 4.3.1 Theory

#### 4.3.1.1 Soft ground effects

As the seismic wave travels from its source to the surface, the first part of its path is in rock. The last part, usually not greater than several tens of meters, is traveled through the soils overlying the bedrock. It was recognized as early as 350 BC by the Greek scientist Aristotle that soft ground shakes more than hard rock in an earthquake.

The intensity increments caused by this effects can sometimes be as large as 2 to 3 degrees in on the Mercalli intensity scale (Bard, 1994). Because large urbanised areas often are located along or near fertile ground, usually of alluvial or volcanic origin, this type of site effect is of great importance in earthquake hazard assessment worldwide.

#### 4.3.1.2 Amplification on soft soils

The fundamental phenomenon responsible for the amplification of motion in soft sediments is the entrapment of body waves in the soft materials. This is caused by the impedance contrast that exists between soft sediments and bedrock. The impedance of a material is defined as:

$$I = V_s \cdot \gamma \qquad [1]$$

Where:

I = Impedance, in kgm-2s-1

$V_s$ = Shear wave velocity, in m/s
$\gamma$ = Mass density, in kg/m$^3$

Shear wave velocity is a very important soil parameter in earthquake engineering. Intuitively, one can already understand that a very strong or rigid soil (or a soil with a high shear wave velocity) behaves differently under vibration by an earthquake. The wave velocity is dependent on the soil's maximum shear modulus. Shear modulus can be determined under laboratory conditions and several theoretical and empirical relationships exist between shear wave velocity and shear modulus.

$$G_{max} = \gamma \cdot V_s^{\,2} \qquad [2]$$

Where:

$\gamma$ = Mass density (kg/m$^3$)
$V_s$ = Shear wave velocity (m/s)

The contrast in impedance determines the amount of wave energy that is reflected when a seismic wave passes a layer boundary where the material properties change. This is shown by Zoeppritz' equation (Drijkoningen, 2000):

$$R = \frac{I_2 - I_1}{I_2 + I_1}$$

[3]

in which $R$ is the reflection coefficient

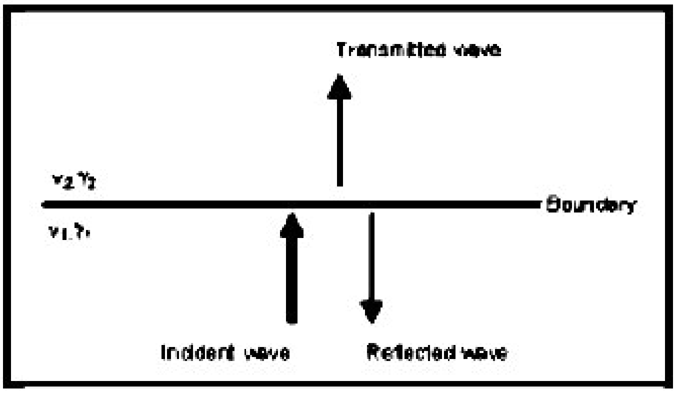


Figure 4.3.1. Reflected and transmitted energy at layer boundary (Adapted from Drijkoningen, 2000)

Using some standard values for rock ($\gamma$=2700 kgm$^{-3}$, $V_s$=1000 ms$^{-1}$) and soil ($\gamma$=1750 kgm$^{-3}$, $V_s$= 1000 ms$^{-1}$), it can be concluded that for a wave passing through a boundary between soft soils and bedrock roughly 50% of the wave energy is reflected. At the surface, all of the energy is reflected because in air the shear wave velocity $V_s$ is zero.

Upon entrapment, interference of the waves will start to occur. Apart from the initial wave, the reflected waves too become sources of motion. When looking at a horizontally layered structure, the problem simplifies to a one-dimensional one, incorporating only the trapping of body waves that travel up and down in the soft surface layers. When lateral discontinuities occur within the structure, the surface waves are influenced as well, making the situation very complex.

