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# **Relevance of Site Characterization in Seismic Studies**

# S. K. Prasad<sup>1</sup>\*, K. V. Vijayendra<sup>2</sup>

<sup>1</sup>Department of Civil Engineering, Sri Jayachamarajendra College of Engineering, Mysore, Karnataka, India. <sup>2</sup>Department of Civil Engineering, Bangalore Institute of Technology, Bengaluru, Karnataka, India.

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## ABSTRACT

Earthquakes have been devastating all over the globe. Earthquakes have not only caused strange problems, but many of the behaviors of structures during earthquake are difficult to understand. Very strong and stable structures are found to be vulnerable sometimes. Tall structures on some occasions have performed better than short structures making the researchers to think beyond the quality of structures. Many times, the ground condition at the site plays a significant role in controlling the performance of structures resting on it. The ground condition at the site is termed as "site effect" and proper characterization of site is necessary to analyze the structures for their seismic performance. This paper discusses the relevance of site characterization with examples and presents the summary of some of the earlier works of the authors regarding site characterization. The effect of Bhuj earthquake of 2001 on buildings in Ahmedabad far off from epicenter is presented. Resonance effect and amplification in ground motion are considered major culprits for damage to more than 100 buildings in Ahmedabad. More accurate method of assessing the natural frequency of ground is necessary for which a simplified and effective approach suggested by authors is presented. Input for such evaluations is shear wave velocity of soil. Many times, it is difficult to determine shear wave velocity at a site. Hence, the author's contribution of summarizing shear wave velocity from standard penetration number is discussed. In summary, rational and simplified methods of analysis with simple input data are more effective to understand the ground behavior during earthquakes. For decades, such studies have been attempted by many researchers to refine the understanding of actual ground behavior during earthquakes.

Key words: Site effect, Earthquake, Shear wave velocity, Resonance, Ground amplification.

# **1. INTRODUCTION**

Uninterrupted functioning of infrastructure facilities is essential for urban society. Most importantly after natural disaster, civil engineering facilities such as transportation, structures housing hospitals, schools, community centers, and other facilities need to be functional. Evidently, post-disaster operations are hampered because of failure of these facilities. The interruption to post-disaster relief operations due to failure of infrastructural facilities is, therefore, directly responsible for increased fatalities and physical damages particularly in an urban society. One of the major natural disasters is earthquake. The direct and indirect effects of earthquakes are responsible for poor performance of built environment eventually leading to their failures. Therefore, it is essential to design structures to withstand extreme seismic forces without significant damages.

The major damages to urban infrastructure observed during past earthquakes include collapse of elevated

and underground transportation systems apart from damages to buildings accommodating essential services. The earthquakes of recent past, including the seismic events of developed countries such as the USA and Japan have clearly demonstrated the vulnerability of urban infrastructure.

It is well established that the major cause for failures is unexpected amplification of seismic waves resulting in enhanced seismic forces than the design forces that are obtained as prescribed in the appropriate code of practice. Figure 1 demonstrates effect of local site condition (characterized by depth of the soil deposit) on performance of buildings as observed during Caracas earthquake of 1967 in Venezuela. This figure clearly demonstrates that the damage potential of a structure depends on closeness of its fundamental period with that of soil deposit.

After the great Kanto earthquake of 1923, it was identified that ground motion at some sites was



Figure 1: Effect of depth of soil deposit and intensity of structural damage observed during 1967 Caracas earthquake [6].

much higher than that at the other sites [2]. During the Michoacan Earthquake of 1985 in Mexico site effect was more clearly identified. In Figure 2, it can be seen that the 44-floor Torre Latinoamericana office building in the background remained almost totally undamaged in contrast to the totally destroyed office building in the foreground. Torre Latinoamericana office building further performed exceptionally during the 1957 earthquake.

During the Loma Prieta earthquake of 1989 which had a moment magnitude of 6.9, it was shown that the ground motions on outcrop of bedrock, ground made of soft mud and ground comprising of sand and gravel were very different in the bay area of Oakland, San Francisco as shown in Figure 3.

### 2. SEISMIC GROUND MOTION

It should be noted that no two earthquake motions are similar. Even during one earthquake, different sites show varying magnitudes frequencies in motion making earthquake engineering more difficult to handle. Figure 4 shows some typical ground motions.

