Proceedings of IOE Graduate Conference, 2015
pp. 63–68

Analysis of Shallow Seismic Waves to Determine Geo-technical Characterization of Major Earthquake Affected Sites of Kathmandu Valley

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Abstract
The Gorkha earthquake of April 25, 2015 and others have generated intense interest with in the engineering and geological community due to reports of massive inhomogeneous pattern of ground failures and structural collapse in Kathmandu Valley. MASW is used in different sites of Kathmandu Valley to determine geotechnical characterization of near surface materials. Tabulated values of compressional wave velocity (V_p) and shear wave velocity (V_s) can be extracted from inverse modeling are employed in established empirical expressions to determine allowable bearing capacity (q_a) and elastic modulus (E) of soil. The result shows the presence of silty-sand, clay and loose gravel soil with low bearing capacity and elastic modulus in most of the sites are responsible for devastation. Some structural defects or use of low quality construction materials during manufacturing might be the cause of destruction in soil with comparative high allowable bearing capacity and elastic modulus.

Keywords
Gorkha Earthquake – MASW – Compressional wave velocity – Shear wave velocity – Allowable bearing capacity – Elastic Modulus

1. Introduction

The Kathmandu valley, falls in one of the most active tectonics zones of the Himalayan belt and has experienced many recurring destructive earthquakes in the Past [1]. Since the Kathmandu valley is the parts of active collisional orogenic belt, combining rapid crustal shortening and thickening, that causes frequent strong earthquakes. Major historical earthquakes which are reported to devastate the Kathmandu valley were occured in 1255, 1408, 1681, 1803, 1810, 1833, 1866 and 1934 [2, 3]. Recently in April 25, 2015 at 11:56 NTC, other powerful earthquake ripped through Central Nepal (28.24°N and 84.75°E) at about 77 km northwest from the capital city of Nepal, Kathmandu [4]. This earthquake was later termed as the Gorkha earthquake (after the name of the district where the epicenter was located) and was estimated as having a moment magnitude (Mw) of 7.8. The earthquake was followed by 393 aftershocks of greater or equal to 4 local magnitudes (until 4th September, 2015) along with another major shock of 7.3 Mw on May 12, 2015 with epicenter in Dolakha district (27.82°N and 86.12°E). In the aftermath of the earthquake, the Nepal government reported 8,792 people died and more than 750 thousands houses were either collapsed or damaged partially [5].

The Gorkha earthquake and others have generated intense interest with in the engineering and geological community due to reports of massive inhomogeneous pattern of ground failures and structural collapse. The reconnaissance surveys of different destructive areas of Kathmandu, Figure 1 have been conducted for the quick assessment of its inhomogeneous nature. To say the cause of destruction is whether due to deformation of soil (presence of weak soil) or due to some structural defects during foundation design of the structures was debatable. Reach to the conclusion, this geophysical survey has been conducted at the major earthquake damaged sites inside the Kathmandu valley to determine the allowable bearing pressure in the soil and elastic modulus of soil.

Recording shear wave as well as compressional waves

Figure 1: Some of the major destructions in Kathmandu valley. Figure (1a-1c) complete collapsed buildings in Gongabu, Balkhu and Sankhu area respectively. Figure 1d and 1e is the subsidence and displacement of the ground in Kausaltar area of Bhaktapur, Figure 1f shows the buckled floor in the newly constructed building in Balaju area and destruction in the apartments of horizon in Dhapasi area (Figure 1g)

during seismic acquisition as well as logging provides additional information about the subsurface [6, 7]. A reliable and fast non destructive testing method, MASW[1] allows the propagation of compressional wave and shear wave into the layered earth profiles and calculates the time-depth plot intercept of shallow surface P-wave and S-wave in order to find their velocities [8]. Both waves and their velocities are greatly influenced by the lithological properties (grainsize, shape, compaction, consolidation etc), physical properties (porosity, permeability, density, pressure etc) and elastic properties (shear modulus, bulk modulus, youngs modulus, poisson's ratio etc.)[9]. The differential changes of the velocity with depth infer the subsurface condition. The measured compressional wave velocity (V_p) and shear wave velocity (V_s) relate with these properties leading to the determination of allowable bearing pressure for shallow foundation and elastic modulus of soil.