Trapped waves interfere, causing amplification of motion and resonance patterns. Resonance occurs when wave peaks coincide, resulting in a addition of amplitudes and a larger amplitude for the motion caused by these waves. Resonance does not occur at one specific frequency, but at several, resulting in site- and material specific resonance patterns. The mathematics behind this are explained below (from: Kramer, 1996):

The resonance spectrum for a uniform damped soil on rigid rock will look like the one in Figure 4.3.2.

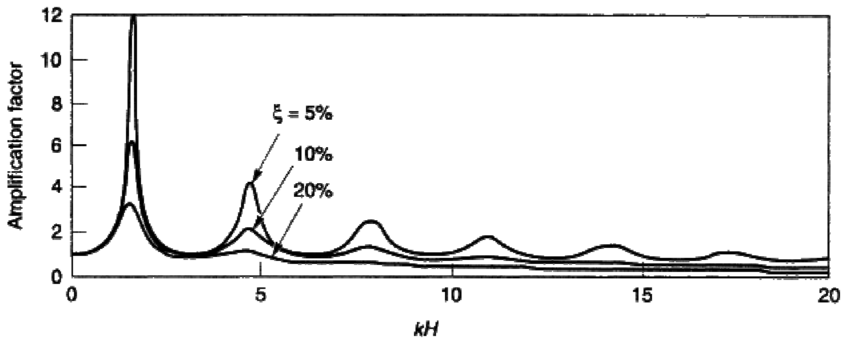


Figure 4.3.2. Resonance spectrum for uniform damped soil on rigid rock (From Kramer, 1996).

While amplitude varies with damping, natural frequencies do not. The natural frequencies of a soil deposit are given by:

$$f_0 = \frac{V_s}{4H} \qquad \text{(fundamental)} \qquad [3]$$

$$f_n = (2 \cdot n + 1) \cdot f_0 \qquad \text{(harmonics)} \qquad [4]$$

With:

$f_0$, $f_n$ = frequency for the first and n-th peak, in Hz

Vs = shear wave velocity, in ms-1

H = thickness of the soft soil layer, in m

As can be seen in Figure 4.3.2, amplification peaks quickly decrease in size due to damping. Because of this, the most important amplification occurs at the fundamental frequency. The fundamental frequency or the associated *characteristic site period* provides already a very useful indication of the frequency or period of vibration at which the most important amplification can be expected.

### 4.3.1.3 Surface motion

Upon arrival at the surface, the seismic waves cause a vibrating motion of this surface. The most important aspect of this motion is the acceleration. When a structure is subjected to a certain acceleration, this will result in a force acting on that structure. The physics behind this can be explained in a very simplified form by stating Newton's second law of motion:

$$F = m \cdot a \qquad [5]$$

Where:

F = Force, in Newton

m = Mass of the object, in kg

a = Acceleration to which the object is subjected, in $m/s^2$

Since the mass of the object is invariable, the force exerted on it is directly proportional to the acceleration, making this the most important parameter in a microzonation study.

Besides the acceleration, the frequency at which it occurs is another property of surface motion that is of great importance in causing structural damage. Every object has its own natural frequency ($f_N$, mainly determined by its stiffness ($k$) and mass ($M$). A relationship is given in the equation below:

$$f_N = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \qquad [6]$$

Generally, a high building is less stiff (more flexible) than a smaller building and a high building is obviously heavier than a small building. Intuitively, but also considering the previous equation, one can see that taller buildings generally have lower natural frequencies than a small buildings.

In order to determine the exact typical frequency of an object is a very complex issue, and therefore the International Conference of Building Officials have issued a number of rules of thumb for estimating it. The most commonly used one, though originally designed for moment frames and not for concrete and masonry buildings, is:

$$T = 0.1 \cdot N \quad \text{or} \quad f_N = \frac{10}{N} \quad \text{(Day, 2001)} \qquad [7]$$

in which $N$ stands for the number of storeys of the building, and $T$ and $f_N$ denote period in seconds and natural frequency in Hertz, respectively.