Earthquake waves that originate at some depth below the ground in hard rock at the hypocenter, travel through the rock and later soil onto the surface. The thickness and type of overburden soil is different at different locations. Sometime, rock outcrop may be encountered and sometimes thick layered soft alluvium may be found. During the travel in such ground waves may change form and shape. Figure 5 shows that earthquake waves can be idealized as onedimensional wave though they are three dimensional in nature as they pass through layered soil profile as vertically propagating shear waves.

Figure 6 indicates that the waves that move vertically upward in layered soil will undergo reflection and



**Figure 2:** Survival of Torre Latino Americana office building during Michoacan Earthquake of 1985 in Mexico amid other destructions.



**Figure 3:** Surface motion on different grounds during Loma Prieta earthquake of 1989 [9].



**Figure 4:** Different accelerograms indicating that no two earthquake motions are similar [1].



Figure 5: Earthquake waves propagation through rock and soil from source [3].

| E 1                | ♦ F 1                       | 1   | $H_1 G_1 \zeta_1 P_1 \downarrow Z_1$ |
|--------------------|-----------------------------|-----|--------------------------------------|
| E <sub>2</sub> †   | ¥F <sub>2</sub>             | 2   | ¥z2                                  |
| E <sub>m</sub> ↑   | ¥ <sub>F</sub> <sub>m</sub> | m   | $H_m  G_m  \zeta_m  P_m$             |
| E↑                 | ▼F1                         | m+1 | • ↓ z <sub>m+1</sub>                 |
|                    |                             | 3   |                                      |
| E <sub>n-1</sub> ↑ | ▼ F <sub>n-1</sub>          | n-1 | ↓ z <sub>n-1</sub>                   |
| E <sub>n</sub> ↑   | ▼ F <sub>n</sub>            | n   | ↓z n                                 |

**Figure 6:** Idealization of layered soil profile for one dimensional propagation of earthquake waves.

refraction at multiple levels to create amplification in ground motion at surface which can be explained through one-dimensional wave propagation theory. At the surface, boundary conditions create surface waves which further result in additional amplification of ground motion. Hence, it is important to understand the characteristics and geometry of ground to establish the actual shaking at ground surface.

Site characterization and seismic ground response, therefore, involve the determination of expected ground motions at a site considering the factors such as magnitude of shaking, epicentral distance, focal depth, thickness of overburden, and type of soil from a specified control motion at some point where an observed or estimated motion is available. The procedure involves.

- Determination of the characteristics of the motions likely to develop in the rock formation underlying the site and the selection of an accelerogram with these characteristics for use in the analysis
- Determination of the dynamic properties of the soil deposit
- Computation of the response of the soil deposit to the base rock motions. A one-dimensional method of analysis can be used if the soil structure is essentially horizontal.

The strong earthquake motion characterization involves many factors that influence the surface ground motion. These factors are intensity of input motion (Bedrock motion), frequency characteristics and duration of the input motion that represent seismological factors, soil type, thickness of the soil deposit, underlying rock depth and its type, and geologic structure (topography, basin effects, etc.) that represent geological factors and elastic properties of the soil (low strain values), damping characteristics of the soil, stiffness degradation behavior of the soils due to cyclic load, natural period of the soil deposit, impedance ratio between the bedrock and overlying soil stratum, and stress-strain relationship for soil that represent geotechnical factors.

Other factors regarding analytical and numerical procedures included dimensionality of the problem (1D or 2D or 3D), linear or nonlinear analysis, and continuous or discrete modeling.

In general, the results of seismicity evaluations are presented as the peak acceleration expected for a given return period or as a function of the probability of exceeding the peak values with time. In either case, the acceleration usually corresponds to the shaking at a rock outcrop, not at the surface of a soil profile. Using this site-specific data, estimated acceleration time history of the rock outcrop, as input motion at the bedrock and propagating through soil media the site effects must then be evaluated as a function of soil parameters such as; type, deposit thickness, stiffness properties, damping properties, and the strength of the bedrock motions. There are many empirical, simple, and complex procedures available to compute site-specific dynamic soil response. The site-specific seismic ground response analyses include characterizing the modification in the frequency and amplitude of the seismic waves.

The following are ground motion parameters necessary for seismic analysis.