[1]Multi Channel Analysis of Surface Wave

2. Sites and Geology

The Kathmandu valley, is large oval-shaped Intermounatain basin stretching 30 km east-west and 25 km north-south direction and covering the area of about 650 km^2 lies in the Lesser Himalayan Midland Zone of Cental Nepal. Geologically, the Kathmandu valley is composed of mainly two units – the basement rocks surrounding the terrain of the Kathmandu Basin and the Quaternary lacustrine basin fill sediments overlying the basement rocks. The basement geology of the Kathmandu area has been described in detail by [10]. The basement rock consists of Phulchauki Group and Bhimphedi Group of the Kathmandu Complex of [10] and is formed by Precambrian to Devonian rocks. The Basement rocks of the Kathmandu valley is covered by thick semi-consolidated fluvio-lacustrine sediments of Pliocene to Pleistocene age. Previous Geological and Geomorphological investigations have divided this fluvio-lacustrine sediments of Kathmandu valley into various formations and geomorphic surfaces [11, 12], [13, 14, 15]. [16] has prepared Engineering and Environmental geological map of the Kathmandu valley, and divided fluvio-lacustrine deposits of the valley into seven formations as: Basal Boulder bed, Lukundol Formation, Kobgaon Formation, Kalimati Formation, Chapagaon Formation, Gokarna Formation and Tokha Formation, Figure 2. Correlating with [16], the sites of geophysical surveys located at Kalimati Formation (with dark grey carbonaceous and diatomacious clay beds) where 3 sites of Balaju (Ba1-Ba-3), 2sites of Gongabu(Go1 and Go-2), Balkhu(Bk), Koteswor(Ko), Katunje(Kt) lie and Gokarna Formation (fine to medium sand and silt intercalated with clays and fine gravels) where 3 sites of Kausaltar(Ka1-Ka-3), 2 sites of Dhapasi near Horizon Apartment(Ho-1 and Ho-2), and a site of Sankhu(Sa) lie.

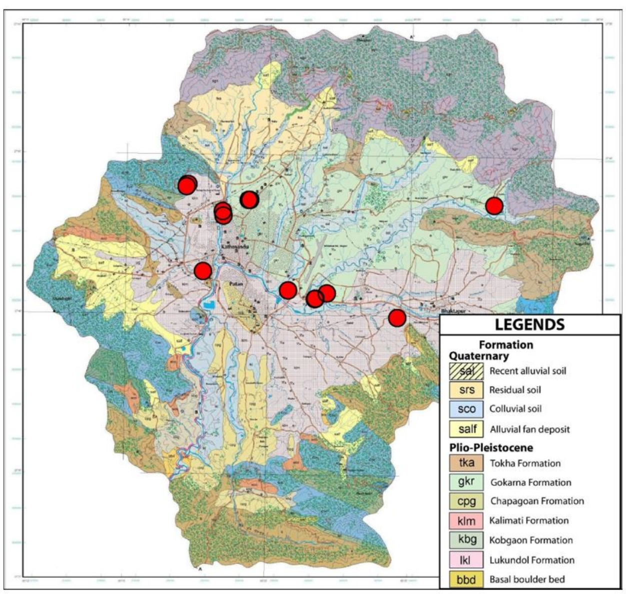

Figure 2: Geological locations of the study sites.(after DMG, 1998)

3. Data Acquisition and Processing

Multichannel analysis of surface waves is a nondestructive seismic method that can be used for geotechnical characterization of near surface materials [8]. That means, in particular the MASW widely used in geotechnical engineering for the measurement of shear wave velocity, identification of the material properties, martial boundaries and special variations of ground etc. The components of MASW consists of 24 channel GEODE Seismograph with 24 geophone of 4.5 Hz. A wooden hammer called Sledge Hammer of 10 kg weight manually impacted on 165 cm^2 aluminium plate was used for creating the energy. Fixed receiver configuration was used and the source was placed between each receiver and at both ends of the survey line. Around 5-10 shots were created and stacked at each location. Data for each shot was digitally recorded and saved in the equipment. The acquired data was then transferred for the analysis. The software Seisimager/SW enables to calculate dispersion curves from CMPCC[2] gathers and create initial 1D-V_s models. These models were finally inverted to generate 2D-V_s models that best fit dispersion curves of observed data. Tabulated values of layer properties (compressional wave velocity, Shear wave velocity, density and Standard Penetration number (N-value) for required channage can be extracted from V_s inverted model.