### 4.3.1.4 Response spectra analysis

As mentioned, the frequency at which a certain acceleration takes place is a very important factor in the analysis of surface motion. In order to obtain a good idea on seismic hazard caused by surface motion, the surface response can be plotted against frequency, producing a graph as shown in Figure.

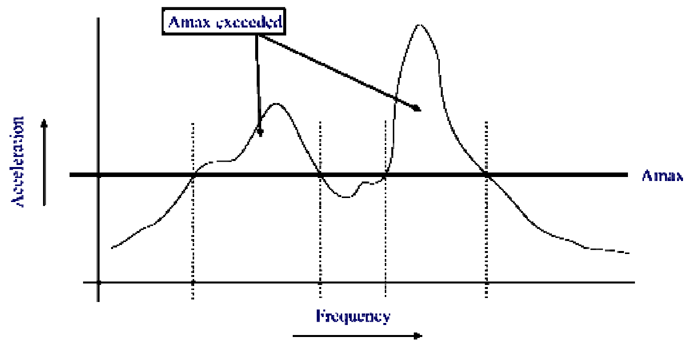


Figure. Frequency dependency of spectral acceleration combined with maximum sustainable acceleration of a building.

As can be seen in the figure, collapse risk of a building capable of sustaining accelerations up to $A_{max}$ depends on the frequency at which shaking takes place. The response spectrum being such an important factor, it usually is the key element in any microzonation study.

## 4.3.2 Calculation of surface response and seismic hazard

### 4.3.2.1 Calculate the characteristic site periods of the overburden.

This step will evaluate the characteristic site periods on the basis of the soil thickness map and different assumed overburden properties.

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- Calculate using MapCalc the *characteristic site period* of the overburden thickness map (`Soilthick`) for 2 different soil conditions on the basis of Equation 3:

$$f_0 = \frac{V_s}{4H}$$

- Calculate a raster map T250 with the characteristic site period for an average shear wave velocity (Vs) of 250 m/s (soft soil).
- Calculate a raster map T500 with the characteristic site period for an average shear wave velocity (V3) of 500 m/s (stiff soil)
- Contemplate what the difference of these different site period maps are in terms of hazard for different building types, i.e. high rise buildings vs. low rise buildings?

### 4.3.2.2 Classification of characteristic site period into hazard zonation map

If the natural period of a building corresponds to the natural period of the overburden at that site, there is a potential hazard that this building will experience large damage. This will due to the large ground accelerations as a results of soil resonance. Particularly in the Kathmandu Valley soil resonance is likely to occur due to entrapment of the seismic signals in the valley because of multiple reflections at the basin's edges.

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- On the basis of equation 7, fill out given below, with the corresponding natural frequencies and periods of the 5 different building classes.
- Make a class domain (`Building class`) on the basis of this table
- Re-classify the maps `T250` and `T500` (use: *Slicing*) into raster maps `T250_class` and `T500_class`, respectively.

Table 1

| Building class | $N_{max}$ | Description | Natural period (s) | Natural frequency (Hz) |
|---|---|---|---|---|
| I | 2 | Single family houses | | |
| II | 5 | Offices, apartment buildings | | |
| III | 10 | Shopping malls, hospital | | |
| IV | 20 | High rise buildings | | |
| V | 100 | Sky scrapers | | |

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- Compare the two classified maps. Is this what you expected? What are your conclusions?
- What type of additional information would you need in order to make a risk assessment on the basis of this hazard zonation?

## References

Bard, P. 1994. Local effects of strong ground motion: Basic physical phenomena and estimation methods for microzoning studies. Laboratoire Central de Ponts-et-Chausees and Observatoire de Grenoble.

Day, R.W. 2001. Geotechnical Earthquake Engineering Handbook. McGraw-Hill, 700 pp.

Kramer, S.L. 1996. Geotechnical Earthquake Engineering. Prentice Hall, Upper Saddle River, New Yersey 07458. 653 pp.