- A. Amplitude parameters
  - Peak acceleration
  - Peak velocity
  - Peak displacement
- B. Frequency content parameters
  - Ground motion spectra
  - Spectral parameters
  - V<sub>max</sub>/A<sub>max</sub>
- C. Duration

## **3. BHUJ EARTHQUAKE - AHMEDABAD GROUND AMPLIFICATION**

Bhuj earthquake of 2001 of 7.3 magnitude caused devastation near the epicenter killing over 15000 people which was acceptable. However, Ahmedabad city over 250 km from Bhuj experienced 2000 deaths and over 100 buildings collapsed which raised many eyebrows. More than 100 multi-storeyed buildings in number situated in Ahmadabad, perhaps on soft alluvium, built relatively recently (after 1990s) of reinforced concrete 4 to 5 and a few even 10 storied buildings suffered serious damage or destruction during the Bhuj earthquake of 2001 killing over 2000 people. These buildings were situated over 250 km away from the epicenter. They survived other natural calamities such as heavy rain. Scientists and engineered argued that the cause may be due to bad construction quality, not following building by-laws of city properly, improper design, not considering

earthquake resistant design methods (zone 3), stress on economy (money and area), poor material standards or liquefaction of ground. However, the analysis of earthquake ground motion recorded at passport office during the Bhuj earthquake of 2001 on soft alluvium of over 15 m overburden adjacent to Sabarmati river by one-dimension equivalent linear approach [5] showed that the ground motion may have amplified by many folds, being highest at a frequency of 3.51 Hz as shown in Figure 7.

Table 1 shows that the natural frequency of the system (ground and buildings) perhaps coincided with the predominant frequency of earthquake at the site causing resonance. Hence, more rational codal provisions may be necessary introducing the concept of microzonation. Further, more precise site investigation to suit the dynamic analysis may be required [4].

## 4. ALTERNATIVE METHOD FOR FUNDAMENTAL FREQUENCY OF LAYERED SOIL

Perceiving its importance in seismic site characterization tasks, many methods have been formulated and proposed to estimate reliably the fundamental period of one-dimensional horizontally layered soil deposit [8]. While implementing these methods, it is essential to idealize the soil deposit as a layered profile as far as possible closely representing the actual shear wave velocity distribution.

 Table 1: Computed natural and predominant frequencies.

| Description   | Frequency (Hz) |
|---|----------------|
| Predominant frequency of earthquake recorded at Ahmadabad | 1.2-3.32       |
| Natural frequency of ground estimated form program SHAKE  | 3.51           |
| Natural frequency of 3 to 7 storeyed building in I Mode   | 1.50-3.50      |



**Figure 7:** Amplification of ground motion from 1-D analysis.

Uncertainty is evident in idealizing the actual profile into an equivalent layered system because of complex variability of soil properties along the depth. The soil deposit may exhibit distinct continuous variation of soil properties depending on its genesis, stress history and another related process. However, questionably, even such deposits displaying distinct continuous variation soil properties are approximated as layered system. In such situations, employing the methods derived for layered profiles may be inappropriate for estimation of fundamental period.

The authors have proposed a new method [8] for estimating the fundamental period of a layered soil deposit involving a simple procedure. This method requires fewer steps like weighted average shear wave velocity or simplified Rayleigh's methods in which no iterative process is required unlike Madera's or exact Rayleigh's methods. Basically, the distribution of versus across the depth is idealized as the best fit straight line using statistical approach. Following are the steps involved in the proposed method:

- a. The data  $v_{si}$  and mid depth of the corresponding layer ( $Z_{i(mid)}$ ) of layered shear wave velocity profile are tabulated.
- b. The sums S. (Szz, Svv and Szv), the statistical parameters are computed.
- c. Fitting parameters  $v_{so}$  and  $\bar{a}$  are computed.
- d. Shear wave velocity ratio  $\mu = v_{sH}/v_{so}$  is computed where,  $v_{sH} = v_{so} + \bar{a}H$
- e. The fundamental period  $T^{New}$  is computed using the equation.

$$\Gamma^{(\text{New})} = \frac{2\pi H}{v_{s0}(0.324 + 1.254 \mu^{0.853})}$$

Here,  $v_{si}$  is the shear wave velocity at the mid height of a layer,  $v_{so}$  and  $\bar{a}$  are fitting parameters obtained from linear regression analysis and H is the thickness of overburden soil. Figure 8 compares fundamental periods for four field data. From the figure, it can be observed that the error involved in the computation of fundamental frequency by the proposed method is less compared to other methods and the computational efforts are much simpler.