4. Inserting Seismic Velocities in Empirical Expression

Recording shear waves and compressional waves during seismic acquisition provides additional information about the subsurface [17, 7]. Shallow foundations are those that transmit the structural loads to the near-surface soil or rock [18]. Empirical expression for the allowable soil pressure q_a - underneath a shallow foundation by seismic velocities, the systematic boundary value approach used earlier by [19, 20, 21] will be followed.

When ultimate bearing capacity is expressed in terms of shear wave velocity, the ultimate bearing capacity may be written as:

$$q_{\text{ult}} = g \times \rho \times V_s \times T \quad (1)$$

Since,

$$\gamma = g \times \rho$$

So,

$$q_{\text{ult}} = \gamma \times V_s \times T \quad (2)$$

where, g = 9.81 m/s^2 is the gravity value, ρ is the density of soil beneath foundation, V_s is the shear wave velocity, γ is the unit weight of the soil beneath foundation and T is the time value that is unknown in equation 1 and 2

[2]Common Mid Point Cross Correlation

should be determined as a constant value and equals to 0.1 obtained from calibration process. For this purpose, a typical hard rock formation will be assumed to exist under the foundation with the velocity parameters as suggested earlier by [19, 20]; allowable bearing capacity q_a to be 10,000KN/m^2, shear wave velocity V_s to be 4,000m/s and unit weight γ to be 35KN/m^2 and factor of safety F_s to be 1.4.

According to [21], it is well known that the presence of groundwater affects the soil bearing capacity. In granular soils, the position of the water table is important. Effective stresses in saturated sands can be as much as 50% lower than in dry sand. Seismic wave velocities are also affected from the groundwater. The water saturation in the granular soil causes compressional wave velocity to increase and shear wave velocity to decrease. As a result, V_p/V_s velocity ratio increases depending on the water saturation in granular soil. The safety coefficient value is generally used as 3 for the saturated granular soil. Also, the velocity ratio (V_p/V_s) to be obtained for the same saturated granular soils equal nearly to 6. Therefore, there is no need to reduce bearing capacity as in soil mechanics when, V_p/V_s is used as the safety factor.

Thus, allowable bearing capacity is defined as the ratio of the ultimate resistance or ultimate bearing capacity of the earth structure to the safety factor. i.e.,

$$q_a = q_{ult}/F_s \tag{3}$$

The determination of density will be suitable from the shear wave velocity is given by [20] as,

$$\rho = 0.44 \times V_p{}^{0.25} \tag{4}$$

Where, the density unit is in g/cm^2 and V_s unit is in m/s. For the soil layer No. 2 just under the foundation, several parameters of elasticity, such as shear modulus (G), Modulus of Elasticity or Young's modulus (E) and Poisson's ratio (σ) may be obtained easily [22]. G is related to V_s by the following relations:

$$G = \rho V_s{}^2 \tag{5}$$

Where, ρ= mass density given by $\rho = \gamma/g$ where, γ and g are unit weight and gravity respectively.

$$E = 2(1+\sigma)G \tag{6}$$

where,

$$\sigma = (0.5(V_p/V_s)^2 - 1)/((V_p/V_s)^2 - 1) \tag{7}$$

5. Results and Discussion

Equations 1 - 7 have been used to establish the interrelationship between geotechnical and elastic properties and relationships among the elastic properties in earthquake shaken soil of Kathmandu valley. The tabulated values of layer properties determined from inverse modelling are used in these equations to determine both allowable bearing capacity(q_a),Shear Modulus (G) and Elastic modulus (E) of soil. Here, both compressional wave velocity(V_p) and Shear waves velocity(V_s) are utilized to determine velocity ratio (V_p/V_s), Poisson's ratio(σ), density(ρ), unit weight(γ) and these parameters are again used to compute allowable bearing capacity and elastic modulus. The result is interpreted in two ways:

1. All the values of V_p and V_s of each layers upto 10 meters depth are analysed to compute all q_a , G and E to know the soil properties with depth and know the reason of amplification of seismic waves in the study sites Figure 3 and Figure 4 . High contrast in bearing capacity and elastic modulus is noticed with depth. The values of allowable bearing capacity has been clustered between 90KPa to 120KPa and 30 MPa to 50 MPa of modulus of elasticity. Result shows the presence of medium to stiff silty- sandy clay to coarse to medium sand or sand with little gravel when correlated with [23, 24].
2. The average value of V_p and V_s is determined to summarize q_a , G and E of different sites and for quick comparison of the risk associated in these sites Table 1. The soil of Koteswor have lowest bearing capacity and Elastic modulus of 20 KPa and 9.6 MPa respectively. The highest value of bearing capacity and modulus of Elasticity is possed by the soil of Horizon 2 which are 180 Kpa and 106 Mpa respectively. Sankhu and Gongabu also have more stiff soil with comparatively high values of allowable bearing capacity and elastic modulus.

Destruction pattern of recent earthquake and computed geotechnical parameters of soil in Kathmandu valley shows good extent of harmony. Most of the area of devastation comprises shallow soil with low bearing capacity and elastic modulus which might be the cause of

Table 1: Summary of the seismic and elastic parameters in the study sites

	Location		Velocity		Velocity	Poissions	Density	Unit	Result		
Site	Latitude(N)	Longitude(E)	V_p	V_s	Ratio V_p/V_s	Ratio		wt	qa (Kpa)	G (KPa)	E (MPa)
Balaju1(Ba1)	27°41.31’	85°17.3’	177.36	100	1.774	0.267	1.391	13.64	76.92	13910	35
Balaju2(Ba2)	27°41.32’	85°17.3’	178.28	108.95	1.636	0.202	1.422	13.95	92.90	16879	40
Balaju3(Ba3)	27°41.29’	85°17.3’	161.76	95.53	1.693	0.232	1.376	13.49	76.17	12557	30
Balkhu(Bk)	27°41.22’	85°17.59’	193.99	126.58	1.533	0.13	1.476	14.48	119.56	23649	53
Gongabu1(Go1)	27°43.94’	85°18.55’	247.83	168.25	1.473	0.073	1.585	15.54	177.60	44868	96
Gongabu2(Go2)	27°43.78’	85°18.59’	228.42	158	1.446	0.042	1.56	15.30	167.22	38944	81
Horizon1(Ho1)	27°44.4’	85°19.47’	260.86	174.01	1.499	0.099	1.598	15.67	181.97	48385	106
Horizon2(Ho2)	27°44.8’	85°20.3’	159.16	93.72	1.698	0.234	1.369	13.43	74.12	12024	29
Katunje(Kt)	27°39.74’	85°24.62’	235.23	147.24	1.598	0.178	1.533	15.03	138.57	33235	78
Kausaltar1(Ka1)	27°48.48’	85°21.75’	187.17	116.02	1.613	0.188	1.444	14.16	101.89	19437	46
Kausaltar2(Ka2)	27°40.50’	85°21.81’	166.24	114.87	1.447	0.043	1.44	14.12	112.13	19000	39
Kausaltar3(Ka3)	27°40.71’	85°22.17’	157.96	99.8	1.583	0.168	1.391	13.64	86.03	13854	32
Koteswor(Ko)	27°40.84’	85°20.67	163.87	52.9	3.098	0.442	1.187	11.64	19.88	3321	9
Sankhu(Sa)	27°43.66’	85°27.72’	239.6	143.6	1.669	0.22	1.523	14.94	128.55	31406	76