### 5. VS FROM SPT TEST

Many sophisticated techniques have been developed for *in-situ* and laboratory measurements of dynamic properties of soil. However, they are costly, time consuming, and may not be convenient for use in all cases. Hence, researchers have proposed many empirical relationships to estimate the shear wave velocity using results from *in-situ* tests such as standard penetration test. Recognizing the fact that these empirical equations are widely spread in nature, number and results, [7] attempted to validate three relationships, with respect to their general

| Methods         | Ohta and Goto (1978)                                |                       |                                | JRA                               | Lee (1992)  |
|-----------------|---|-----------------------|--------------------------------|-----------------------------------|---|
| Origin          | -   | Alluvial              | Diluvial                       | -                                 | -   |
| Clay            | $V_s$ =62.14 $N^aH^b$                               | $V_s$ =68.79 $N^aH^b$ | $V_s = 89.63 N^a H^b$          | V <sub>s</sub> =100N <sup>a</sup> | V <sub>s</sub> =86.10N <sup>0.116</sup> (H+1) <sup>0.244</sup> (recommended<br>for CL group of soil)  |
| Silt            |   |                       |                                | -                                 | V <sub>s</sub> =82.79N <sup>0.134</sup> (H+1) <sup>0.233</sup> (recommended<br>for ML group of soils) |
| Sand            |   |                       |                                |                                   |   |
| Fine            | $V_s$ =67.79 $N^aH^b$                               | $V_s=74.71N^aH^b$     | $V_s=97.34N^aH^b$              | V <sub>s</sub> =80N <sup>a</sup>  | $V_s$ =68.77 <sup>0.075</sup> (H+1) <sup>0.340</sup> (recommended<br>for SM group of soils)           |
| Medium          | V <sub>s</sub> =63. 49N <sup>a</sup> H <sup>b</sup> | $V_s = 73.33 N^a H^b$ | $V_s=95.55N^aH^b$              |                                   |   |
| Coarse          | $V_{s}$ =68.68 $N^{a}H^{b}$                         | $V_s = 78.08 N^a H^b$ | $V_s = 101.73 N^a H^b$         |                                   |   |
| Sand and Gravel | $V_s$ =71.52 $N^aH^b$                               | $V_s$ =79.32 $N^aH^b$ | $V_s \!\!=\!\! 103.35 N^a H^b$ | -                                 | -   |
| Gravel          | $V_s$ =92.28 $N^aH^b$                               | $V_s = 99.61 N^a H^b$ | $V_s = 129.79 N^a H^b$         | -                                 | -   |

 Table 2: Summary of empirical correlations for shear wave velocity.



Figure 8: Percentage error in fundamental periods computed from different methods.

applicability, by comparing their results with the field data. The results are tabulated in Table 2.

## 6. CONCLUDING REMARKS

The following are a few important inferences from this paper.

- a. Although at macro level, India is divided into four seismic zones, it is important to understand the geometry and properties of overburden soil at the site. Microzonation sometimes may be helpful. However, proper site investigation involving determination of dynamic properties of soil in seismically active zones for important buildings is essential.
- b. The ground motion at the surface can vary depending on the type of soil many times leading to amplification in ground motion. Resonance is a possibility that can result in rigorous shaking at ground surface and eventual damage to infrastructure.
- c. For accurate analysis of site response, precise evaluation fundamental frequency of ground is essential which is difficult to determine. The method proposed by the authors has distinct

advantages over the others.

- d. Acquiring proper input data for the analysis may be a challenge. Estimation of shear wave velocity from standard penetration number is convenient.
- e. Researchers worldwide are trying to bridge the gap between actual behavior during earthquakes and our understanding of the phenomenon. Although the goal has not yet been fully achieved, it is possible to reduce the gap.

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## \*Bibliographical Sketch



The corresponding author Dr. S. K. Prasad is a Professor of Civil Engineering at Sri Jayachamarajendra College of Engineering, Mysore with a doctorate in earthquake engineering from University of Tokyo in Japan. He has over 30 years of experience in teaching and research and has published over 140 papers in conferences and journals.

Dr. K. V. Vijayendra is an Associate Professor at Bangalore Institute of Technology with over 28 years of Experience in Teaching and Research. He obtained his Bachelore and Masters Degree in Civil Engineering from Bengaluru University and doctorate from National Institute of Technology Karnataka at Suratkal. He has a number of Publications and has Organized many Conferences and Seminars at his Institution.