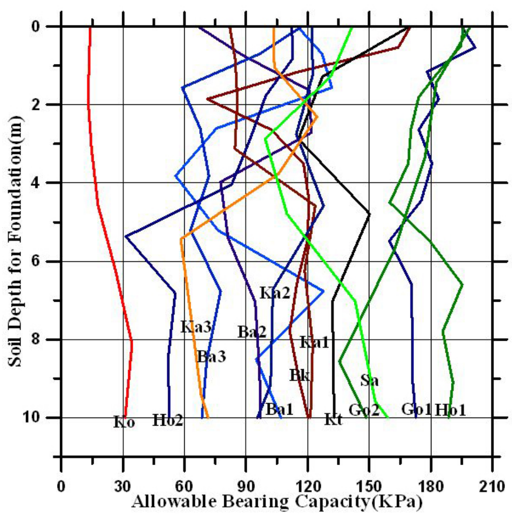

Figure 3: Allowable bearing capacity of soils with depth in different sites

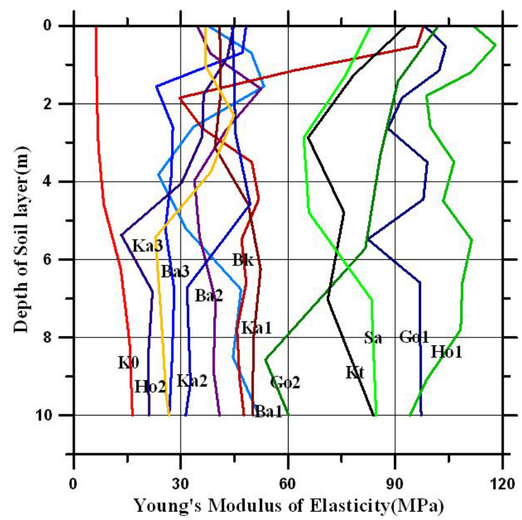

Figure 4: Modulus of elasticity of soil with depth in different sites

structural collapse. The soil of Balaju, Balkhu, Horizon-2 and Kausaltar area have low bearing capacity and low elastic modulus providing low shear strength might be the cause of devastation. However, the destruction around every sites are not only due to deformation of soil. The soil with comparately high bearing capacity and high modulus of elasticity (for example, Gongabu area, Horizon-2 and Sankhu) have encountered large devastation than at the low bearing soil of Koteswor. In those sites, the problems might be due to some structural defect during manufacturing of the foundations or due to use of poor quality construction materials. The value of both allowable bearing capacity and modulus of elasticity is not uniform with depth. There is noticeable contrast in their value with depth which indicates the presence of thin strata of different material. So for shallow foundation in Kathmandu valley, it is not always necessary that increase in depth makes the foundation better. Recognizing the most bearable soil layer and its thickness is necessary for safe foundation design.

6. Conclusion

Both Compressional Wave Velocity (V_p) and Shear Wave velocity (V_s) are the important tool to determine the geotechnical property of soils. MASW enables to determine both V_p and V_s with more accuracy. The velocity ratio (V_p/V_s), Poisson’s ratio(σ), density (ρ), unit weight(γ) which are determined from the existing empirical expressions. These parameters further help to compute allowable bearing capacity(q_a), shear modulus(G) and Elastic Modulus(E). These all geotechnical parameters are summed up to interpret the shallow soil condition and destruction related to earthquake of April 25 and May 12 2015.

The soil of Kathmandu in major consist of soft silty-sandy clay to gravel with low bearing capacity and low modulus of elasticity might be the major the cause of devastation. Some structures being in relatively stiff soil possesed destruction which might be due to some structural defect during designing of foundations or due to use of low quality construction material.

The bearing capacity and Elastic modulus of soil with depth is not consistent, so better understanding and investigation of soil is necessary before designing and construction of structures.

Acknowledgments

The project was supported by the CGER[3] Pvt. Ltd., Kathmandu. The authors express their gratitude to all members of CGER for support and co-ordination. The authors are also indebted to Dr. Kamala Kant Acharaya, Dr. Sunil Kumar Dwevedi and Er. Naresh Kumar Giri, for their valuable guidance and help throughout the research.

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